Bearing Capacity Parameters for Pipe Piles in Stiff to Hard Highly Plastic Clays

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Abstract

The design of steel pipe piles in clay soils is faced with insufficient information regarding the parameters used for estimation of their static ultimate load capacity, namely the adhesion factor and plug length.This paper gives guides for the selection of the mentioned parameters. Direct shear and adhesion tests were performed. The soil tested is highly plastic silty clay statically compacted in the shear box at constant dry density and varying water content covering dry and wet of optimum water content. The adhesion factorwas computed for each test condition. An average value of 0.48 was found for the interface resistance when the water content is lower than the plastic limit. The factor was found to increase with increase in water content for water content higher than the plastic limit.

The Plug length data was generated from a construction site in Melut Basin in Southern Sudanwhere steel pipe piles of different sizes were driven in very stiff to hard silty clay to about the same length and driving records were recorded with extra data regarding plug lengths. Geotechnical investigation preceded the construction activities. The plug data was analyzed for the effects of pile diameter and soil conditions on the plug length. Plug length to diameter ratio ranged between 3.8 and 8.0. Plug length increased linearly with increasing pile diameter and an excellent linear relationship was obtained between the average plug length for each diameter and pile diameter. Piles with small

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diameter gave lower resistance to penetration compared with those with larger diameters.

Keyword: Pipe pile, plug length adhesion factor, highly, plastic clay.

مستخلص

إن تصميم الركائز الفولاذية المفتوحة في التربة الطينية يواجه عدم توفر المعلومات الكافية و المتعلقة بالعوامل المستخدمة في تقدير قوة تحملها للضغط الرأسي وبصفة رئيسة معامل التلامس وارتفاع التربة داخلها. هذه الورقة تعطي موجهات لإختيار العوامل المذكورة. استخدمت تربة طينية فوارة في اجراء اختباري القص والتلامس وذلك بغرض دراسة تأثير الضغط الرأسي للتربة عند كثافة جافة ثابتة ومحتوى مائي متغير.من خلال التجارب المعملية تم التوصل الي ان القيمة المتوسطة لمعامل التلامس هي ٠,٤٨ عندما تكون قيمة المحتوى المائي أقل من معامل اللدونة وتتزايد قيمة معامل التلامس مع ازدياد قيمة المحتوى المائي.

تم جمع المعلومات المتعلقة بارتفاعات التربة داخل الركائز الفولاذية من موقع للتشييد في جنوب السودان. حُللت النتائج لمعرفة تأثير قطر الركائز علي أرتفاع التربة داخلها. ووجد ان النسبة بين أرتفاع التربة داخل الركيزة الي قطر الركيزة تتراوح بين ٣,٨ – ٨,٠ ، كما لوحظ أن ارتفاع التربة داخل الركائز يزداد خطيا بزيادة القطر وتم التحصل علي علاقة خطية ممتازة بين متوسط ارتفاع التربة داخل الركيزة وقطرها. كما درس تأثير قطر الركائز المفتوحة علي مقاومتها للإختراق وتبين ان الركائز صغيرة القطر تعطي أقل مقاومة من الركائز الاكبر قطرا.

1. Introduction

The use of steel pipe pilesbecame more popular in recent years. The major advantage of these piles is the high strength of the steel used, easiness and high speed of installation, can be used for variable pile lengths since splicing is relatively easy and their ductility allows and encourages their use in seismic areas. Small diameter pipe piles have been extensively used in the petroleum rich areas in the Southern Sudan and South-Western Sudan where a lot of development activities had been going on and very stiff to hard highly plastic potentially expansive soils dominate. Their selection was mainly due to scarcity of natural construction materials, the small loads from the structures that need to be supported and their easiness of construction. A major shortcoming of their use is that their interaction with the stiff to hard clays has not been well understood. This paper attempts to provide guidelines for determination of the ultimate capacity of steel pipe piles in highly plastic swelling clays with special emphasis given to the formation of plugging in these piles.

