LABORATORY EVALUATION OF TORQUE AND UPLIFT CAPACITY RELATIONS FOR SCREW PILES IN GRANULAR SOIL

C

A Thesis

by

MD. SALAHUDDIN

Submitted to the Department of Civil Engineering,
Bangladesh University of Engineering & Technology, Dhaka
in partial fulfilment of the requirements for the degree
of

MASTER OF SCIENCE IN CIVIL ENGINEERING

July, 1986

LABORATORY EVALUATION OF TORQUE AND UPLIFT CAPACITY RELATIONS FOR SCREW PILES IN GRANULAR SOIL

A Thesis

by

MD. SALAHUDDIN

Approved as to style and content by:

A.M.M. Safiullah

(Dr. A.M.M. Safiullah) — Chairman
Professor of Civil Engineering,
BUET, Dhaka.

M. Hossain Ali

(Dr. M. Hossain Ali) — Co-Chairman
Associate Professor,
Dept. of Civil Engineering,
BUET, Dhaka.

(Dr. M. Shamim Z. Bosunia) — Member
Professor and Head,
Dept. of Civil Engineering,
BUET, Dhaka.

Alamgir Habib

(Dr. Alamgir Habib) — Member
Professor of Civil Engineering,
BUET, Dhaka

(Dr. A.J. Khan) — Member (External)
Director, PMACS Ltd.
Road No.2, House No.34,
Dhanmondi, Dhaka.

July, 1986

ABSTRACT

Model screw piles of different geometry and dimension are installed in uniform density granular sand beds by application of torque at pile head. On installation the piles are subjected to uplift load. Devices are fabricated to apply and measure torque, uplift load and deflections. Effect of pile geometry and blade dimension on the torque required for installation and uplift capacity of the piles have been evaluated.

Mathematical expressions are derived to relate pile geometry (blade dimension and spacing) with torque required for installation and uplift capacity. A good correlation is found between measured torque at pile head with that calculated from the derived mathematical expression and also between measured uplift capacity with that calculated from derived expression.

A good correlation is observed between the torque required for installing a pile and its uplift capacity. Based on the experimental results emperical relations are proposed to relate driving torque with uplift capacity. Some aspects of screw pile installations in granular soils and uplift capacity evaluations are highlighted.

ACKNOWLEDGEMENTS

The author expresses his profound gratitude and indebtness to his supervisor Dr. A.M.M. Safiullah, Professor of Civil Engineering, BUET for his sincere help, encouragement, guidance and co-operation in making this research possible.

The author wishes to express his sincere gratitude to his co-supervisor Dr. M. Hossain Ali, Associate Professor of Civil Engineering, BUET for his untiring assistance and affectionate guidance to make this study possible.

The author is highly obliged to Dr. Alamgir Habib, Professor of Civil Engineering, BUET and Dr. M. Shamim Z. Bosunia, Professor and Head of Department of Civil Engineering for their inspiration in completing the thesis.

The author also tender his thankfulness to Mr. Habibur Rahman and Mr. Alimuddin for their help in various stages of laboratory investigations.

Finally the author expresses his thanks to Mr. Md. Abdul Malek for typing and Mr. Md. Shahiduddin for drawing the figures of the thesis.

TABLE OF CONTENTS

		Page
ABSTRACT		iii
ACKNOWLEDGEMENTS		iv
CHAPTER 1	INTRODUCTION	
1.1	General	1
1.2	Tension/Anchor Piles for Resisting Both Uplift and Compression	2
1.3	Screw Piles	4
1.4	Installation Records of Screw Piles	6
1.5	Driving Torque and Uplift Capacity Related to Soil Condition	6
CHAPTER 2	LITERATURE REVIEW	
2.1	Introduction	8
2.2	Uplift Capacity of a Uniform Pile	8
2.3	Uplift capacity of Foundation with Enlarged Base	14
2.4	Uplift Capacity of a Screw Pile	25
2.5	Upward Displacement of Piled Foundations Subjected to Uplift Loading	30
2.6	Driving Torque and Friction Characteristics of Screw Pile	35
2.7	Summary of the Literature Review	38
CHAPTER 3	THE RESEARCH SCHEME	
3.1	Introduction	40
3.2	Objective of the Research	40
3.3	Scope of the Work	41
3.4	Test Program	47

Page

CHAPTER 4 DRIVING TORQUE AND UPLIFT LOAD RELATIONS

4.1 Theoretical Torque and Friction Characteristics of a Screw Pile 49

4.2 Evaluation of Theoretical Uplift Capacity 54

CHAPTER 5 LABORATORY EXPERIMENTAL PROGRAM

5.1 General 58

5.2 Preparation of Uniform Bed of Sand 61

5.3 Torque Meter 67

5.4 Installation Test Procedure 71

5.5 Arrangements for Uplift Load Test 73

5.6 Measurement of Upward Movement of Pile 77

CHAPTER 6 RESULTS OF LABORATORY INVESTIGATION

6.1 General 81

6.2 Density of Uniform Sand Bed 84

6.3 Factors Affecting Driving Torque of Screw Pile 87

6.3.1 Effect of Shaft Diameter on Driving Torque 88

6.3.2 Effect of Blade Radius on Driving Torque 91

6.3.3 Effect of Blade Spacing on Driving Torque 93

6.3.4 Effect of Arrangement of Screw Blades in a Pile on Driving Torque 96

6.4 Factors Affecting Uplift Capacity of Screw Pile 99

6.4.1 Effect of Shaft Diameter on Uplift Load 99

Page

6.4.2 Effect of Blade Radius on Uplift Load 102

6.4.3 Effect of Blade Spacing on Uplift Load 102

6.4.4 Effect of Arrangement of Screw Blades in a Pile on Uplifting 107

6.5 Relation between Uplift Load and Driving Torque 109

6.6 Upward Movement of Piles During Uplifting 112

6.7 Summary of Test Results 116

CHAPTER 7 CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE RESEARCH

7.1 Conclusions 119

7.2 Recommendation for Future Research 120

REFERENCES 122

APPENDIX-A NUMERICAL EXAMPLES FOR THE THEORETICAL EQUATIONS 125

APPENDIX-B DETERMINATION OF RELATIVE DENSITY OF SAND IN LABORATORY 130

বাংলাদেশ প্রকৌশল বিশ্ববিদ্যালয়
নং 66097
তারিখ 29/7/86
লাইব্রেরী, ঢাকা

CHAPTER 1

INTRODUCTION

1.1 General

Piles are structural members of timbers, concrete and/or steel, used to transmit foundation loads to deeper soil layer. Normally piles are used to overcome the difficulties of placing foundation on weak soils. These members are of small cross-sectional area compared to their length, and are usually installed by a driver consisting of a hammer or a vibrator. They are often grouped into clusters or rows, each containing enough piles to support the load delivered by a column or wall.

Based on the functions or the use, piles may be classified as:

1. End bearing piles
2. Friction piles
3. Compaction piles
4. Tension or uplift piles
5. Anchor piles

End bearing piles are used to transfer load through water or soft soil to a suitable bearing stratum and derive their resistance through end bearing. A friction pile transfer its loads to a depth by means of skin friction along the length of the pile . Compaction piles are displacement piles used to densify loose granular soils, thus increasing their bearing

capacity. The compaction piles themselves carry very little load. Hence they may be of weaker material sometimes of sand only. Tension or uplift piles are used to anchor down the structure subjected to uplift due to hydrostatic or wind pressure or due to overturning moment. Anchor piles are also used to provide anchorage against horizontal pull from sheet piling or other pulling forces.

The design of a pile is based on three important considerations : the condition of soil in which it is to be placed, the type of pile that is to be used and the construction procedure that is followed for their installation.

1.2 Tension/Anchor Piles for Resisting Both Uplift and Compression

When piles are installed beneath structures like dry dock, basements, pumping station, electrical transmission towers etc. they may be subjected to uplift forces. In the case of dry dock, when it is dewatered, the hydrostatic pressure below the floor may exceed the downward loads on the deck, resulting in upward thrust or uplifting of the foundation. To prevent uplifting the foundation needs to be anchored to the ground. In submerged conditions, the loads on the dry dock act downward. In the case of electrical transmission towers and other elevated structures the lateral forces such as wind loads try to over-turn the structures

resulting in tension or uplifting of foundation on the windward side and compression on the other side. When no lateral force is acting the foundation is subjected to compression. Thus, the foundation for such structures require to resist both uplift and compression.

The simplest method of resisting uplift is to employ a pile that is sufficiently long, in which case the uplifting forces will be resisted by the friction between pile shaft surface and the surrounding soil. However, it is not always possible to drive the piles deep enough to mobilize the required frictional resistance. In such cases the shaft resistance must be augmented by adding dead weight to the pile to overcome the uplift load or by anchoring the pile at the bottom. Adding dead weight to counteract uplift loading is not usually feasible or economical. Experience has shown that base enlargement of the pile is the most economical means of increasing the required uplift resistance as well as the compressive load capacity of a pile.

Base enlargements can be formed when bored piles are constructed in the soil. The enlargements are usually made by

the belling tools and providing a support of the bore hole by bentonite slurry. The size and stability of an enlargement made in this manner has its problems and further no checks can be made for its size. Full scale loading tests are essential to provide the reliability of the method for any particular site. Base enlargements can also be made by providing anchor plates at the bottom of the pile. But this type of pile has the installation problem at the greater depths.

Screw pile may be considered as one type of base enlarged piles. In this type of piles the size of the base is the diameter of the screw at the bottom and therefore uncertainity regarding base enlargement is eliminated. The excavation problems which are encountered in the conventional enlarged base piles is also eliminated. This type of pile therefore provides an effective means of resisting both uplifting and compressive forces and forms the subject matter of this thesis.

1.3 Screw Piles

Fig. 1.1 shows commonly used screw piles. The pile essentially consists of one or more helical blade or blades at the base, so that the pile may be screwed to the ground. The shaft may be solid or hollow with a closed end. The screw may be formed on a tube that is open at the bottom so that the soil entering the tube may be removed. The screw head may be detachable.

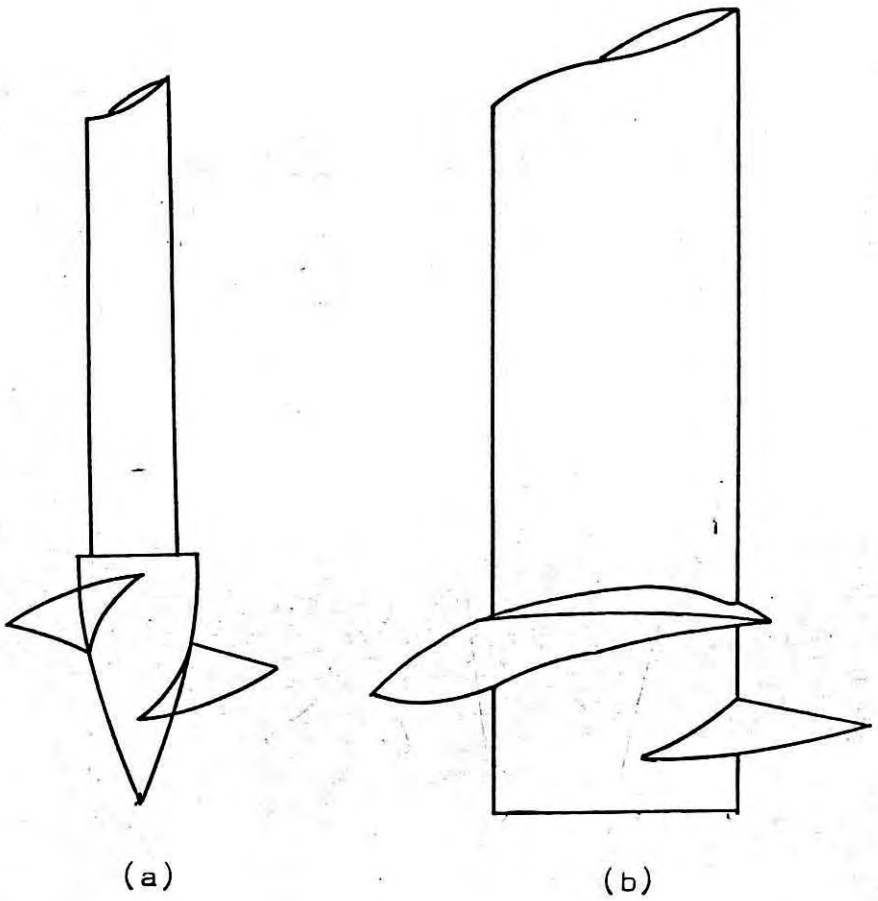


Fig. 1.1 Screw piles (a) Early pattern with cast iron screw on a shaft about 250 mm diameter. (b) Modern screw cylinder about 1 m diameter open at the bottom, the core being removed as screw wing proceeds. (after Whitaker, 1976).

Screw piles have been used in several countries for mast and tower foundations and for underpining works. Such piles have been used for the towers of the East-West Electrical Interconnector Project in Bangladesh.

The screw pile is driven into the ground by applying external torque, usually a truck mounted device is used for this purpose.

1.4 Installation Records of Screw Piles

Available screw pile installation records (Abedin 1983) suggest that there is a correlation between driving torque and uplift capacity, the nature of such correlation and factors that affect them are not clearly understood, very little information is available on this aspect.

1.5 Driving Torque and Uplift Capacity Related to Soil Condition

There are several methods of soil exploration such as standard penetration test, swedish sounding tests etc. The method used for a particular site will depend on the site condition, economic feasibility and other factors. The Swedish sounding test was used as a means of soil exploration in the East-West Electrical Interconnector Project. In this method a screw point is twisted into the soil stratum of interest and the corresponding resistance is measured for judging the

consistency and stratification of the soil. The test is generally applicable to all soils of N-value less than 15, except in gravelly soils. Here N-value relates to the Standard Penetration Test (SPT) value. N is the number of blows required by a hammer of 140 lbs dropped on to a drilling rod from a height of 30 inches to penetrate a standard penetrometer 12 inches into the soil.

When torque is applied to the screw pile during its driving operation, it is resisted by the strength of the soil and when this resistance is overcome, the penetration of the pile is obtained. So it is obvious that there must be some relationship between the driving torque and the soil strength. The factor that effect this relation is not completely known.

Again when the pile is subjected to uplift forces the soil surrounding the pile tends to resist the pile movement in upward direction. The amount of upward displacement is a function of the magnitude of applied load and strength characteristics of the soil. The stress zones that are formed during uplift and nature of failure surface are not completely known. In order to understand failure mechanism of screw piles in uplift condition, it is necessary to know the type of failure surface and factors that affect it in different type of soils. In this research a simplified approach based on granular soil and piles of known geometrical shapes are used.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

A review of literature relevant to the mechanism of screw pile installation in granular soils by application of torque at pile head and uplift capacity of piles have been made in this chapter. Review includes effects of soil density, pile geometry and blade dimensions on torque requirements for driving screw piles to a fixed depth of embedment. A very limited amount of published literature is available on the above aspects of screw piles. However, several researchers studied the behaviour of other types of foundations against uplift loading which has been included and forms the main source of information of this review.

2.2 Uplift Capacity of a Uniform Pile

The uplift capacity of a uniform pile in the clay is given by

$$P_{uu} = C_a A_s + W_p \qquad (2.1)$$

in which,

P_{uu} = ultimate uplift capacity

C_a = average adhesion along the pile shaft

A_s = surface area of the pile shaft

W_p = weight of the pile.