2. Resistance of pipe piles to ioading

Pipe piles are open ended piles and they are often considered as non-displacement, however, their behavior is generally intermediate between non-displacement and displacement piles [1]. As a pipe pile is driven into the soil, a soil column is formed inside the pile as it penetrates the ground. This soil column is termed plug and the plug length is always smaller than the penetrated pile length.

The load capacity of a driven pipe pile depends on the effective length of the plug developed in addition to the resistance developed along the pile shaft and at the pile annulus [2] [1]. The magnitude of the end-bearing resistance of a pipe pile depends on the effective length of the soil plug developed within the pipe. Studies on the plugging effect of pipe piles have been carried out by several researchers [3] [4] [5]. The formation of soil plug takes place during driving.Unplugged or fully plugged modes take place during the initial stages of driving. The formation soil plug starts to develop as driving continues. Internal friction between the plug and the pile helps in densifying the soil in the lower part of the soil plug. When the frictional resistance reaches a certain level, intrusion is prevented and as driving continues fully plugged condition takes place.

For open ended pipe piles the ultimate bearing capacity Qu is expressed by[2] [1]

$$Qu = Qf + Qann + Qplug \ldots\ldots\ldots\ldots(1)$$

Where Qf is the outer frictional resistance, $Qann$ is the end resistance of the steel pile section or annulus and $Qplug$ is the contribution of the plug (Figure 1)

$$Qf = \pi\, do\, \alpha\, Cu\, Ld \ldots\ldots\ldots\ldots\ldots\ldots(2)$$

$$Qpf = \pi Ca\, di\, Lp \ldots\ldots\ldots\ldots\ldots\ldots(3)$$

Here do and di are outer and inner diameters, respectively; Cu is the undrained strength of the penetrated clay along its depth Ld;Ca is the average adhesion of the plug along its length Lp and α is the adhesion factor between the pile and surrounding soil.

Building codes often apply a reduction factor to the end bearing resistance of a closed ended pile when the static pile formulae are used [2]. This factor depends on the penetration depth of the pile into the bearing stratum (Ldin Figure 1).

To apply the relationships given in equations 2 and 3 the adhesion factor α and plug length Lpshould be known. The factor α could be estimated from simulated laboratory tests. However, there is lack of measurement records of the plug length for full-scale piles in the field, specially in clay soils.

This paper presents the results of a laboratory testing program for obtaining the adhesion factor between high plastic swelling clay and a steel surface. Data from a construction site in Southern Sudan clay plains, where steel pipe piles with different diameters were driven into stiff to hard clay of high plasticity and plug lengths were measured, has been analyzed to predict plug length and its relationship to pile diameter.

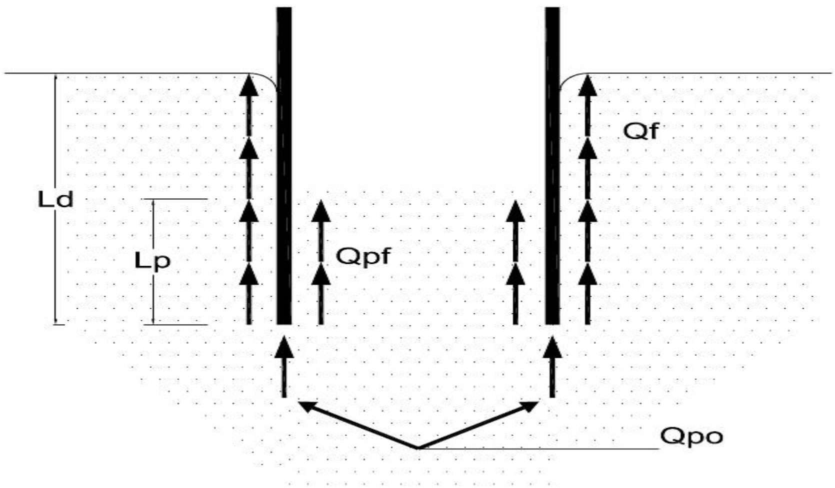

Fig 1: Soil plug formed in open-end pipe pile

3. The laboratory program for determination of the adhesion factor

The testing program constitutes measuring the shear strength of compacted highly plastic clay prepared at varying water content in the direct shear apparatus and the interface strength between the pile and a steel plate in the same apparatus. The adhesion factor is the ratio of the interface strength to the shear strength under the same testing conditions, i.e, water content and vertical stress.

The engineering properties of the soil used in the study are given in Table 1. The shear box size is 60mm x 60mm. For the shear strength tests, known quantities of soils were prepared at different water contents covering dry and wet of optimum moisture (14%, 18%, 23%, 27% and 30%). Each sample was compacted in the shear mould to a target dry density of 1.4 g/ cm^3. The soil was statically compacted in the three layers inside the box cutter using square wood dolly. After compaction the soil was delivered to the shear box machine. A vertical load of 50 Kpa was applied and the sample was sheared at a strain rate of 0.1 mm/min. The data was recorded by a data logger and plotted for the determination of the peak strength.

As for the interface shear tests, the prepared soil samples were compacted inside the lower part of the shear box to the target density at the same water contents used for the shear tests and following the same procedure for sample preparation. A steel plate was cut to the required size and placed at the soil surface to represent the contact surface between steel pipe pile and the CH soil. The machine was operated to measure the shear stress between the plate and the compacted soil. The interface tests were performed under the same vertical load applied for the shear tests (i.e. 50 KN/m^2). The test results are given in Table 2. The adhesion factor (α) is the ratio of the interface shear strength to the peak shear strength for the same water content, dry density and vertical stress. The values of α were computed, presented in Table 2 and plotted in Figure 2.

Table 1: The engineering properties of the soil used for interface tests

Group Symbol	Liquid Limit (%)	Plastic Limit (%)	Specific Gravity	Optimum Moisture (%)	Proctor Maximum Dry Density (KN/m3)	Fines Content (%)
CH	75	23	2.77	23	15.75	86

Table 2: Shear and interface strength test results

Water content %	Peak Undrained Shear Strength (KN/m2)	Peak Interface Shear Strength (KN/m2)	Adhesion Factor (α)
14	94.72	47.48	0.50
18	63.96	33.68	0.53
23	50.69	23.73	0.47
27	34.90	18.66	0.53
30	21.48	15.45	0.72

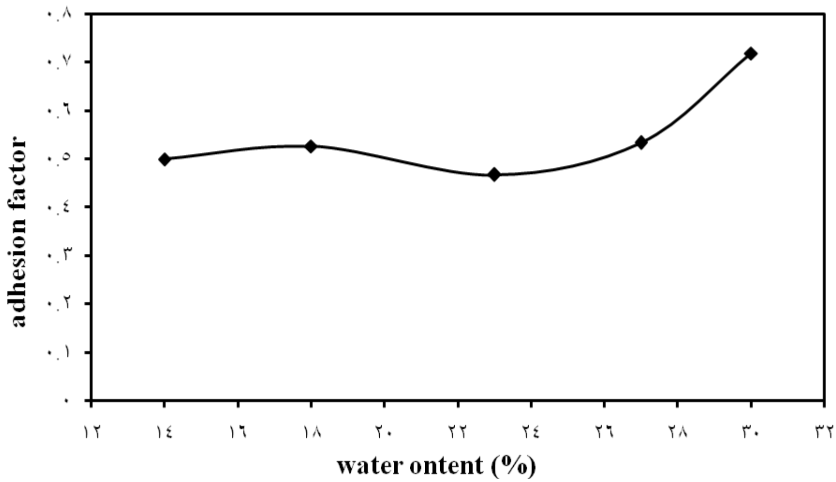

Fig 2: The adhesion factor at different water content

4. The field investigation

Geotechnical investigation was carried out for the New Operation Base Camp in Adar in the Upper Nile state, Republic of South Sudan[6]. The objective was to furnish design parameters for the designing steel pipe piles in the site.The piles were to be designed to support light structures for the Field operation Camp. The contractor was instructed to measure the plug lengths for all the constructed piles.