Poulos and Davis (1980) report a summary of results given by Sowa (1970). The ratio of the adhesion C_a to the average undisturbed undrained shear strength C is termed α. One of Tomlinson's (1957) major conclusions was that the ratio α decreases with increasing undrained shear strength in the manner illustrated by the two lines shown in Fig. 2.1. Tomlinson attributed the reduction of α due to formation of gaps between the pile and the soil on account of the transverse vibrations caused during driving. The gaps close up in the softer clays but have a greater tendency to remain open as the stiffness of the clayey soil increases. A thorough review of the values of α obtained from the pile load tests on concrete cast in situ piles has been undertaken by Skempton (1959) for piles constructed in London clay one of the basic results of Skempton's study was that the average value of α was approximately 0.45 and this result has been plotted as a dashed line in Fig. 2.1 for the range of shear strength investigated values as low as 0.3 could be obtained for the cases in which the clay became completely remoulded and softened during construction, and as large as 0.6 for piles constructed very carefully under the most favourable conditions. The reduction of α has been attributed to a loss in shear strength of the clay in contact with the concrete pile shaft due to an increase in water content caused by the boring operation. The studies undertaken by Tomlinson and Skempton were for piles tested by increasing the bearing load to failure. The number of

results reported by other authors for pile pulling tests and in particular for tests on cast-in-situ piles, is considerably less and plotted in Fig. 2.1. A considerable amount of scatter is evident and this may be partly due to the short length of some of the piles. Nevertheless, there is a general trend for the ratio α to decrease with increasing shear strength, and roughly to correspond to the values given by Tomlinson and Skempton. It is believed that the pile pulling capacity of concrete cast-in-situ piles in cohesive soils can be estimated from the relationship between α and the undrained shear strength illustrated by the lower Tomlinson curve in Fig. 2.1.

Poulos and Davis (1980) suggested that the ultimate uplift capacity for piles of uniform diameter in sand, may be calculated as the sum of the shaft resistance plus weight of the pile. A few data that are available on the skin friction and uplift loading are to some extent conflicting. Tests reported by Ireland (1957) on piles driven into the fine grained sand suggest that the average skin friction for uplift loading is equal to that for downward loading. But data summarised by Sowa (1970), Down and Chieurzzi (1966) indicates considerable variations in average skin friction in different tests. There is a tendency for the values to be lower for upward loading than for downward loading, especially for cast-in-situ piles. In absence of the other informations,

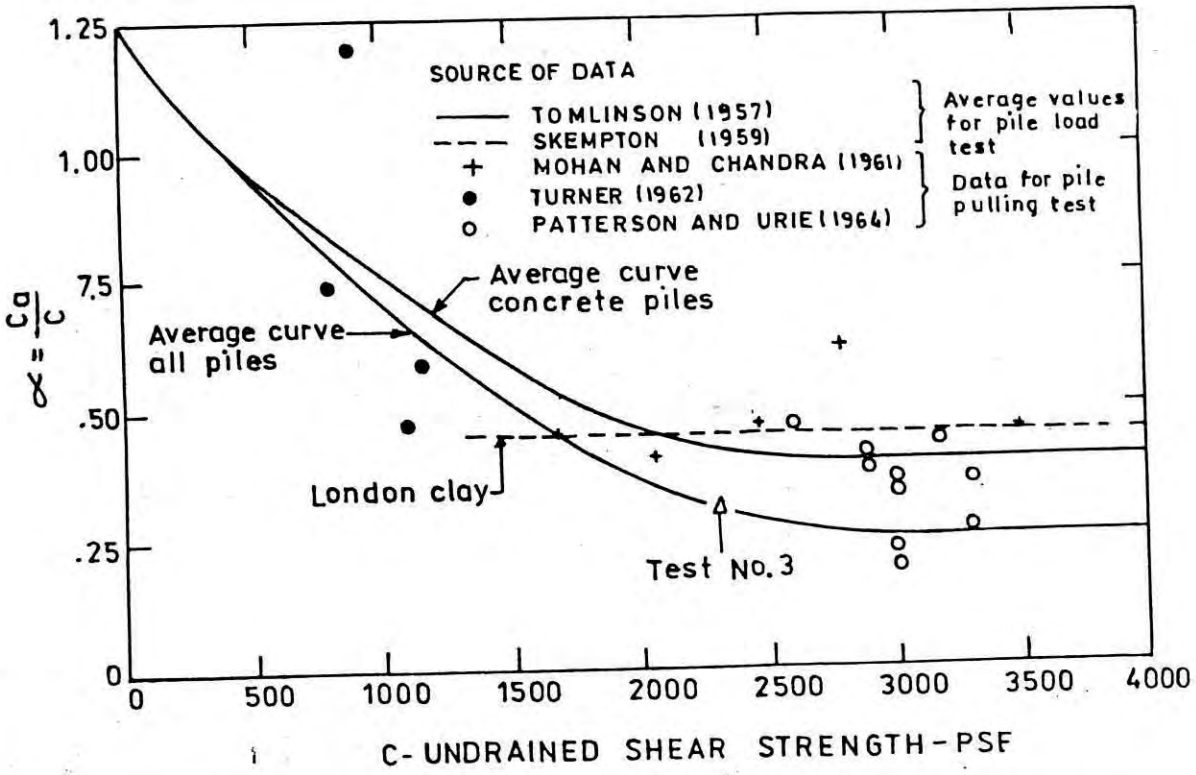


Fig. 2.1 Relationship between C_a/C and undrained shear strength for pulling tests (after Poulos and Davis, 1980).

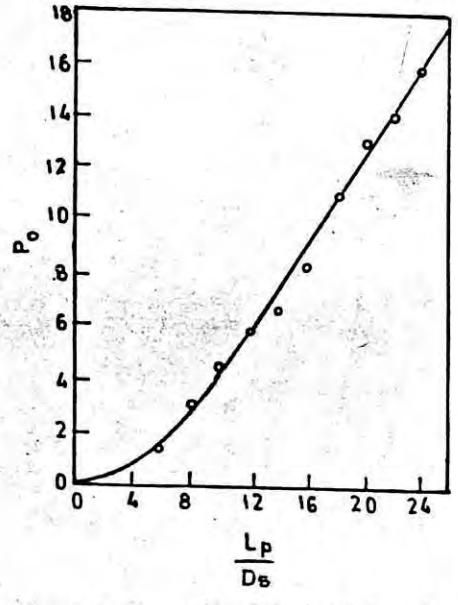


Fig. 2.2 Plot of net ultimate uplift load versus embedment ratio.

a reduction to two thirds of the calculated shaft resistance for uplifting is recommended by Poulos and Davis (1980).

Begemann (1965) suggested that the calculated skin friction for downward loading be adjusted by a reduction factor depending on the soil and pile type. Static cone penetration tests are used as a basis for estimating uplift skin friction. Eq. 2.2 then becomes

$$P_{uu} = W + \pi D \frac{L}{2}^2 k\gamma \text{ than } \phi \qquad (2.3)$$

This equation is also some times expressed as

$$P_{uu} = \bar{W} + fa\ (\pi DL) \qquad (2.4)$$

where, fa = average skin friction or average shear strength along the shaft. Based on this model Kulhawy Kozera and Withiam (1979) reached the conclusion that the shear surface along which the shafts failed were determined to be cylindrical and to be of the order of 1/4 inch out from the soil-pile interface.

Investigating the uplift capacity of buried model piles in sand Das and Seeley (1975) reported that the variation of unit skin friction for piles is approximately linear with depth upto a critical embedment ratio which is about 10-12 pile diameter and then remained constant. He used the following formula for calculating the uplift capacity of vertical piles in granular soil.

$$P_{uu} = \int_{o}^{L_p} f \pi D_s \, dL_p \qquad (2.5a)$$

where,

f = skin friction factor

D_s = diameter of the pile

L_p = embedment length

For short piles the unit friction is calculated by using the formula,

$$f = K_u \gamma L_p \tan \partial \qquad (2.5b)$$

where,

K_u = nominal uplift coefficient of earth pressure on vertical plane through footing edge which is a function of

γ = effective unit weight of soil

∂ = angle of friction between soil and pile material

ϕ = angle of internal friction of soil.

Das and Seeley mentioned that due to arching in granular soil the skin friction factor f, may reach a limiting value at certain critical depth. The variation of skin friction factor at various depths over the embeded length may be evaluated from the formula

$$f = \frac{1}{\pi D_s^2} \left(\frac{\Delta P_o}{\Delta \left(\frac{L_p}{D_s} \right)} \right) \qquad (2.5c)$$

where,

$P_o = P_{uu} - W_p$

W_p = self weight of the pile

$\frac{\Delta P_o}{\Delta(\frac{L_p}{D_s})}$ = slope of p_o vs. L_p/D_s curve (Fig. 2.2)

Uplift capacity for piles in clay is given by Eqn.2.1 or 2.4, while that of in granular soil is shown by Eqn. 2.5a.

2.3 Uplift Capacity of Foundation with Enlarged Base

Tomlinson (1977) commented on the performance of uplift capacity of piles with base enlargement. According to him for end enlargements formed on precast concrete or steel piles, compressive resistance increases when driven to a dense or hard stratum. But do not offer much uplift resistance since a gap of loosened soil is formed around the shaft as the pile is driven down.

Two theories of uplift resistance of pile were mentioned by Poulos and Davis (1980): first one considering a slip surface rising vertically from the edge of the enlarged base and the second considering the failure surface rising at 30^o degree from the vertical called cone method of failure. For the vertical slip surface consideration the dead weight of the soil is to be considered along with the shearing resistance.

Turner (1962) showed that the cone method of failure surface is usually conservative at shallow depth, but can be

quite opposite at large depth. Poulos and Davis (1980) mentioned studies of Parr and Vanner (1962) who have shown that the vertical failure surface approach did not apply to flared out footing in clay but it could apply to backfilled footings where the strength of the backfill is effectively mobilised. Turner (1962) considered several modes of failure of flared out footings in clay and concluded that the slope of failure surface varied with the footing dimension and soil strength. He noted a distinct difference in behaviour between shallow and deep footings. Shallow footings are those located just below the lowest part of the super structures which they support deep footings extend considerably deeper into the earth. He suggested the use of emperical equations bōth for deep and shallow footings, the undrained strength and the footing dimensions being variables.

Balla (1961) showed that in dense sand the failure surface for shallow foundation was approximately circular in elevation, and that the tangent to the surface of ground contact was at an angle of approximately $(45^{o} - \phi/2)$ to the horizontal.

Meyerhof and Adams (1968) reports the experiments of Macdonald (1963) which showed that for shallow depths the failure surface was approximately parabolic and for greater depths the failure plane was approximately vertical, the diameter of the cylinder formed being 1.75 times the base

diameter of the footing. Macdonald developed two theories to account approximately for this behaviour. For shallow case, failure was assumed to be conical with angle of inclination equal to one-half the angle of internal friction; for the deep case, failure was assumed to be cylindrical with a cylinder diameter of 1.75 times the base diameter.

Meyerhof and Adams (1968) also reported about a series of model tests on footings carried out by the Ontario Hydro Research Division. Briefly the model footings consisted of small metal discs varying from 1 to 4 inches in diameter. Tests were carried out at various depths in uniformly graded and well graded sands in both loose and dense condition. A few tests in uniform sand were made at relative densities intermediate between the loose and dense condition. These tests generally showed that in dense sand the uplift capacity increased with depth. In well graded material the uplift capacity were appreciably higher. In loose sands the increase in uplift capacity with depth is almost linear and much less than in the dense material.

Meyerhof and Adams (1968) investigated the uplift resistance of a circular plate embedded in a partly cohesive (C-ϕ) soil and established the formula

$$P_{uu} = \pi CBH + 1/2\, \pi s\gamma\, B(2D-H)H\, K_u \tan\phi + W_s \qquad (2.6)$$

where P_{uu} = uplift resistance of the plate

B = diameter of the plate

H = height of the block of the soil lifted by the pile (Fig. 2.3)

P_o = the surcharge pressure above the level of the failure surface (Fig. 2.3)

$P_o = \gamma(D-H)$

C = cohesive strength of the soil

S = shape factor (Table 2.2)

γ = density of the soil (the submerged density being taken below ground water table).

D = depth of the plate

K_u = nominal uplift co-efficient of earth pressure as obtained from Fig. 2.4

ϕ = angle of shearing resistance of the soil

W_s = weight of the soil resisting uplift by the plate.

If the equation is adapted to a pile with an enlarged base the weight of the pile is taken in conjunction with the weight of the soil when calculating W_s.

For deeply embedded plates or pile enlargements, H does not extend upto ground level and its value can be obtained from the tests made by Meyerhof and Adams (1968) which gave the results as in Table 2.1.

The shape factor s for deep foundations (including piles) is equal to (1 + m H/B), where m is a co-efficient which depends on the angle of shearing resistance ϕ of the soil. The values of m and the maximum permissible value of shape factor are shown in Table 2.2.

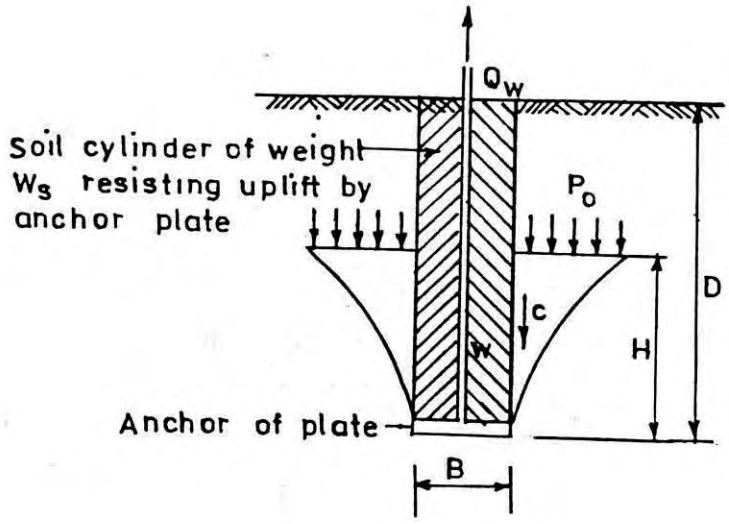


Fig. 2.3 Soil block lifted by anchored pile in c-ϕ soil (after Meyerhof and Adams, 1968).

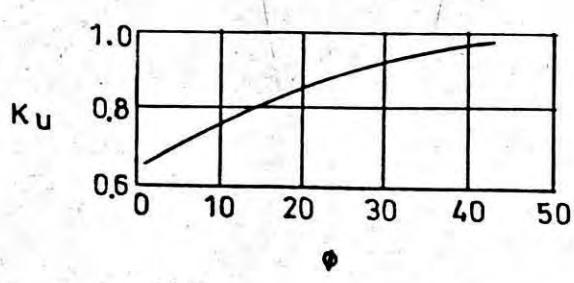


Fig. 2.4 Coefficient K_u and ϕ relationship (after Meyerhof and Adams, 1968).