Nine boreholes were drilledin the investigation stage to cover the study site. Disturbed samples were obtained at 1.0 m intervals for visual classification. Undisturbed soil samples were obtained from cohesive soil layers by driving U4 samples into the soil at the given depth. Standard Penetration Test (SPT) was performed at 1.5 m intervals in cohesionless deposits and where the ground was so hard that undisturbed samples could not be retrieved.The collected samples were transported to the laboratory for testing. The tests performed included grain size analysis, Atterberg limits and unconfined compression strength (UCS) test on selected undisturbed soil samples. Typical profile description for five boreholes and summary of the test data are given in Figure (3).

a. Subsurface conditions

The boreholes revealed about similar sub-surface conditions. The upper 5.0 meters is dominated by very stiff highly plastic silty clay with high to very high fine content; that changes to hard plastic clay below 5.0 meter.Very dense clayey sand dominates below the plastic clay. Small pockets of thin low plastic silty clay layer were detected in the upper layers.

The high plastic silty clay measured very high liquid limit and therefore high plasticity index. The clay is desiccated; this is an indication of very high swelling potential of the formation at this site. Ground water table was not struck during this soil investigation; hence it has no effect on the performance of the foundation in this case.

b. The piles and driving system

Fourty five pipe piles with external diameter 0.168m, 0.219 m, 0.273 m and 0.324 m and wall thickness 7 mm, 8 mm, 9 mm and 10 mm respectively were driven in the site by a hydraulic hammer weighing 5 tons and falling freely from a height of 2.5 m (Plate 1). The piles were driven to 8.4m depth bearing in the hard clay (N>50).

The number of blows were counted and recorded for each 30 cm penetration. The contractor was instructed to measure the total plugging length of the soil at the end of driving operations for all the piles.