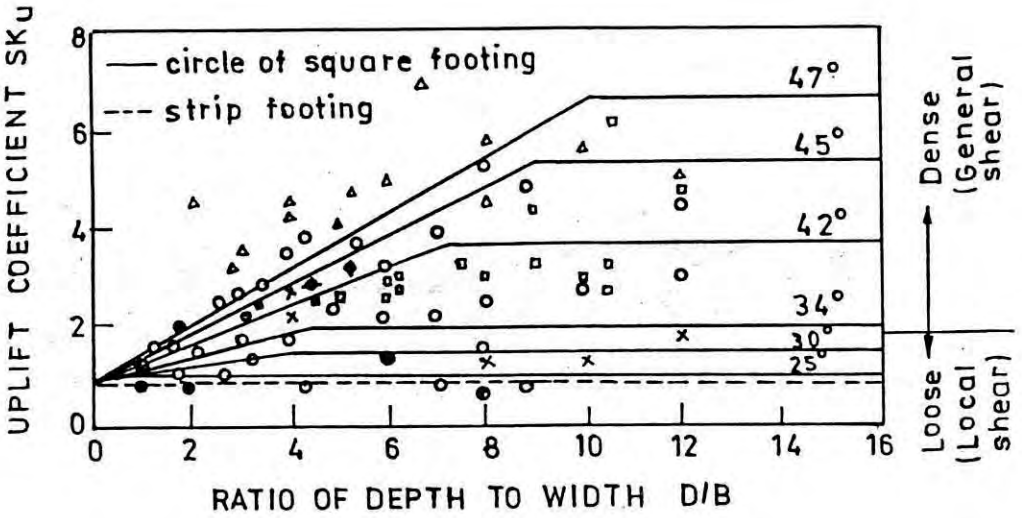
Table 2.1 ϕ and H/B relations (after Meyerhof and Adams, 1968)

ϕ	20^o	25^o	30^o	35^o	40^o	45^o	48^o
H/B	2.5	3	4	5	7	9	11

Table 2.2 Angle of shearing resistance, m and s relations (after Meyerhof and Adams, 1968)

ϕ	20^o	25^o	30^o	35^o	40^o	45^o	48^o
m	0.05	0.10	0.15	0.25	0.35	0.50	0.60
Max. factor, s	1.12	1.30	1.60	2.25	3.45	5.50	7.60

In order to compare the results of the model tests with the theory of uplift resistance Meyerhof and Adams (1968) analysed the experimental data to determine the value of skin friction in the proposed equation for circular and long rectangular footing at various ratios of (D/B). The results are shown in Fig. 2.5. The test results indicate a rather wide scatter of points, which is to be expected due to the different types and densities of sand used. For a given type of sand, the uplift co-efficient $S.K_u$ for circular footings increase with ϕ and with the ratio of D/B to a maximum value, which remains roughly constant for large ratios of D/B. On the other



Recent data rectangular footings slender shafts (Meyerhof) well graded sand $\phi = 45^{\circ}$

- o Dense 1.5 x 12"
- ● Loose 1.5 x 12"

Published data – circular footings – slender shafts

- o Dense silica sand $\phi = 34^{\circ}$ Adam and Hayes (1967)
- o Dense concrete sand $\phi = 47^{\circ}$ Adam and Hayes (1967)
- ▫ Dense silica sand $\phi = 42^{\circ}$ Baker and Konder (1966)
- △ Dense sand $\phi = 45^{\circ}$ Macdoland (1963)
- ● Loose silica sand $\phi = 28^{\circ}$ Adams and Hayes (1967)
- \+ Loose sand $\phi = 31^{\circ}$ Macdoland (1963)

Fig. 2.5 Comparison of theory and model tests for footings in sand (after Mayerhof and Adams, 1968).

hand, the values of $S.K_u$ for long rectangular footings are independent of the friction angle of the sand and the ratio of D/B.

The results of additional model tests on circular and long rectangular shafts were analysed in a similar manner, and the results were compared with the corresponding footing data as shown in Fig. 2.6. It was found that the uplift resistance of the shaft increases with the degree of roughness of the shaft and that the footing resistance corresponds to as angle of skin friction of roughly two thirds of the friction angle ϕ.

Balla (1961) showed that in dense sand the failure surface for shallow foundation was approximately circular in elevation, and that the tangent to the surface of ground contact was at an angle of approximately $(45^o - \phi/2)$ to the horizontal.

While investigating the uplift capacity of anchor foundation in clay Meyerhof and Adams (1968) observed tension crack in soils. They appeared however, to be restricted to rather shallow depths where the soil is stressed largely in flexure. Negative pore water pressure had been recorded both above and below model anchors which substantiate a tension force in the clay mass. At large depth, however, according to them the flexing of clay mass would be prevented by the weight

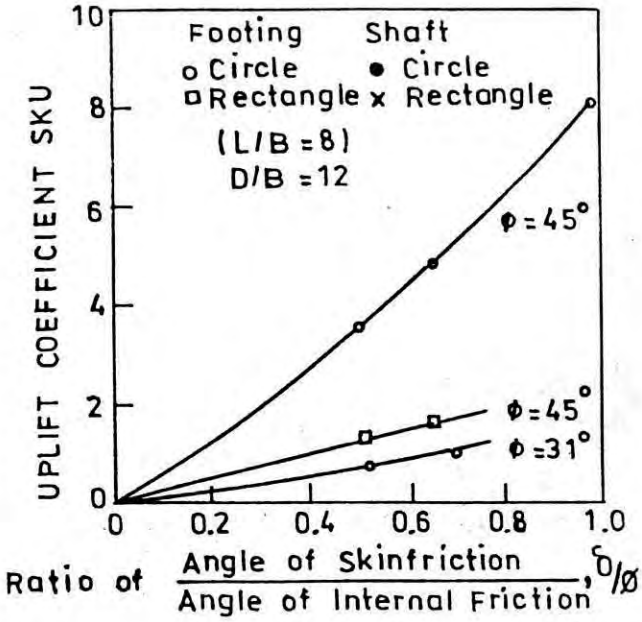


Fig. 2.6 Observed laboratory relationship between uplift coefficient and friction angle (after Meyerhof and Adams, 1968).

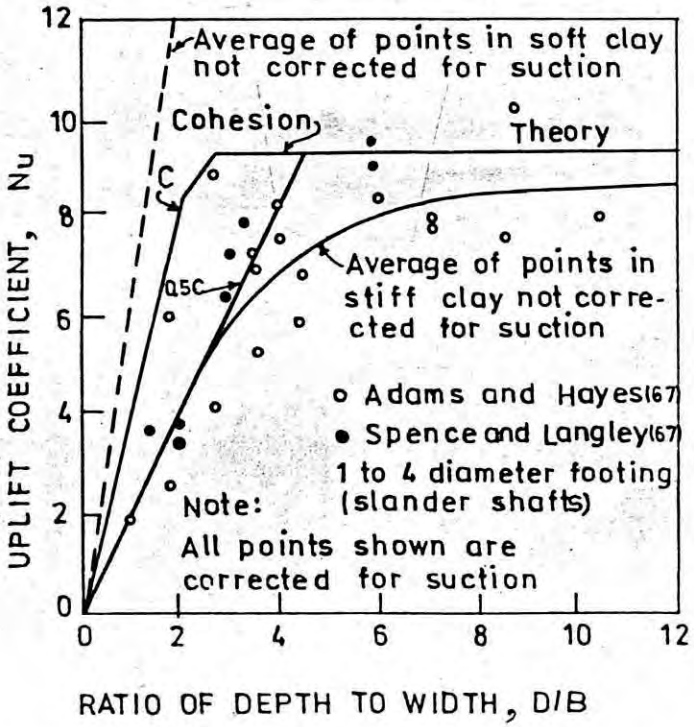


Fig. 2.7 Comparison of theory and model tests for footings in clay (after Meyerhof and Adams, 1968).

of the overburden and that the resistance to uplift would be determined by the shear strength of the clay.

To test this assumption Meyerhof and Adams analysed the results of model tests using the following expression for uplift capacity

$$P_{uu} = (\pi B^2/4) C N_u + W \qquad (2.7)$$

where,

N_u = an uplift co-efficient and its experimental value were calculated from pull out loads and plotted against D/B ratio, and is presented in Fig. 2.7.

Davie and Sutherland (1977) investigated the uplift resistance on circular anchors in purely cohesive soil. They made dimensional analysis to establish similarity conditions between prototype and models, and the relative contributions of body forces and soil strength to total uplift resistance were examined.

In estimating the uplift resistance the following model was used

$$P_{uu} = f(g, \gamma, C, t, E, \nu, \Delta, D, B, B_c) \qquad (2.7a)$$

where,

P_{uu} = ultimate uplift resistance

g = acceleration due to gravity

γ = density of the soil

C = cohesion of the soil/shear strength

t = tensile strength of soil

E = elastic modulus of soil

ν = Poisson's ratio of soil

Δ = plastic volumetric strain of soil

D = depth of placement of anchor

B = diameter of anchor plate

B_c = diameter of test container.

Using a dimensionless group B, γ and g the formula was modified to a form,

$$\frac{P_{uu}}{\gamma g B} = f\left(\frac{C}{\gamma g B}, \frac{t}{\gamma g B}, \frac{E}{\gamma g B}, \nu, \Delta, \frac{D}{B}, \frac{B_c}{B} \right) \qquad (2.7b)$$

In order to compare the predictions of uplift resistance theories with the results of the laboratory and field tests, the dimensionless factor, F_u, was used.

$$F_u = \frac{P_{uu} - \gamma g D}{C} \qquad (2.7c)$$

F_u is called the ultimate uplift resistance factor. They considered F_u as the equivalent to the bearing capacity factor, N_c for circular footings in cohesive soils.

Davie and Sutherland (1977) concluded that dimensional analysis applied in relation to both shallow and deep anchor theories indicates theories indicates that caution must be exercised in the choice of soil shear strength to be used in

the uplift model. If $C/\gamma_g B$ or $C/\gamma_g D$ for the prototype is less than about two and soil of the same shear strength as in the prototype is used in the model, the ultimate resistance of the prototype may be underestimated.

The model tests indicated three categories of D/B ratio, (a) shallow anchors with $0 < D/B \leq 2$ in which a general type of failure occurs due to a combination of yielding above and below the anchor caused by shear and tensile stresses and cracking in the material. (b) the intermediate depth anchor $2 < D/B \leq 4.5$ in which combination of general and local type of failure occurs. (c) deep anchors with $D/B > 4.5$ in which local type of failure occurs.

2.4 Uplift Capacity of a Screw Pile

Trofimenkov and Mariupolski (1965) analysed the data of screw pile tests carried out by Fundamental Prockt Institute and the design Institute of the communication service of the U.S.S.R. in order to develop reliable methods of determining the uplift capacity of screw piles, depending both on their size and type of loading and on the properties of soil.

Uplift loads on the piles were increased to a critical value so that the pile displacement continued without a noticeable increase in load. In most cases small piles were pulled out until they were fully extracted on the soil surface.

The analysis of the test results shows that in pulling out and pushing in tests the rupture of the soil foundation of the single screw pile, depends on the ratio of the pile plate depth to its diameter (D/B). The test results are shown in Fig. 2.8 when a pile plate is at such a depth that D/B is more than some critical value of D/B the failure of the soil takes place inside the earth mass and is not accompanied by surface rise. In this case the pile capacity depends little on the plate depth, the load is transferred to soil through both-the plate and the shaft. The value of D/B critical depends on the type of loading (pulling out or pushing in) and soil conditions. Pulling out test showed D/B critical is 4 to 5 in clay soil and 5 to 6 in sand.

On the basis of experiments Trofimenkov and Mariupolski (1965) developed a formula for ultimate capacity of a screw pile blade.

$$P_{ult}(\text{Pulling}) = A.C + A'D \qquad (2.8)$$

where,

A and A' are dimensionless co-efficients depending on the angle of internal friction of the soil.

C = cohesive strength of soil

γ = unit weight of the soil above pile plate level (submerged value below ground water level)

D = depth of the pile plate.

The values of A and A' are shown in Fig. 2.9.

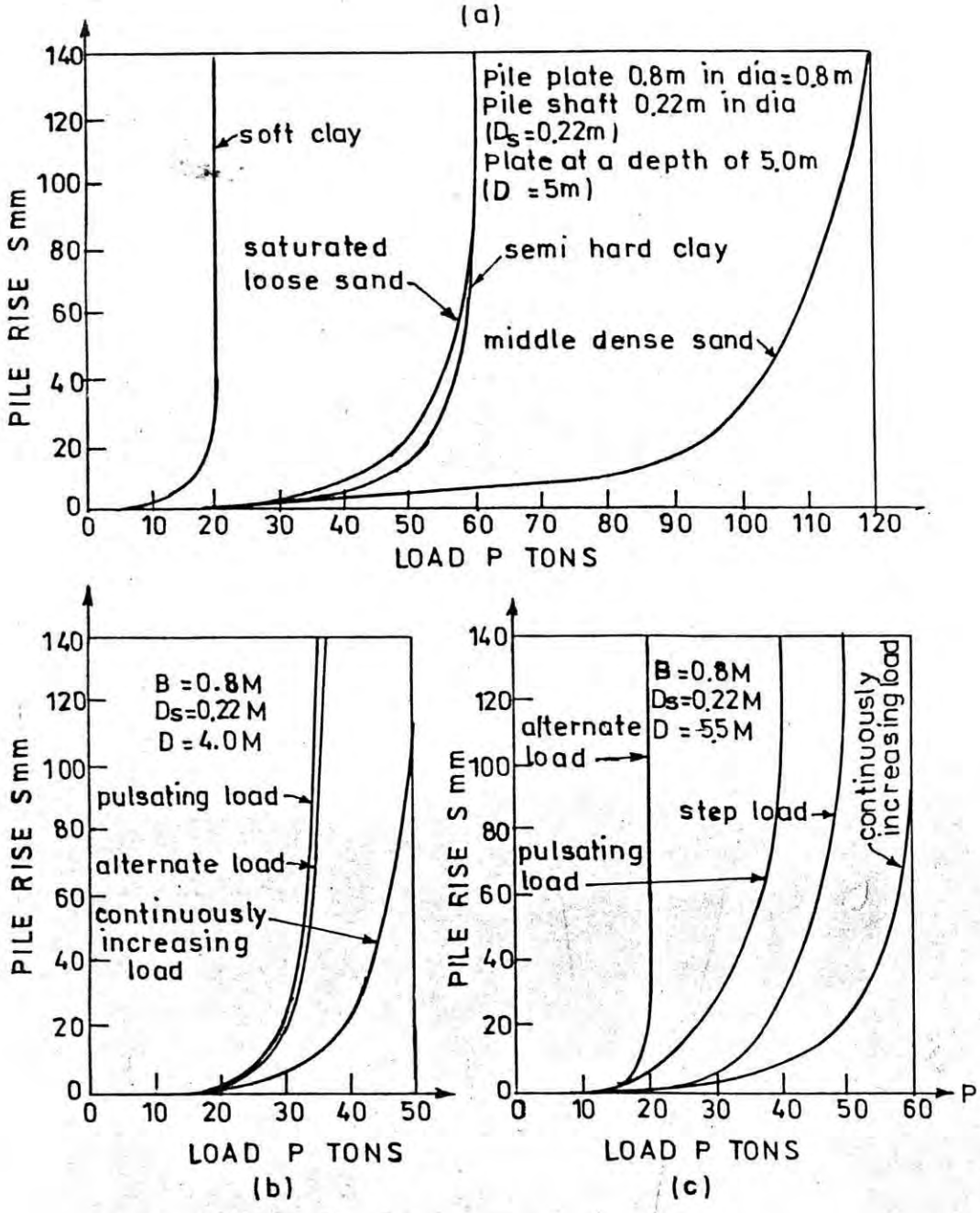


Fig. 2.8 Results of tests on screw piles (after Trofimenkov and Mariupolski, 1965) (a) Continuous pulling out tests made in various soils. (b) Pulling out tests made with different loads in semi hard clay. (c) Pulling out tests made with different loads in saturated loose sands.

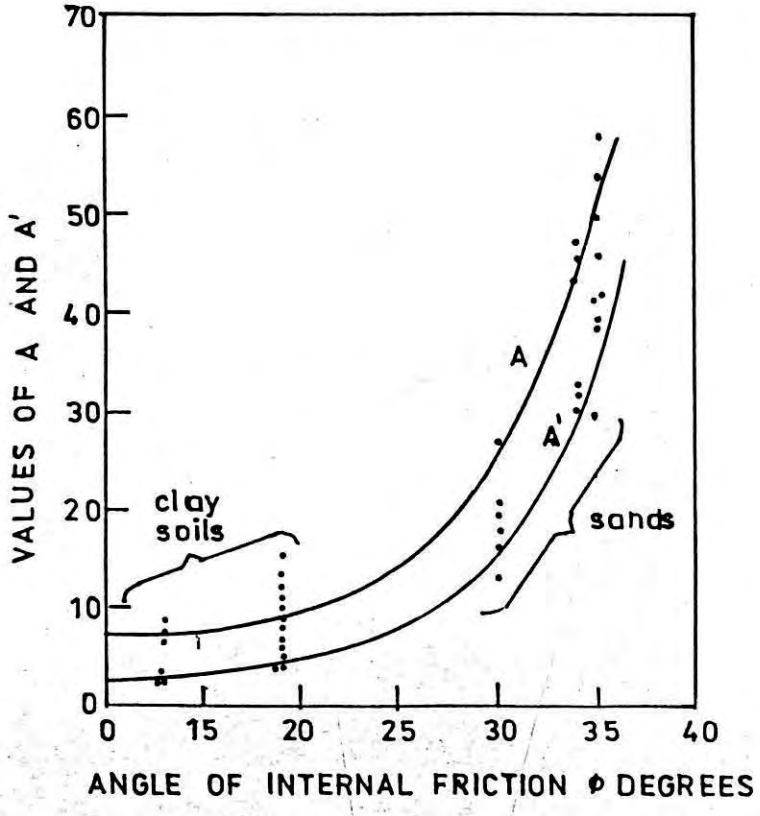


Fig. 2.9 Coefficients A and A' depending on angle of internal friction of soil, Φ (after Trofimenkov and Mariupolski, 1965).

The ultimate load transferred to the soil is determined by the sum of the ultimate loads of a pile plate and that of a shaft.

$$P_{uu} = R_{ult} F_a + f_a u L \qquad (2.9)$$

where,

f_a = friction along the pile shaft

F_a = working area of the plate (the height of the working zone may be taken approximately equal to the plate diameter)

L = length of the pile shaft

u = perimeter of the pile shaft.

In pulsating, alternate and continuously increasing loads, the reducing coefficient m, are to be used dpending on the type of load and the soil conditions. The values are given in Table 2.3.

Thus the actual ultimate uplift capacity would be

$$P_{ult} = P_{uu} \times m$$

In an unpublished technical note Hitachi Cable Co.(1980a) made an analysis for the ultimate uplift capacity of screw pile. They assumed a vertical imaginary rupture surface, as shown in Fig. 2.10 in this analysis. They evaluated the screw pile uplift capacity by the formula

$$P_{uu} = A_{pnm} \times C_{nm}$$

Table 2.3 Reducing co-efficient m (after Trofimenkov and Mariupolski)

Kinds of soil in working zone	Types of load		
	Continuously increasing	Pulsating	Alternate
CLAY SOILS Hard, very stiff and stiff	0.8	0.7	0.7
Medium	0.8	0.7	0.6
Soft	0.8	0.6	0.4
Very soft	0.8	0.5	0.3
SANDY SOILS Partly saturated	0.8	0.7	0.7
Saturated and dry	0.8	0.5	0.3

where,

P_{uu} = ultimate uplift capacity

A_{pnm} = surface area of the imaginary rupture surface surrounding the screw plate and the pile shaft (from a depth m to a depth n)

C_{nm} = cohesion for the soil layer within depths n to m

2.5 Upward Displacement of Piled Foundations Subjected to Uplift Loading

One of the main design considerations of piled foundation subjected to uplift load is the displacement in the

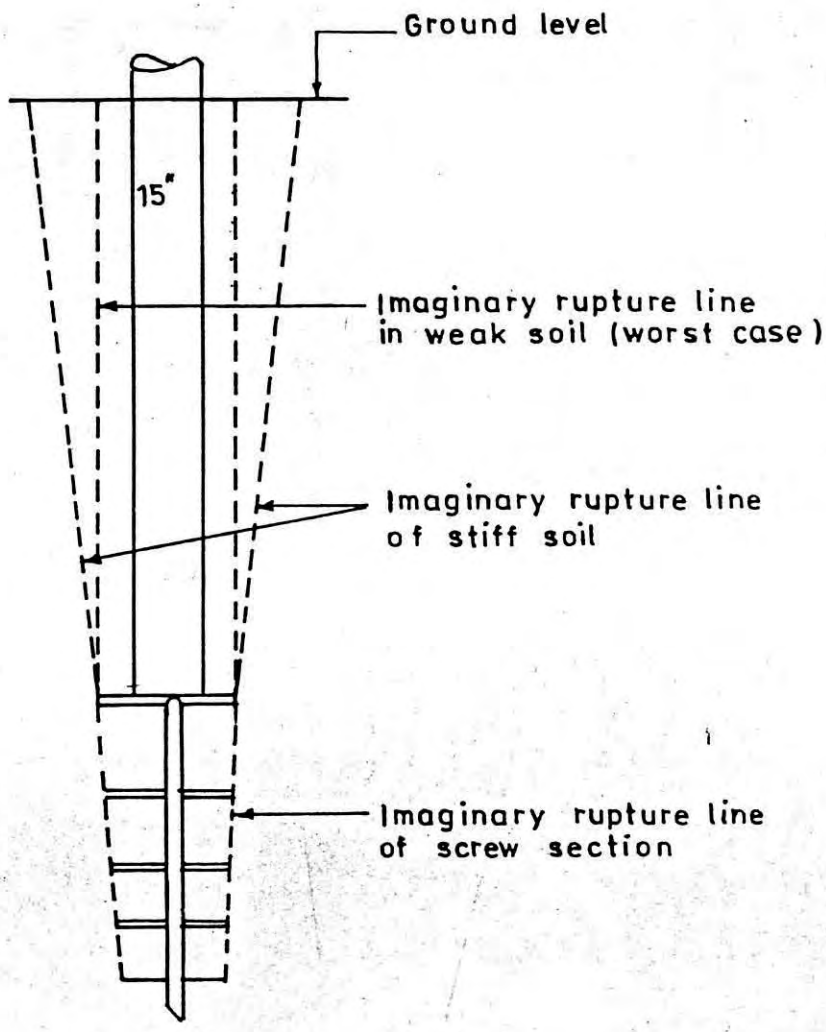


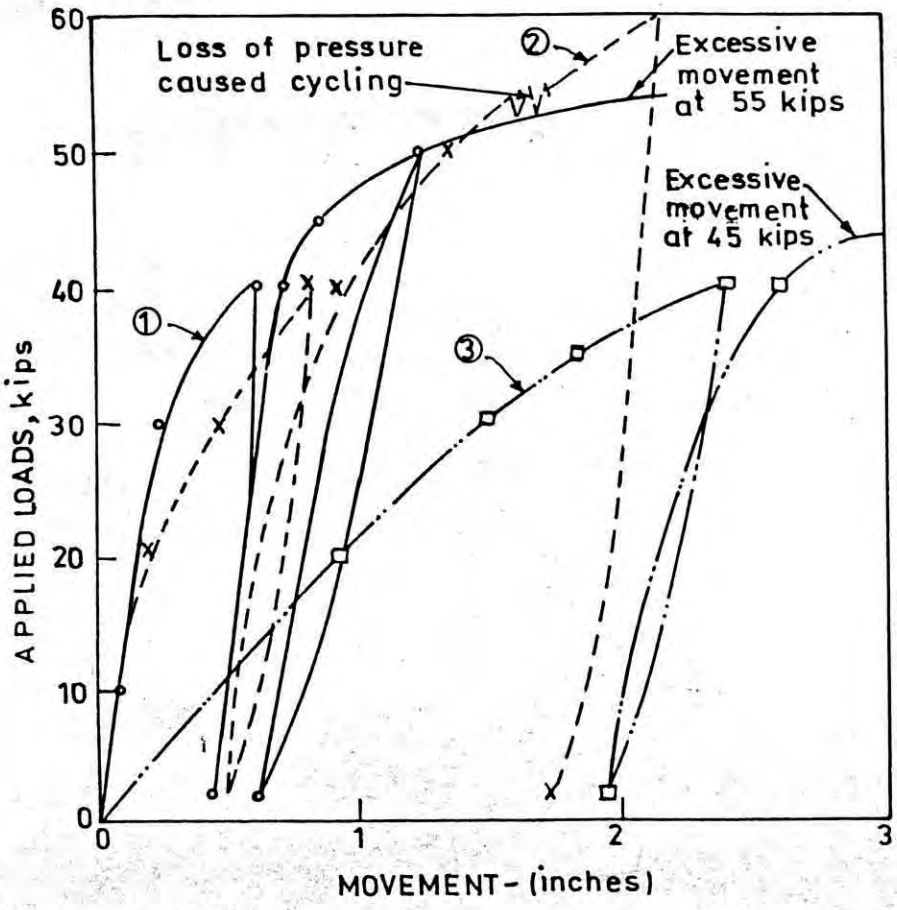
Fig. 2.10 An illustration of imaginary soil rupture surface when the uplift force of pile is applied (after Hitachi Cable Co. 1980a).

direction of loading. Only a few researchers, worked on this basic design criteria on different types of pile such as uniform, anchored, or screw. A brief literature review on this aspect is given in the following paragraphs.

Kulhawy and Kozera (1979) conducted a research on instrumented piles in uniform sand bed and concluded that during the uplift loading the strain in the shaft showed a general parabolic distribution from 0% at the tip to 100% at the butt. This distribution implies a soil skin friction on the shaft that increases linearly with depth from zero at the surface.

In order to find the most suitable anchored foundation for guyed transmission towers Robinson and Taylor (1969) worked with the five types of anchored piles, buried plate with compacted backfill, buried steel mat or grillage with loose backfill, cast in place concrete with loose backfill, power installed helical and grouted rod anchors. The results, as shown in Fig. 2.11, of upward displacement for screw pile indicates that the displacement is a function of applied load, soil type and screw characteristics.

Trofimenkov and Mariupolski (1965) investigated the displacement of screw pile subjected to upward loading. The results were presented by a graph as shown in Fig. 2.12 which indicates a non-linear relationship between d/B and p/P_{uu}, where, d = displacement, B = diameter of the screw plate, P = applied load and P_{uu} = ultimate uplift capacity.



Test	Symbol	No. of helix	Helix Size in inches	Spacing of helix	Pile length	Angle	Soil classification
1	o	2	$10, 11\frac{5}{16}$	3.5'	11'	55°	Stiff to hard sligltly sandy clay
2	x	4	$8, 10, 11\frac{5}{16}, 13\frac{1}{2}$	3.5'	21'	67°	Medium density silty fine sand
3a	a	2	$13\frac{1}{2}$, 15	3.5'	15'	80°	Medium Density Silty Fine Sand.

Fig. 2.11 Helical anchor test results (after Robinson and Taylor, 1969).

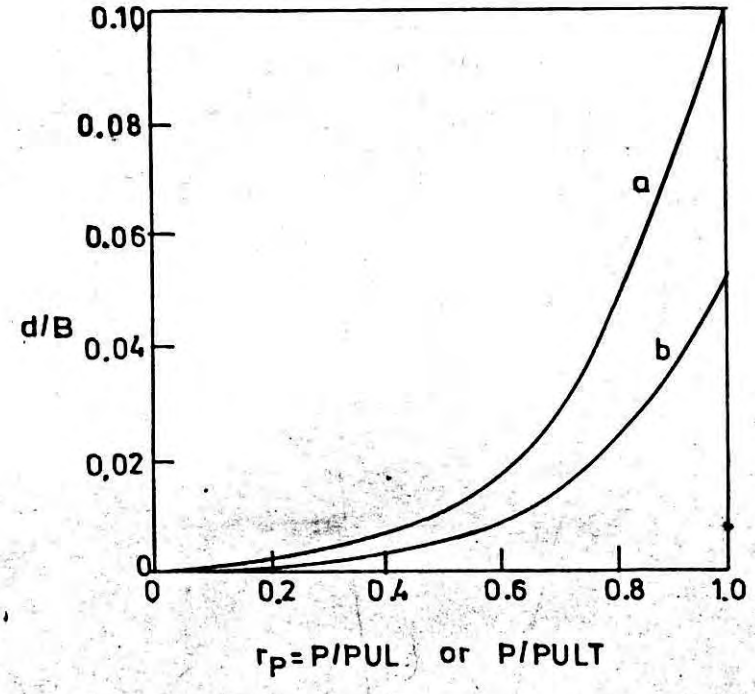


Fig. 2.12 Graph of d/B - r_p (after Trofimenkov and Mariupolski, 1965).

(a) $r_p = p/p_{uu}$ when load increases continuously

(b) $r_p = p/p_{ult}$ when load is pulsating and alternating or is increasing by steps.

2.6 Driving Torque and Friction Characteristics of a Screw Pile

Published literature showing relationship between the driving torque and screw pile characteristics are very few. However, in many published literature it is mentioned that the driving behaviour of a screw pile would be similar to-that of the vane shear test.

In an unpublished technical note of Hitachi Cable Cp. (1980a) it is mentioned that the torque generated (T_s) during the driving operation on the sides of the screw blades are

$$T_s = \frac{2\ \pi C_a}{3}\ (R_s^3 - R_p^3) \qquad (2.11)$$

where,

T_s = torque generated on the screw blade.

R_s = radius of the screw blade

R_p = radius of the pile shaft

According to this report the generated torque of the pile shaft (T_p) would be

$$T_p = 2\pi R_p^2\ L\ C_a \qquad (2.12)$$

where,

T_p = torque generated on the pile shaft

L = embedment length of the shaft or screw pile

The derivation of eqns. 2.11 and 2.12 are given in art. 4.1 in Chapter 4.

The quantities $\frac{2}{3}\pi(R_s^3 - R_p^3)$ and $2\pi R_p^2 L$, are termed as the torque characteristics of screw blade and pile shaft respectively, C_a is described as the adhesion between soil and the screw blade or soil and the pile shaft and its magnitude depends on the type of soil and the loading condition.

According to Abedin (1983) total applied driving torque on the screw pile is theoretically equal to the resisting torque. Therefore,

$$T = \Sigma T_s + \Sigma T_p$$

or $$T = \Sigma (K_{s1} + K_{s2})\, C_1 + K_p\, L\, C_2 \qquad (2.13)$$

where,

L = length of the pile shaft embedded in the soil

T = applied external torque

K_{s1} = torque characteristics of a screw plate for side 1.

K_{s2} = torque characteristics of a screw plate for side 2.

C_1 and C_2 are the cohesion of soils at the screw and pile levels, summation sign is used to consider for more than one screw blades. By considering average cohesion in the screw and shaft portion the equation (2.13) becomes

$$T = K_{st} \cdot C_{1av} + K_p\, L \cdot C_{2av} \qquad (2.14)$$

where,

K_{st} = total torque characteristics of screw portion

C_{1av} = average cohesion in the screw portion

C_{2av} = average cohesion in the shaft portion.

Considering soil disturbance and maximum amount of torque during penetration, equation (2.14) modified to

$$T = \alpha K_{st} C_{1av} + \beta K_p L C_{2}av + \gamma \qquad (2.15)$$

where,

α , β and γ are three constants introduced in equation (2.15) to take care of above mentioned limitations.

As there is an approximately linear relationship between N value and cohesion, equn. 2.15 is modified as

$$T = \alpha_n K_{st} N_{1av} + \beta_n K_p L N_{2av} + \gamma n \qquad (2.16)$$

Thus Eqns. (2.15) and (2.16) constituted two models for the torque-soil strength relations.

From statistical analysis of field test results Abedin (1983) obtained constants for his model for calculating driving torque of screw piles. The data was obtained for piles used in the East-West Interconnector Project (in Pabna region, an alluvial deposit in Bangladesh). His relation became:

$$T = 0.872 C_{1av} K_{st} + 0.125 C_{2av} K_p L + 2796 \qquad (2.17)$$

where,

T = torque in ft-lb

C_{1av} = average undrained shear strength in the screw portion in psf

C_{2av} = average undrained shear strength in the shaft portion in psf

K_{st} = total torque characteristics of screw portion in ft^3.