Plate 1: View of the site and the **driving system of the steel pipe piles**

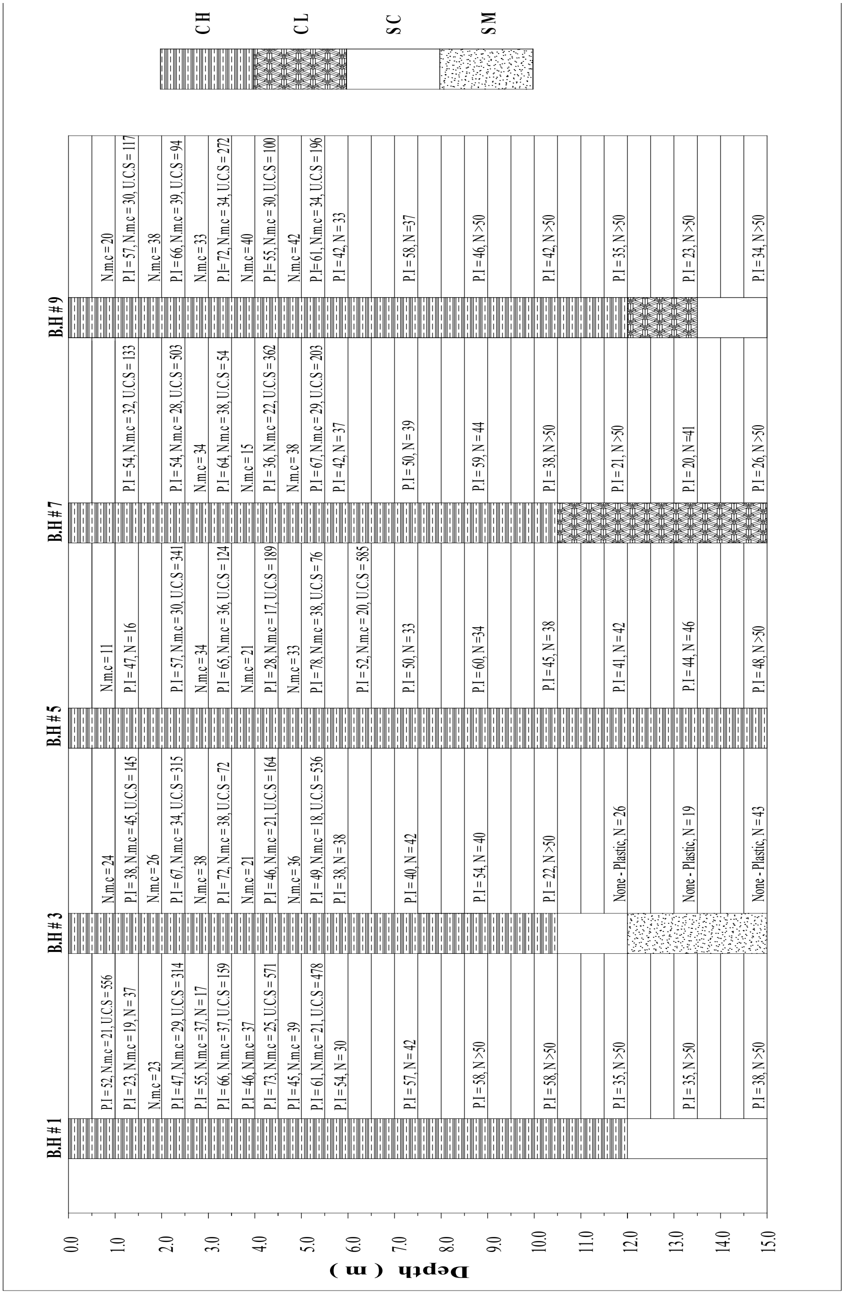

Fig 3: Typical soil profile for Boreholes (1, 3, 5, 7 and9)

5. Results, analysis and discussion

The parameters needed for the determination of the ultimate pile capacity (see equations 2 and 3) are the adhesion factor α and plug length L_p . The undrained strength Cu could be directly obtained using appropriate laboratory tests (unconfined strength, triaxial shear test) or indirectly from penetration tests, e.g. SPT-N value and cone resistance qc.

a. Adhesion factor

The results of the interface shear strength tests are given in Table2. The highest value of interface shear strength was measured at the lowest water content. The variation of α with water content is given in Figure 2. The adhesion factor has an average value of 0.48 for moisture content values lower than the plastic limit of the soil (23%) whereas α increases with increase in water content for water content greater than the plastic limit. The highest computed value of α is 0.72 and the lowest is 0.47. The values agree with those obtained for the adhesion between swelling clays and concrete piles [7].

b. Plug length

Four diameter sizes were driven (0.168m, 0.219m, 0.273 and 0.324m). The piles lengths ranged from 8.0 m to 8.4 m and they were totally embedded in the hard expansive soil. The length to diameter ratio (Ld/d) is greater than 20 therefore the piles could be considered as long piles. Plug length was measured for each pile at the end of driving.

Table (3) presents average pile embedment and plugging length for each pile diameter. It can be seen that plug length (L_p) to diameter ratio (L_p/d) ranges from (3.8– 11.9). Also it is noted that the ratio plug length to pile embedded length (L_p/

Ld) increased with increasing the pile diameter.

Figure4 illustrates the relationship between the average pile plugging length L_p and the pile diameter (d). From theseFigures, it is clear that the plugging length of the pile increased linearly with increasing the pile diameter and it follows the equation:

$$Lp = 12.822\, d - 1.5322 \ldots\ldots\ldots\ldots..(4)$$

The above equation has a correlation coefficient of 0.9986 which indicates an excellent relationship between the average pile plugging length and the pile diameter. It is evident from the analysis of the field data that for piles driven into very stiff to hard highly plastic clays the plug length is strongly related to pile diameter for the same driving energy input.