K_p = torque characteristics of pile shaft in ft^3/ft

L = length of the pile shaft driven in ft.

The above equation is valid for units specified only.

The constant term in eqn. (2.17) i.e. 2796 ft-lb, may be interpreted as a threshold torque (external torque required just to obtain penetration in the soil) and this quantity depends on the characteristics of the screw pile and the soil.

2.7 Summary of the Literature Review

Following points may be summarised from the above literature review:

1. Almost all the theories reveal that deep foundation subjected to uplift load has a cylindrical failure surface which is parallel to the face of the pile or edge of the enlarged base. However, there are doubts regarding the diameter of the failure surface.
2. The uplift capacity of a uniform pile is a function of adhesion between soil and pile material and the weight of the pile.
3. The uplift capacity of base enlarged pile (including screw pile) depends on the soil strength and the dimensions of the base plate or screw plate.

4. From Abedin's (1983) work a good correlation (R = 0.77) has been observed between undrained shear strength as estimated from SPT value of the alluvial soil and driving torque for screw piles.

CHAPTER 3

THE RESEARCH SCHEME

3.1 Introduction

Driving a screw pile requires application of torque at pile top. Amount of torque depends on the shear strength of the soil, blade dimension, shaft dimension and center to center spacing of the blade of the screw pile. If shear strength of the soil is large, then driving torque required to overcome the friction is also large. Again, if the diameter of the shaft,

or of the blade is increased or the number of blades/ft is increased, the torque required to drive a screw pile is likely to increase. Similar reasoning also applies to the uplift capacities of the screw piles.

This research is organised to establish the effect of pile geometry, blade dimensions and spacing of blades on torque requirements and uplift capacity of screw piles in a granular soil.

3.2 Objective of the Research

Little published information are available on torque characteristics and uplift capacities of screw piles. The present research is limited to granular soils and has the following objectives:

1) To develop theoretical relationship between pile geometry with driving torque and uplift capacity.

2) To perform experiments to relate

   a) the effect of blade and shaft dimensions on torque characteristics and the uplift capacities of screw piles.

   b) for a given diameter blade, the effect of increase in number of blades on torque characteristics and uplift capacities of screw piles.

   c) effect of blade configuration on torque characteristics and uplift capacities of screw piles.

Ideally the above studies require tests to be performed on sands at a number of relative densities. Unfortunately due to limited time available for this research, such densities were limited to a very close range for various tests.

Thus the effect of shaft and blade dimensions, the center to center spacing of blades on torque requirements and uplift capacities of screw piles were to be studied at predetermined densities of sand. The density used was established from a technique used to form sand beds of uniform densities.

3.3 Scope of the Work

The general shape of screw piles used in the present research are shown in Fig. 3.1, that is (a) pile containing same diameter blades, (b) blade diameter decreasing with depth and (c) blade diameter increasing with depth.

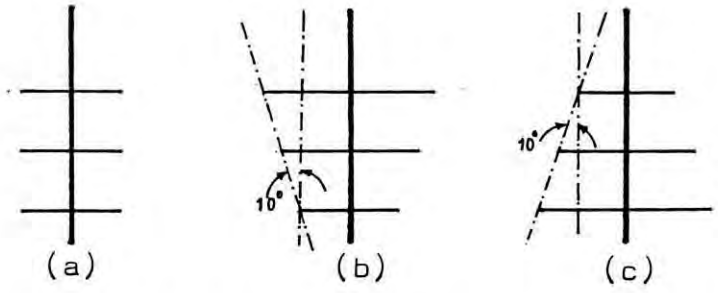


Fig. 3.1 Types of blade configurations.

Seven groups of piles containing total of twenty one different screw piles are prepared for this research (Fig.3.2). These are, Group A_3 : This group contains piles 1, 2 and 3. These three piles are of same shaft diameter (i.e. 0.25 inches). Blade diameter of this three piles are of 0.75, 1.25 and 1.75 inches respectively. The ratio of radius of screw blade to radius of pile shaft (R_B/R_p) for this three piles are 3,5 and 7 respectively. Each pile contain three blades of same diameter. Group A5: This group has three piles 1a, 2a, and 3a, they are of same shaft and blade diameter as those of group A3. Here each pile contains five blades of same diameter.

Group B3: It contains piles 4, 5 and 6. Which have same shaft diameter (i.e 0.5 inches). Blade diameter of these three piles are of 1.5, 2.5, and 3.5 inches respectively. Here R_B/R_p ratio for this three piles are 3, 5 and 7 respectively. Each pile contain three blades of same diameter. Group B5: This group also have three piles 4a, 5a and 6a. Here shaft diameter and blade diameter are same as group B3, only number of blades are increased to five.

Group C3: It contain piles 10, 11 and 12. Each pile has three blades and are of same shaft diameter (i.e. 0.75 inches). Blade diameter are of 2.25, 3.0 and 3.75 inches respectively for this three piles. Here R_B/R_p ratio for this three piles are 3, 4 and 5 respectively. Here piles with five blades are not prepared because it required large driving torque, which could not be measured by the torque meter prepared for this test.

In the above five groups of piles, dimension of pile shaft and blades are varied, center to center spacing of blades are also varied, but all blades in any pile are of same diameter.

Six taper shaped screw piles are also prepared, where each pile contains three blades of different diameter. These are grouped as : Group D3: contains piles 7, 8 and 9, and has same shaft diameter of 0.25 inches. The lower blade diameter of each pile are of 0.75, 1.25 and 1.75 inches respectively. The diameter are decreased in such a way that the cone formed by joining periphery of the blades formed a 10^o angle with the vertical.

Group E3: It has three piles 7a, 8a and 9a. These three piles have same shaft and blade diameters as in group D_3. Only the arrangements of blades are opposite to those of group D_3. That is smaller blades are at top and larger blades at the bottom.

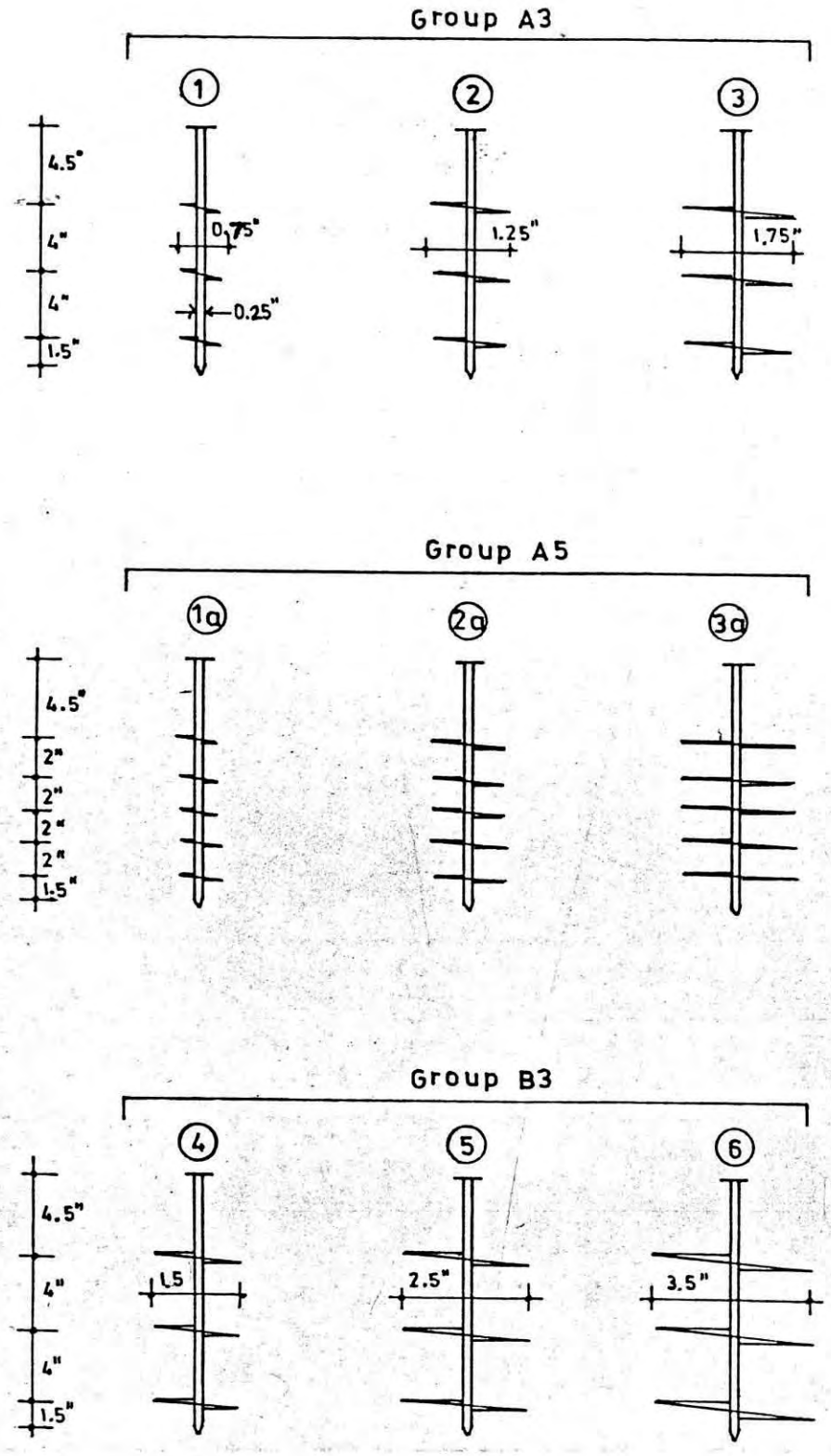


Fig. 3.2(a) Screw pile geometry.

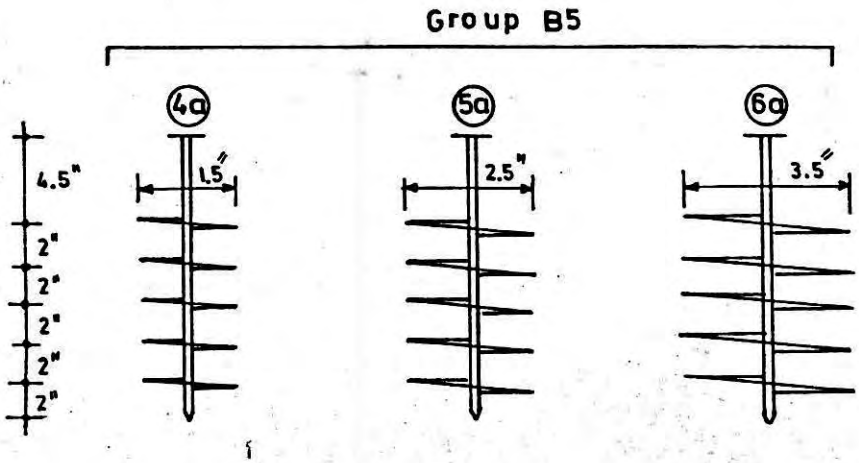


Fig. 3.2(a) Screw pile geometry.

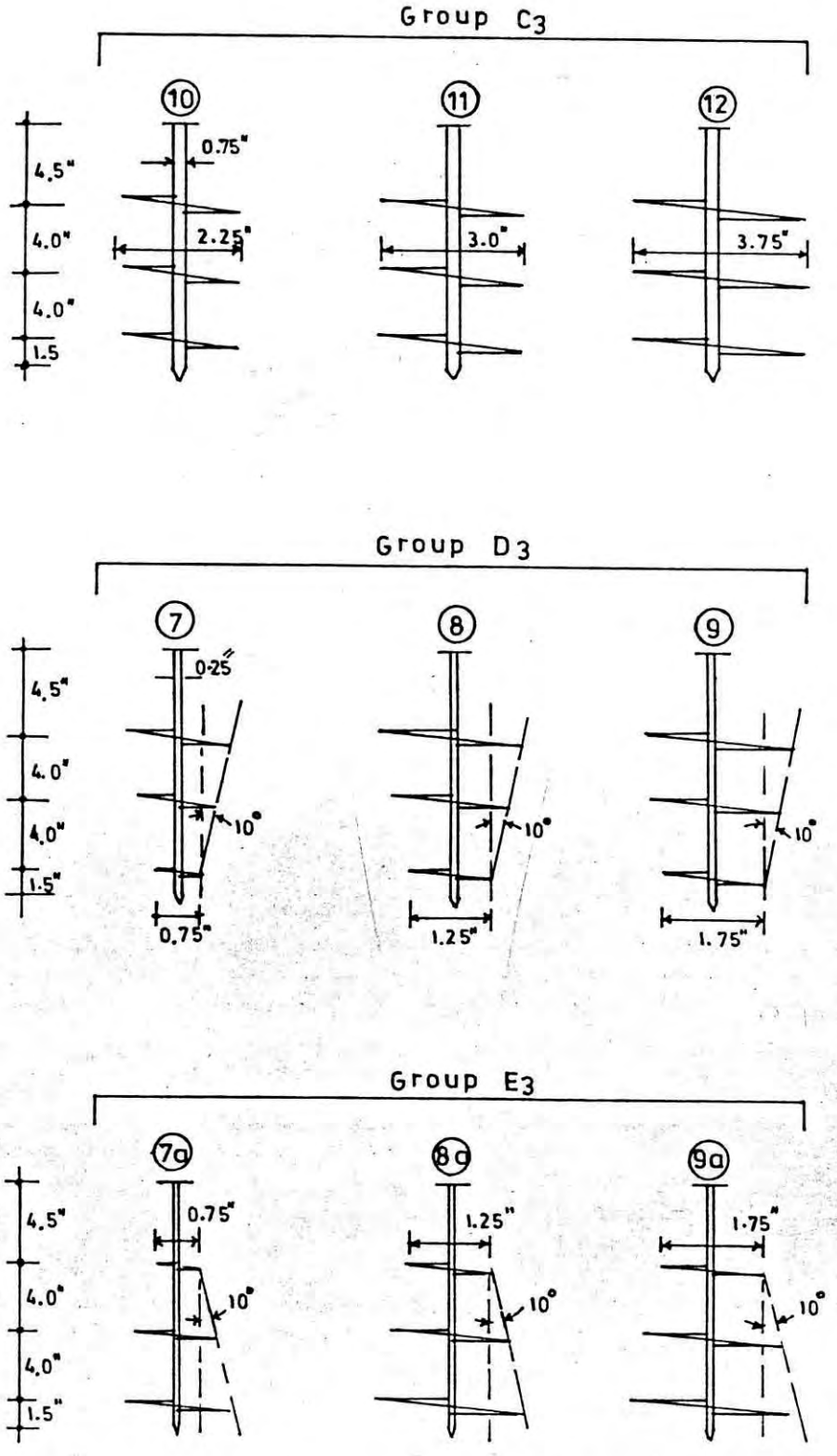


Fig. 3.2(b) Screw pile geometry.

Inclination of each blade with horizontal (θ) was kept fixed i.e. 20^{o} and all these screw piles are driven 14 inches in the uniform sand bed. For each pile the torque required to drive the piles in sand bed is measured by a torque measuring instrument (Torque meter). Uplift capacity is also measured for each pile by a proving ring arrangement.

This research work is done under the following conditions.

i) A particular type of granular soils (passing through sieve No. 16 and retained on sieve No. 50) are used in the laboratory.

ii) Dry granular soils are used throughout the test.

iii) All the screw piles are driven upto a depth of 14 inches.

iv) During preparation of sand bed, height of fall of sand and movement of trolley are kept constant, in order to prepare a sand bed having uniform density.

v) The pile is rotated for penetration at a constant rate.

vi) The pile is lifted at an uniform rate.