Table3: Summary of average pile embedment and plugging lengths

Pile diameter (m)	No. of piles installed	Average plugging length (m)	Average embement length (m)	Lp/d	Lp/Ld
0.168	2	0.645	8.085	3.8	0.08
0.219	12	1.260	8.114	5.8	0.16
0.273	1	1.930	8.420	7.0	0.23
0.324	30	2.653	8.021	8.2	0.33

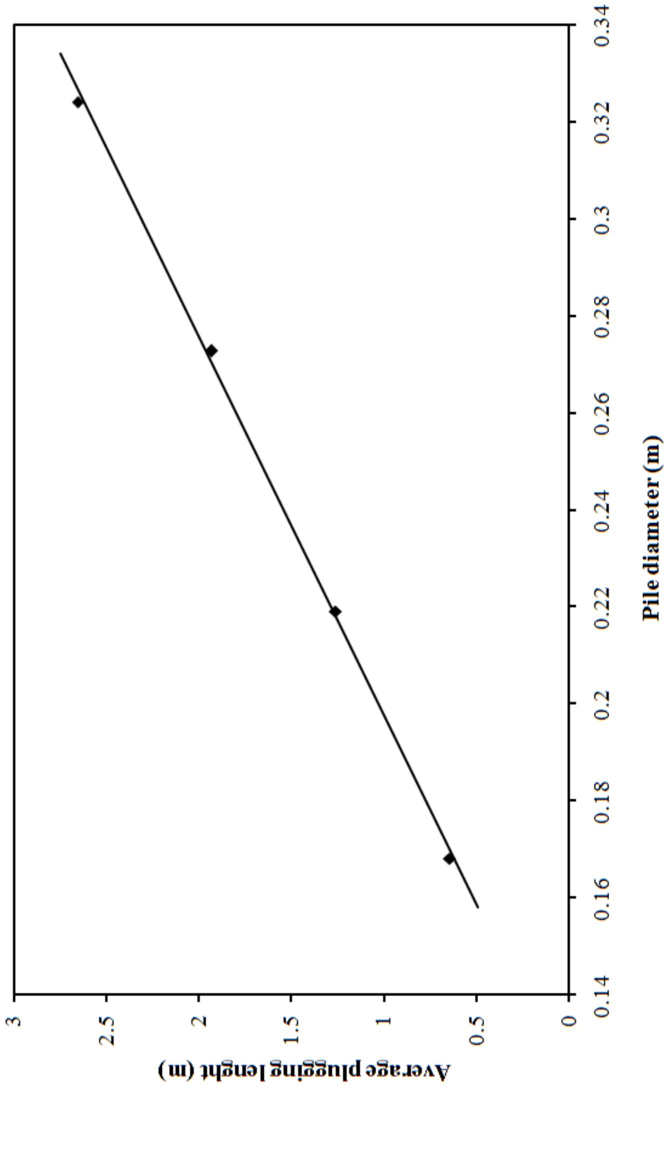

Fig4: Variation of average pile plugging length with the pile diameter

The driving records for the piles were analyzed. An attempt is made to relate the average cumulative number of blows for different pile penetration depths (1.5m, 3.0m, 4.5m, 6.0m, and 8.0m) with the pile diameter. The cumulative number of blows needed to drive the piles to the mentioned depths was computed and averaged for each diameter (Table 4). The average cumulative blows needed to drive the piles with same diameter to 8.0 m depth were plotted against diameter and shown in Figure 5. The correlation coefficient is given in the same Figure.

Table 4: Summary of the average cumulative number of blows for different penetrations lengths.

Pile diaeter (m)	Average cumulative number of blows				
	1.5m	3.0m	4.5m	6.0m	8.0m
0.168	3	9	28	74	224
0.219	6	25	84	163	271
0.273	15	59	142	277	373
0.324	14	77	158	249	411