3.4 Test Program

Installation and uplift tests were performed with each type of pile. Each test consisted of the following stages of performance.

Uniform sand bed preparation: preparation of uniform sand beds with measurement of densities at different locations in the beds. The beds are to be prepared in such a way that the densities of different beds are nearly identical.

Determination of relative density and shear strength parameters of the sand used in each test program.

Pile installation test: On attaining a uniform bed, driving of screw piles in the beds with application of torque at pile top. During driving, the torque is measured by torque meter.

Uplift load test on the piles: During application of uplift loads, simultaneous reading of loads and deflections are noted.

CHAPTER 4

DRIVING TORQUE AND UPLIFT LOAD RELATIONS

4.1 Theoretical Torque and Friction Characteristics of a Screw Pile

Published literature showing the driving torque and screw pile characteristics relations are very few. However, in many published literature such as Hitachi Cable Co. (1980a), Abedin (1983), it is mentioned that the driving behaviour of a screw pile would be in some respect, similar to that of the vane shear apparatus. The circular blade of a screw pile may-be considered to have a radius r sec θ, where θ is the inclination of the blade with the horizontal, r is the radius of blade Fig. 4.1a. If we consider a circular element of thickness dr on the blade as marked by hatched line in Fig. 4.1b, the inclined area of the marked portion is equal to $2\pi r \sec\theta \, dr$.

As torque is applied at the top of the screw pile, frictional resistance on the screw blades are developed. Total frictional torque developed on one side of the screw blade is given as

$$T_s = \int_{R_p}^{R_B} f_1 \, 2\pi r \, \text{Sec}\,\theta \, r \, dr \qquad (4.1)$$

where,

T_s = total frictional torque on one side of a screw blade.

R_p = radius of pile shaft

R_B = radius of screw blade

f_1 = resisting force per unit area (considering resisting force acting between blade material and soil).

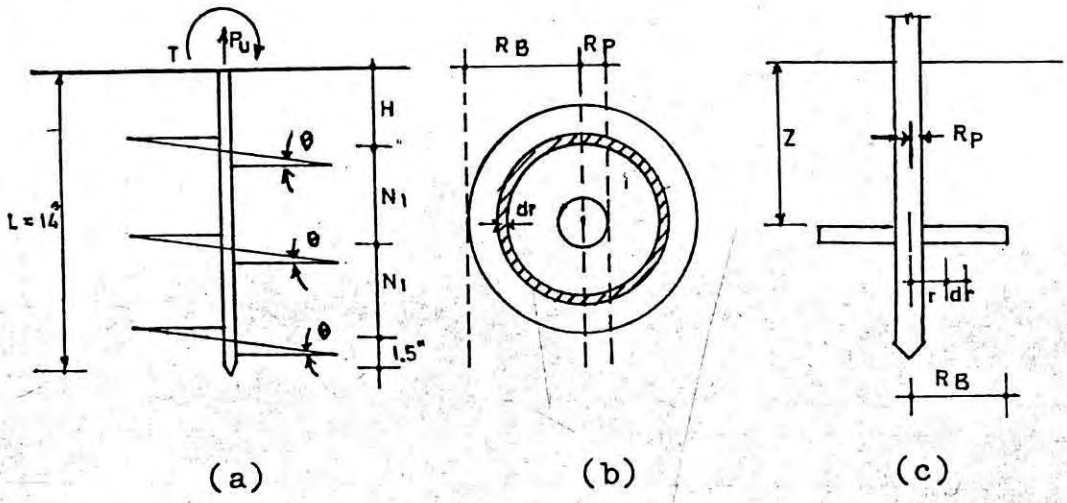


Fig. 4.1 Screw pile (a) Screw pile with inclined blade.

(b) Screw blade.

(c) Screw pile with horizontal blade.

After integration Eqation (4.1) becomes

$$T_s = 2/3\,\pi \sec\theta\,(R_B^3 - R_p^3) f_1 \qquad (4.2)$$

Considering friction between blade material and soil, resisting force per unit area (f_1) can be expressed as

$$f_1 = \int_0^L K_p\,\gamma z \tan\phi \tan\partial\, dz \qquad (4.3)$$

where,

K_p = co-efficient of passive earth pressure

γ = unit weight of soil

ϕ = angle of internal friction of soil

∂ = angle of friction between soil and blade material

z = depth of screw blade

L = length of the embedded portion of the pile.

on integration, Eq. (4.3) becomes

$$f_1 = K_p/2\,\gamma \tan\theta \tan\partial\, L^2 \qquad (4.4)$$

When torque is applied at the top of screw pile, the total friction torque resisted by the pile shaft of radius R_p at unit length will be

$$T_p = 2\pi R_p\, R_p\, f_2 \qquad (4.5)$$

where,

T_p = total frictional resisting torque per unit length acting on the pile shaft

$2\pi R_p$ = surface area of the pile shaft per unit length

f_2 = resisting force per unit area of the shaft (considering resisting force acting between pile shaft and soil)

As in case of f_1, f_2 can be expressed as

$$f_2 = \frac{K_p}{2} \gamma \tan \phi \tan \delta \; L^2 \qquad (4.6)$$

where L is the total length of shaft in between the screw blades within soil.

It is assumed that shear forces between pile shaft and soil as well as between pile blade and soil are mobilised simultaneously. The total applied driving torque (T) on the top of screw pile would, theoretically be equal to the resisting torque. This is expressed as

$$T = \Sigma T_s + \Sigma T_p \qquad (4.7)$$

For a screw pile of length L, with N_2 number of blades (Fig. 4.2a) total driving torque for both sides of screw blades become

$$T = 2.\frac{2}{3} \pi \text{ Sec } \theta \; (R_B^3 - R_p^3) f_1 \; N_2 + 2\pi R_p^2 \; f_2 \qquad (4.8)$$

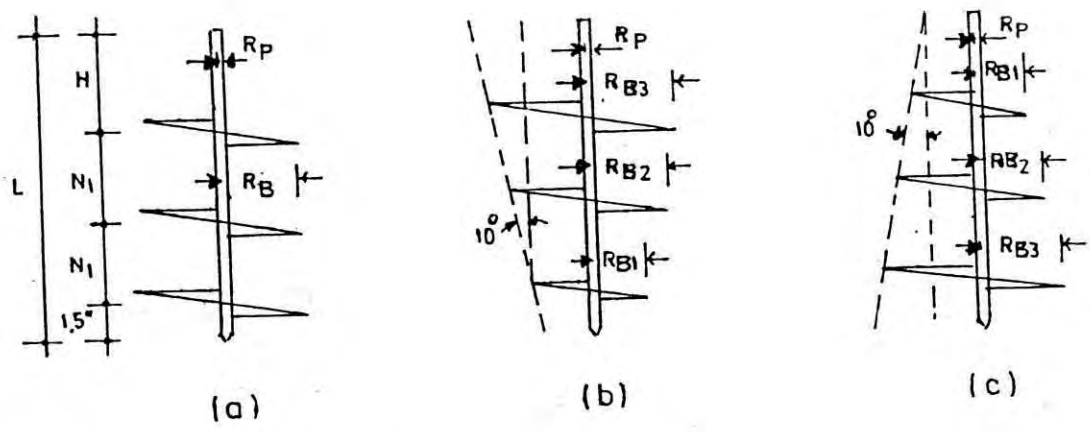


Fig. 4.2 Different types of blade arrangements in screw pile. (a) Blades with same radius. (b) Blades of different radius and radius of blades increases by + 10^{o} with the vertical from the bottom. (c) Radius of blades increases by + 10^{o} with the vertical from the top of pile.

For the screw piles of type (Fig. 4.2b and c) of length L total driving torque for both sides of screw blades become

$$T = \frac{4}{3} \text{ Sec } \theta \, f_1 (R_{B_1}^3 + R_{B_2}^3 + R_{B_3}^3 - 3R_p^3) + 2\pi R_p^2 f_2 \qquad (4.9)$$

where RB_1, RB_2 and R_{B_3} are three screw blade radius as shown in Fig. 4.2b and c. In Eqn. (4.9) co-efficient of earth pressure is assumed to be same in both faces of the screw blade.

In this above Eqns. 4.8 and 4.9, effect of vibration and disturbance during installation is not considered.

4.2 Evaluation of Theoretical Uplift Capacity

A number of models can be proposed for predicting the uplift capacity of a single screw pile. Basically these models fall into the three categories as shown in Fig. 4.3 (Kulhawy and Kozera 1979).

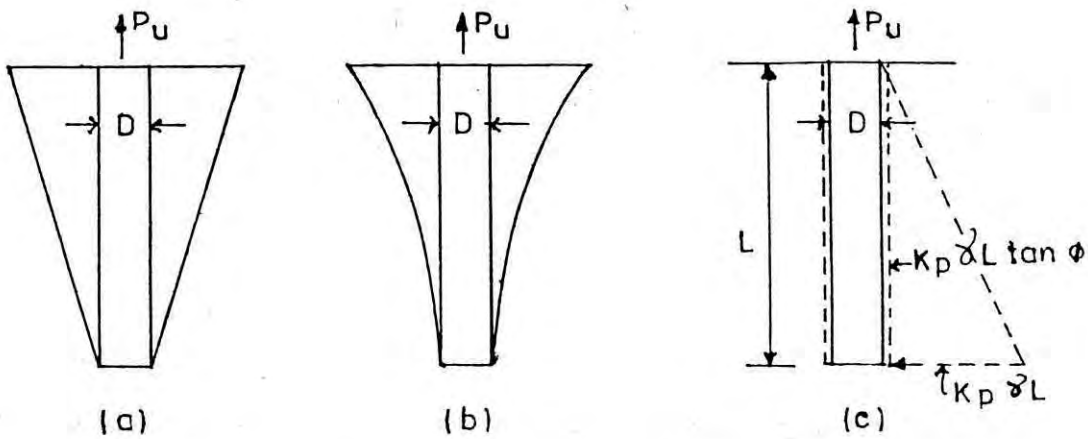


Fig. 4.3 Uplift capacity models (a) Turncated cone (b) Curved surface (c) Cylindrical shear.

In the turncated cone model Fig. 4.3a, the uplift force is resisted by the weight of the pile and the weight of the soil within the turncated cone.

In the curved surface model Fig. 4.3b the uplift force is resisted by the weight of the pile, the weight of the soil above the curved surface and by the cohesive or frictional forces along the surface.

The third model assumes that shear failure occurs on a cylinderical surface along the shaft, and that the uplift force is resisted by the weight of the pile and by the shear strength along the cylindrical surface.

From the above three models, the cylindrical shear failure model is considered for predicting the uplift capacity. The reason is that, in this model, measurement of parameters are very simple than the other two models. In the cylindrical shear model the uplift capacity is given by

$$P_u = \bar{W} + \pi D \int_0^L K_p \gamma z \tan \phi \, dz \qquad (4.10)$$

where,

P_u = ultimate uplift load

$\bar{W}$ = effective weight of the pile

D = diameter of pile

$K_p \gamma L \tan \phi$ = the vertical shear along the shaft

K_p = co-efficient of passive earth pressure.

For a homogeneous soil linear stress increases as shown in Fig. 4.3c.

After integration Eqn. 4.10 becomes

$$P_u = \bar{W} + \pi D \frac{L^2}{2} K_p \gamma \tan \phi \qquad (4.11)$$

For screw pile of type Fig. 4.2a, ultimate uplift load can be predicted as

$$P_u = \bar{W} + \pi(R_B^2 - R_p^2)\gamma H + \pi(R_B^2 - R_p^2)\gamma N_1(N_2-1)$$

$$+ 2 R_B \pi \int_o^L K_p \gamma z \tan \phi \, dz \qquad (4.12)$$

where,

N_1 = spacing of blade

N_2 = number of blades

$\pi(R_B^2-R_p^2)$ = area of each blade of screw pile

$\pi(R_B^2-R_p^2)\gamma H$= weight of soil above the top blade

$\pi(R_B^2-R_p^2)\ N_1(N_{2-1})$ = weight of soil between the blades

$2\pi R_B \int_o^L K_p \gamma\ z \tan \phi \, dz$ = shear strength along the cylindrical shaft formed at the periphery at radius R_B.

Integrating and re-arranging the terms, Eqn. 4.12 becomes

$$P_u = \bar{W} + \pi(R_B^2 - R_p^2)\gamma\{H + N_1(N_{2-1})\} + \pi R_B L^2 K_p \gamma \tan \phi \qquad (4.13)$$

Eqn. 4.13 is used for the screw pile of type Fig. 4.2a. For the screw pile of type Fig. 4.2b and c, failure surface was assumed to be cylindrical. And failure cylinder was considered to be of radius RB_2 (i.e. the middle blade of the piles of Fig. 4.2b and c). For the screw pile of type Fig. 4.2b and c, the equation for predicting uplift capacity is

$$P_u = \bar{W} + \pi(R_{B_3}^2 - R_p^2)\gamma H + \pi(R_{B_2}^2 - R_p^2)\gamma N_1 + \pi(R_{B_1}^2 - R_p^2)\gamma N_1 +$$

$$+ \pi R_{B_2} L^2 K_p \gamma \tan \phi \qquad (4.14)$$

For this above equations 4.13 and 4.14, effect of vibration and any disturbance during installation is not considered.

CHAPTER 5

LABORATORY EXPERIMENTAL PROGRAM

5.1 General

The experimental work is performed in three stages and test program is shown in Fig. 5.1.

1. Preparation of uniform sand bed.
2. Installation of model screw piles.
3. Uplift test on installed piles.

The technique developed for preparation of uniform sand bed is detailed in article 5.2.

The installation technique required measurement of driving torque. A torque meter is designed and fabricated for the purpose, whose working principle, design details and calibration procedure are presented in article 5.3.

The uplift test required measurement of uplift force and displacement. This is detailed in article 5.5 and 5.6.

The experiments are aimed to study the following aspects:

1. Effect of shaft dimension on driving torque: In order to study this, three types of shaft diameters are used and shown in Fig. 3.2a and 3.2b, and described in article 3.3. Length of all the piles are kept fixed i.e. 14 inches.

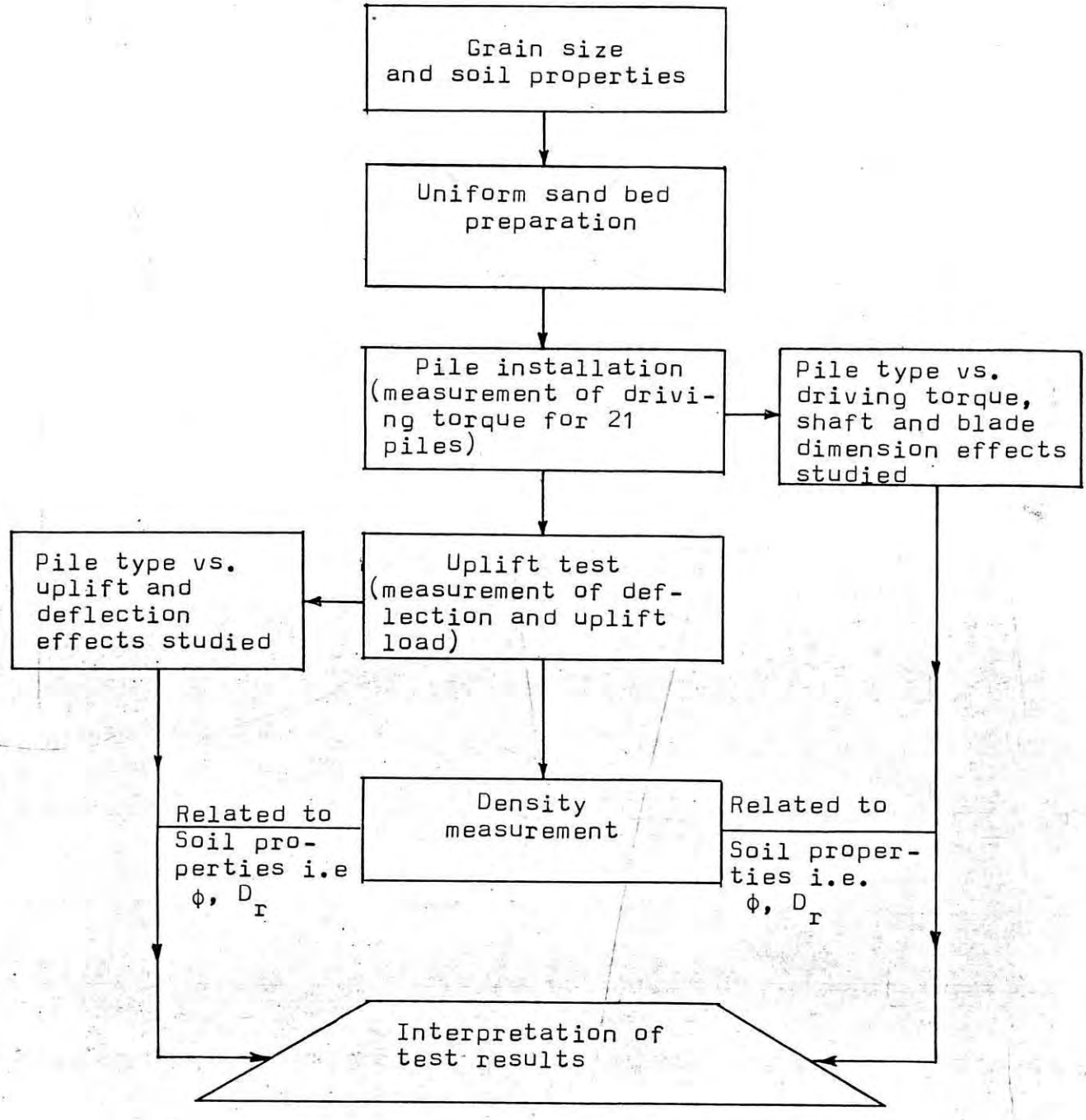


Fig. 5.1 Flow chart for test program.

2. Effect of blade dimension on driving torque: In order to study this, diameters of the blades are varied from 0.75 inches to 3.75 inches, Fig. 3.2a and 3.2b.

3. Effect of number of blades per unit length on driving torque: In order to study this, number of blades are increased from 3 to 5 in a pile. Fig. 3.2a and 3.2b.

4. Effect of blade geometry on driving torque. In order to study this three types of blade arrangements are used as shown in Fig. 3.1.

5. Effect of shaft dimension on uplift load: In order to study this, three types of shaft diameters are used and shown in Fig. 3.2a and 3.2b and described in article 3.3. Length of all the piles are kept fixed at 14 inches.

6. Effect of blade dimension on uplift load: In order to study this, diameter of the blades are varied from 0.75 inches to 3.75 inches Fig. 3.2a and 3.2b.

7. Effect of number of blades in a pile on uplift load: In order to study this, number of blades are increased from 3 to 5 in a pile Fig. 3.2a and 3.2b.

8. Effect of upward displacement against uplift in different types of piles: In order to study this, piles of Fig. 3.2a and 3.2b, are uplifted by a proving ring arrangement and upward movement is recorded by a magnetic dial gauge.

9. Relation between driving torque and uplift load.

All the tests are conducted in a cubical tank measuring 2 ft. on each side. The tank is made of steel frame and galvanised iron sheets.

Twenty one different screw piles having different shaft diameters and blade dimension as shown in Fig. 3.2, and described in article 3.3 are used. Screw blades of all piles are 1/16 inch thick and length of the piles are fixed at 14 inches. Pile shaft and blades are made of mild steel.

5.2 Preparation of Uniform Bed of Sand

For the preparation of uniform bed of sand, 9 cubic feet of uniformly graded sand is used. The sand contained materials passing No. 16 sieve and those retained on No. 50 sieve. Fig. 5.2 shows the grain size distribution. During preparation of the uniform bed of sand, the sand is dropped in the tank from a hopper as shown in Fig. 5.3. The hopper iss placed on a trolley, and sand is allowed to fall freely from a certain height. At the same time the trolley is moved to and fro by a pulley with a constant speed of 4 inches per second. The hopper is held in such a way that the height of fall of sand could be varied. Sand is allowed to fall freely from a height of 4, 8 and 12 inches respectively.

For each height of fall, density of sand is measured by placing empty cans at top, middle and bottom of the box. For different heights of fall of sand, densities at different

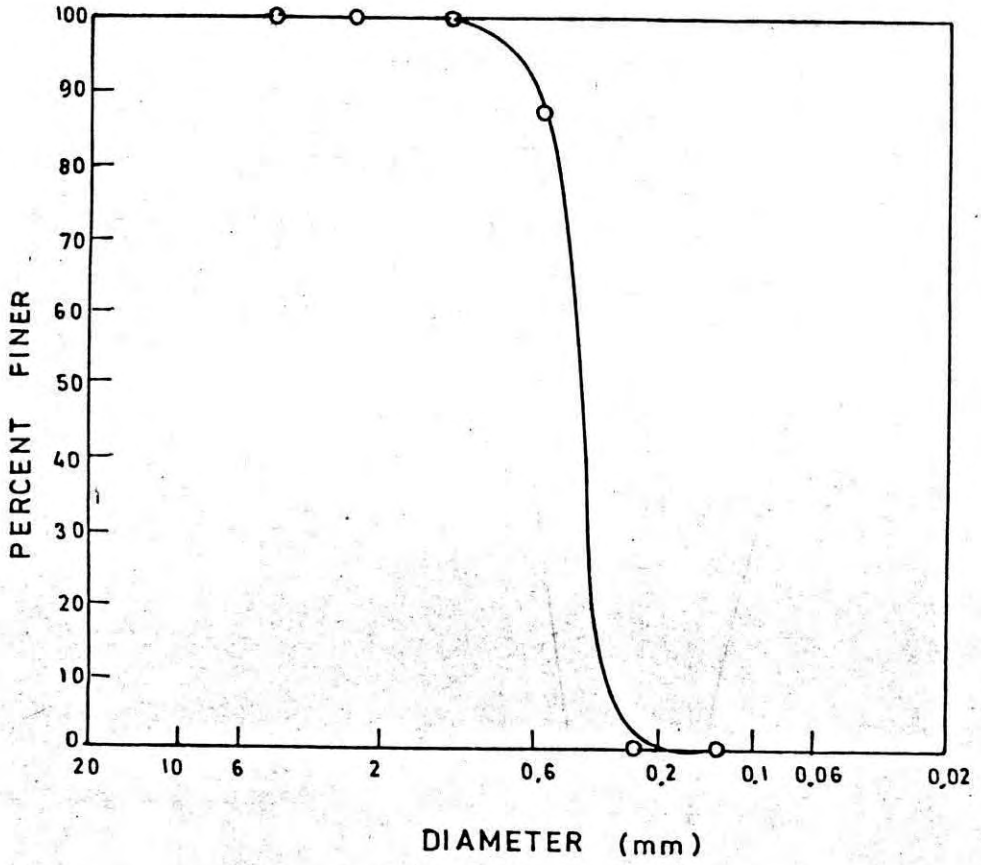


Fig. 5.2 Grain size distribution.

66097

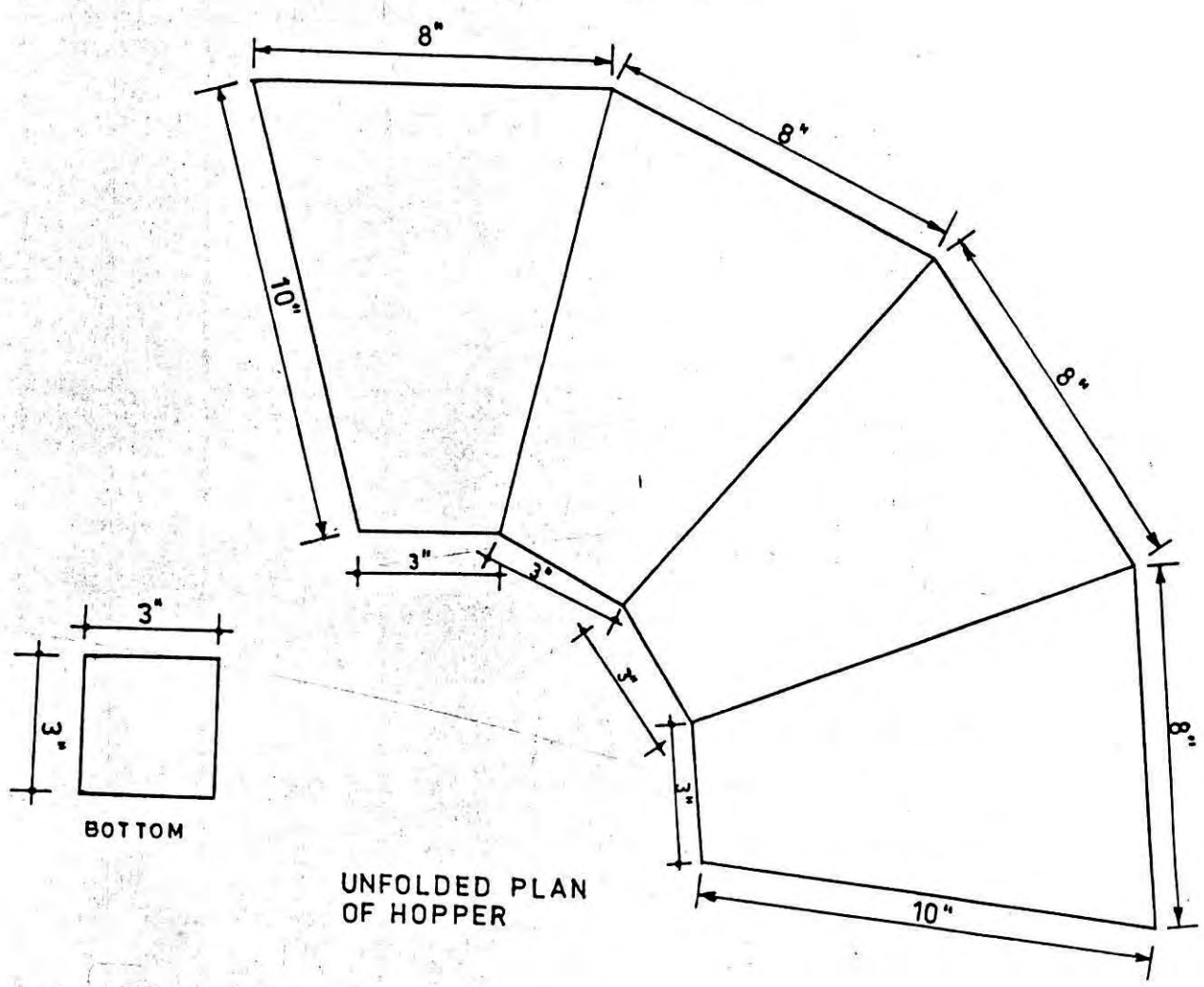


Fig. 5.3(a) Details of sheet work for making hopper.

Fig. 5.3(b) Arrangements for placing hopper on trolley and dropping sand from a specified height.

Table 5.2 Dry Densities of Sand at Different Layers in the Box During Preparation of Sand Bed

1	2	3	4	5
	Height of fall (in)	Density (pcf)	Average density at layers (pcf)	Average density (pcf)
Top	4	84.00 84.75 86.75	85.16	
Mid	4	85.50 86.25 87.50	86.41	86.52
Bottom	4	87.00 87.00 88.80	88.00	
Top	8	85.00 86.00 87.50	86.50	
Mid	8	87.00 87.50 89.00	87.91	87.94
Bottom	8	88.55 90.50 89.23	89.42	
Top	12	87.15 89.21 88.01	88.12	
Mid	12	88.65 90.72 89.45	89.60	89.97
Bottom	12	91.10 93.46 92.05	92.20	

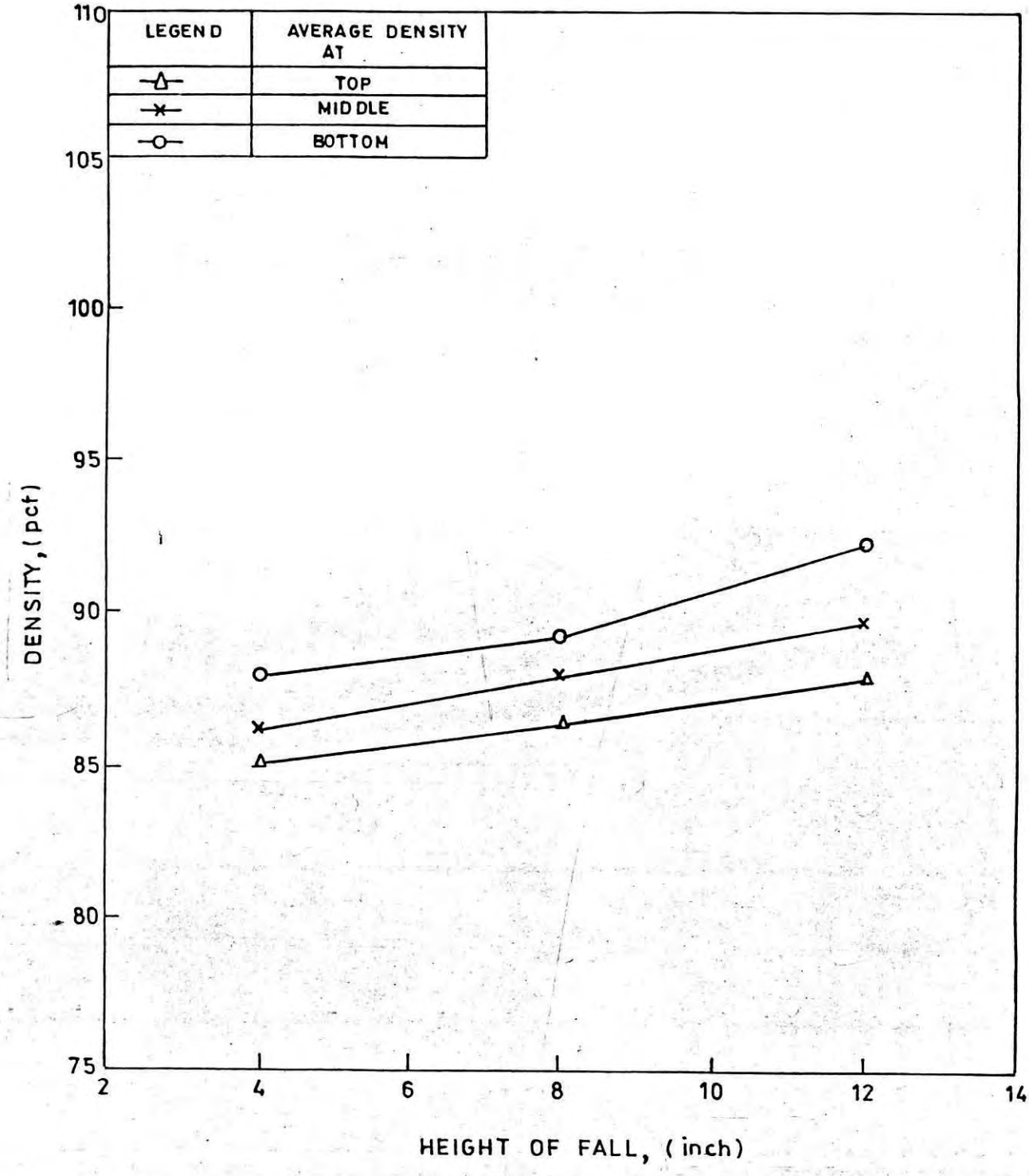


Fig. 5.4 Sand densities at different heights of fall during sand bed preparation.

layers in the box are given in Table 5.2. These densities are plotted against height of fall, and is shown in Fig. 5.4. It is observed that with increase in height of fall of sand from 4 to 12 inches the density of sand bed increased from 86.52 pcf to 89.97 pcf.