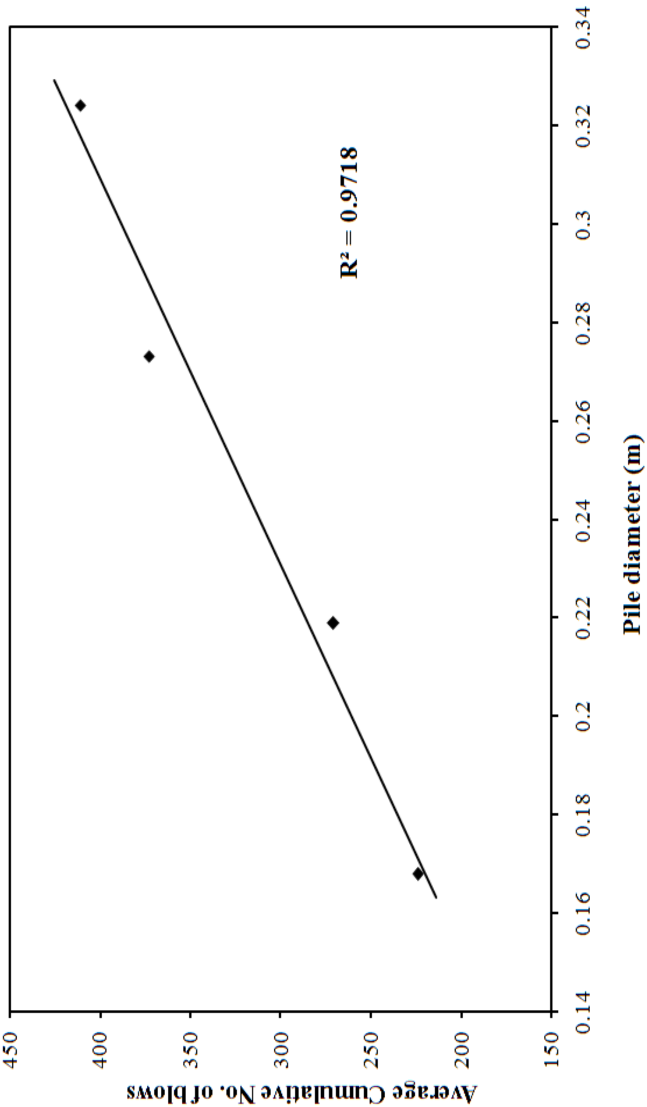

Fig5: Variation of average cumulative number of blows with the pile diameter for pile penetration depth 8.0m

From Table 4 and Figure5 it is evident that the driving resistance of the piles increased with increasing pile diameter. This indicates that piles with small diameter offered lower driving resistance compared to those with higher diameters. The driving resistance is function of the pile diameter when pipe piles are driven into very stiff to hard clays for the same site conditions.

6. Conclutions

Pipe piles have been intensively used to support structural loads in petroleum rich areas in Sudan and South Sudan. Their selection was encouraged by their ease of installation and resistance upheaval forces in swelling soils. However, their design is faced with insufficient information regarding the parameters used for estimation of their static ultimate load capacity, namely the adhesion factor and plug length. This paper presented guidelines for the parameters used for determination of their ultimate capacity, namely the adhesion factor and plug length.

A laboratory test program was carried out to measure the shear resistance of compacted stiff highly plastic clay prepared at a fixed dry density and varying water contents in the direct shear apparatusand the adhesion between the same compacted soil and a steel plate in the same apparatus. The adhesion factor which is the ratio of the peak interface shear strength and peak shear strength for the same test conditions (vertical load, water content and dry density) was determined. An average value of 0.48 was found for the interface resistance when the water content is lower than the plastic limit. The factor was found to increase with increase in water content for water content higher than the plastic limit.

Data from a construction site at New Operation Camp in Adar (Upper Nile State) was used in an attempt to study pile plug length and its variation with pile diameter. The driving records of steel pipe piles having different diameters and driven in stiff to hard highly plastic clay media were collected with extra data regarding plug lengths. The data was analyzed and the following conclusions were reached:

- Piles were successfully driven into the very stiff to hard highly plastic clay. The plugging length to diameter ratios ranges from 3 to 8.
- The plug length to pile embedded length ratios increased with increasing the pile diameter.
- The plug length of the pile increased linearly with increasing the pile diameter. An excellent linear relationship was found between average plug length and pile diameter for the same driving energy. A similar relationship could be established for a specific driving system and used for determination of plug length.
- The analysis of the driving records showed that the piles with small diameters gave lower resistance to driving compared to those with larger diameters.

7. Acknowledgements

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