5.3 Torque Meter

The torque meter which is shown in Fig. 5.5a is made of three circular plates a, b and c (Fig. 5.5b) of diameters 4.0, 1.9 and 2.5 inches respectively. A spring of diameter 1.6 inches and 4.0 inches in height is used. Diameter of spring thread is 0.156 inches. Two collars attached to two circular plates are used to keep the spring in central position. A mild steel spindle of 6 inches in length is used for keeping the three circular plates and spring in central position. The lower two plates "b" and "c" are fixed with the spindle. Upper plate "a" attached with the spindle by a smooth bearing so that the plate can easily rotate around the spindle. A hole of 1/8 inch in diameter is kept at the spindle top for applying uplift load. A pointer is attached with the spindle top, which indicates the angle of deflection during the application of torque. A circular dial marking 0^{o} to 280^{o} is fixed with the plate "a". Fig. 5.5c shows the photograph of the torque meter.

In order to calibrate the torque meter the procedure described below are followed.

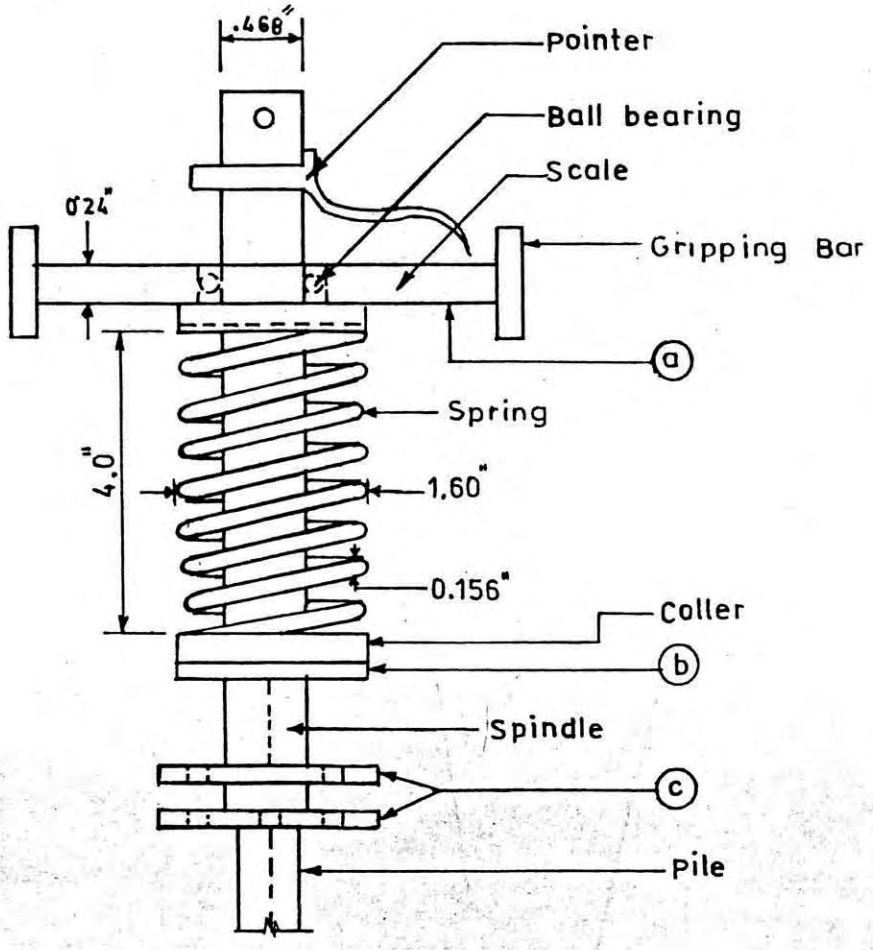


Fig. 5.5(a) Schematic details of the torque meter.

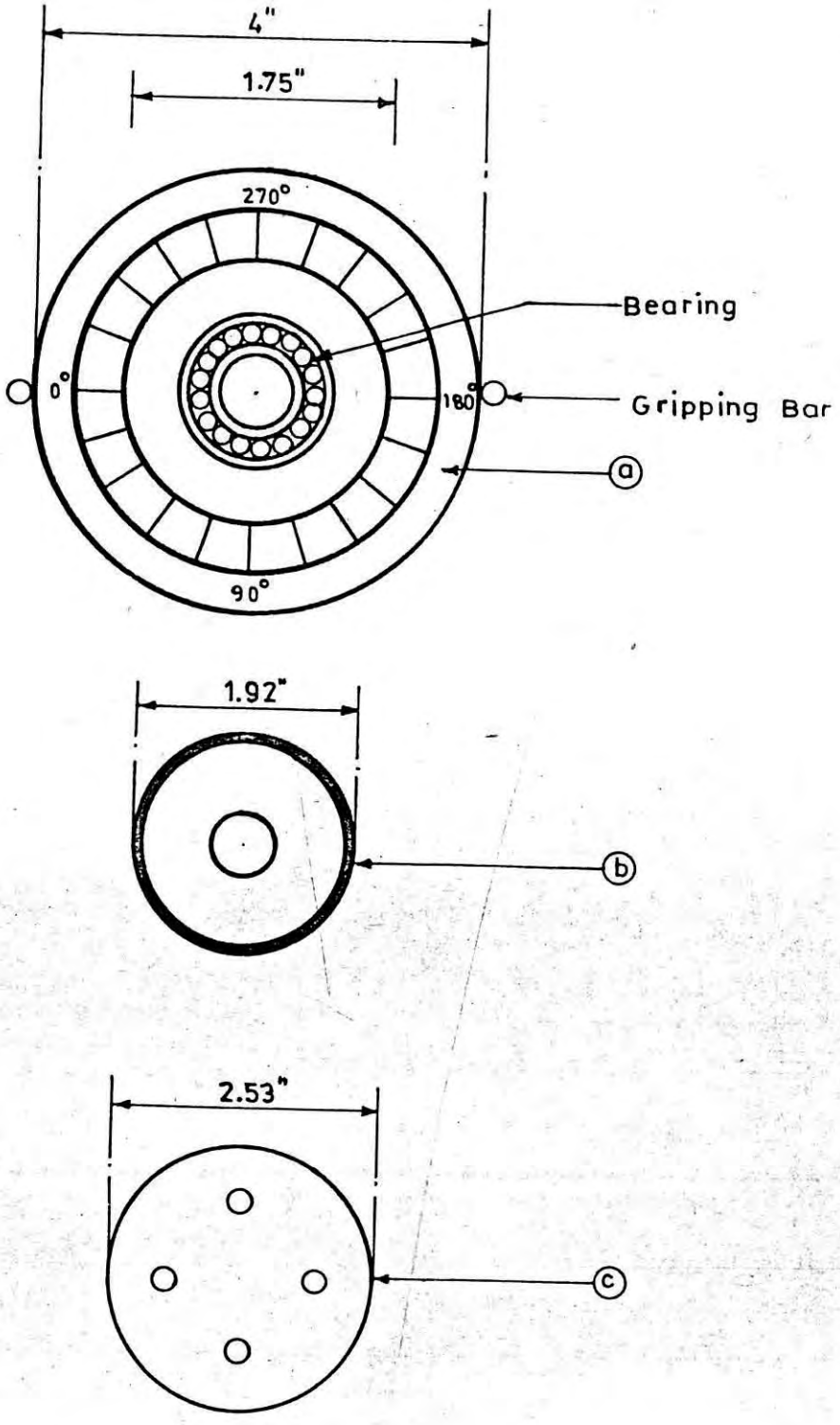


Fig. 5.5(b) Circular plates used in torque meter.

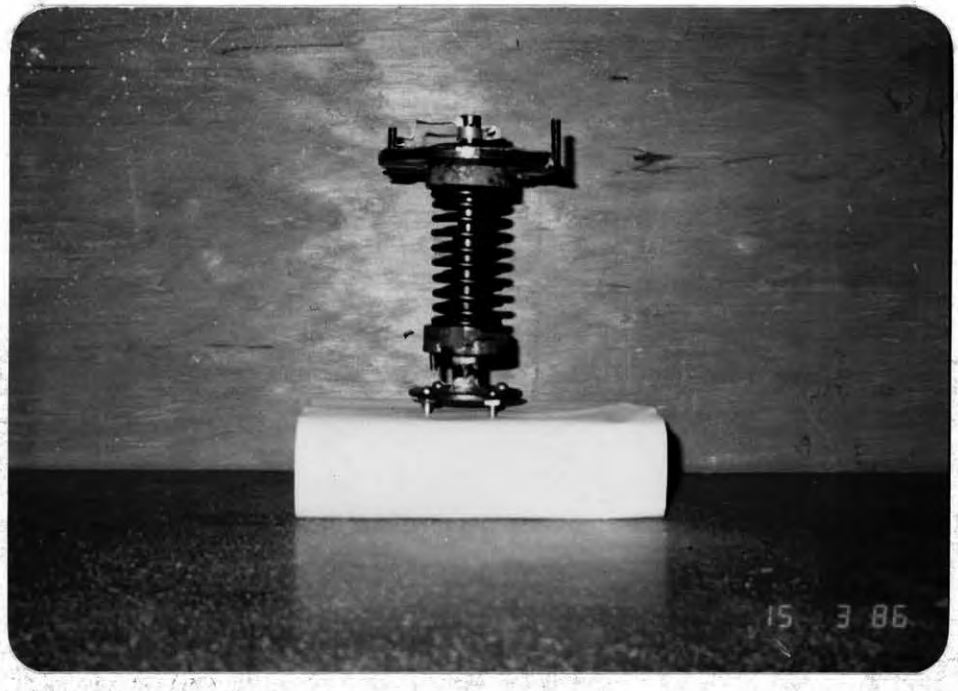


Fig. 5.5(c) Torque meter used in the experiment for measuring torque.

Lower plate "c" of the torque meter is fixed with the spindle. The torque meter is fixed by holding the lower plate "c" with a vice. Then arrangements are made to suspend the loads from the bars attached with the plate "a". Now loads are gradually increased. Multiplying this loads with the lever arm i.e. the radius of plate "a", gives the torque and corresponding deflection angle indicated by the pointer on the plate "a" is measured. Fig. 5.6 shows torque vs. angle of deflection. From this figure torque for respective angle of deflection can be obtained. Photograph in Fig. 5.5c shows the torque meter. By this torque meter, torque can be measured upto 76 lb-in.

5.4 Installation Test Procedure

The piles are installed within sand by application of torque at the pile top. The driving torque is applied and measured by the torque meter. Following steps are followed for measuring the driving torque during installation of piles:

i) The torque meter is fixed to the screw pile by five screws on plate "c" in Fig. 5.5a.

ii) The pile with the torque meter at its top is kept in vertical position on the sand bed.

iii) The top circular plate "a" of the torque meter is rotated by hand at a uniform rate of 30^{o} per second, keeping the pile in vertical position all the time. The pile rotated and at the same time it penetrated into the sand.

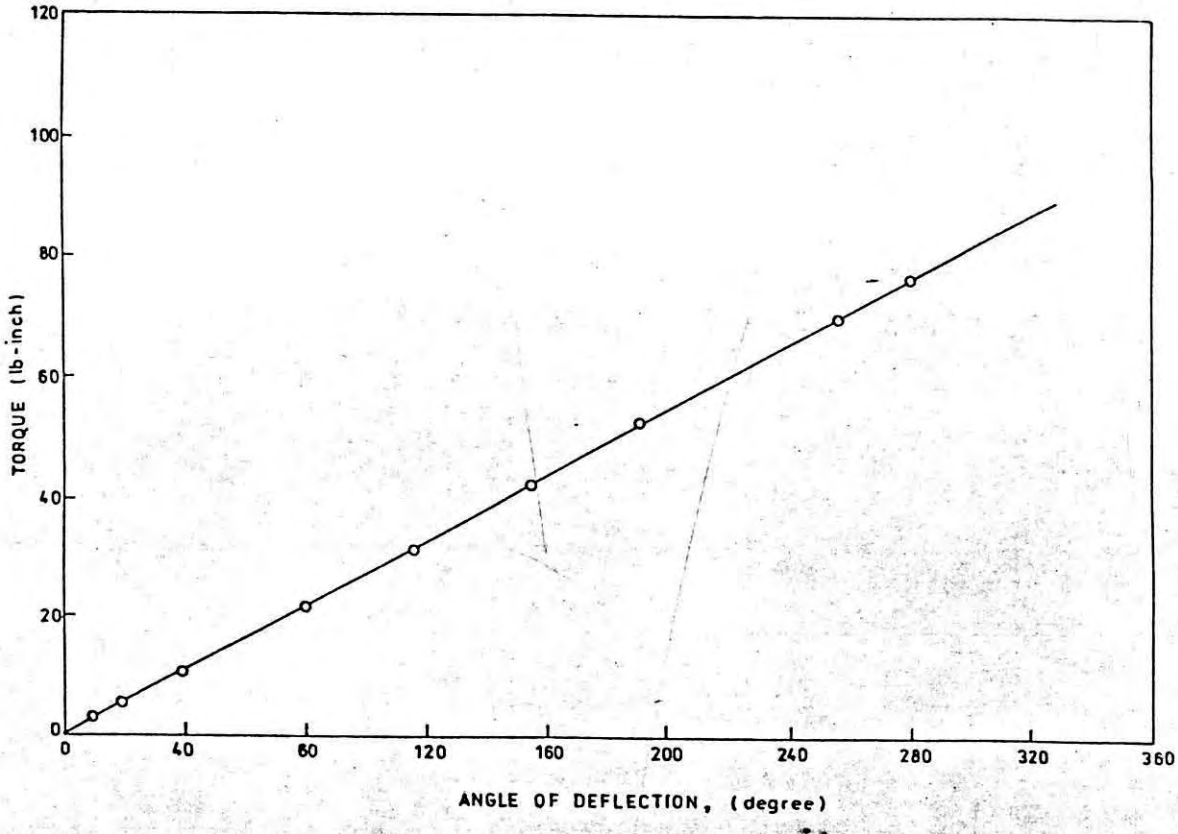


Fig. 5.6 Calibration curve for the torque meter.

iv) The pointer tilted to the large circular plate "a" of the torque meter, indicated the angle of deflection at a specified application of torque.

v) As the pile penetrated the sand, angle of deflection increased. When the pile penetrates upto the desired depth i.e 14 inches into the sand, the value of the angle of deflection is recorded.

vi) From the calibration curve in Fig. 5.6 torque required for the penetration is found for the corresponding angle of deflection.

vii) The test is performed twice for each type of pile.

5.5 Arrangements for Uplift Load Test

Uplift load is measured by a proving ring arrangement as shown in photograph of Fig. 5.7. This proving ring is calibrated earlier for load and deflection, and plotted in Fig. 5.8. In this arrangements a rectangular steel frame (Fig. 5.9) is used and attached by a pin with the top of the torque meter. When proving ring lever is rotated for uplift, then the steel frame compresses the proving ring and the deflection of the proving ring is measured. From Fig. 5.7 uplift load is found from the corresponding deflection. In this way uplift load is measured by a proving ring arrangement.

Fig. 5.7 Arrangements for measuring uplift load by proving ring.

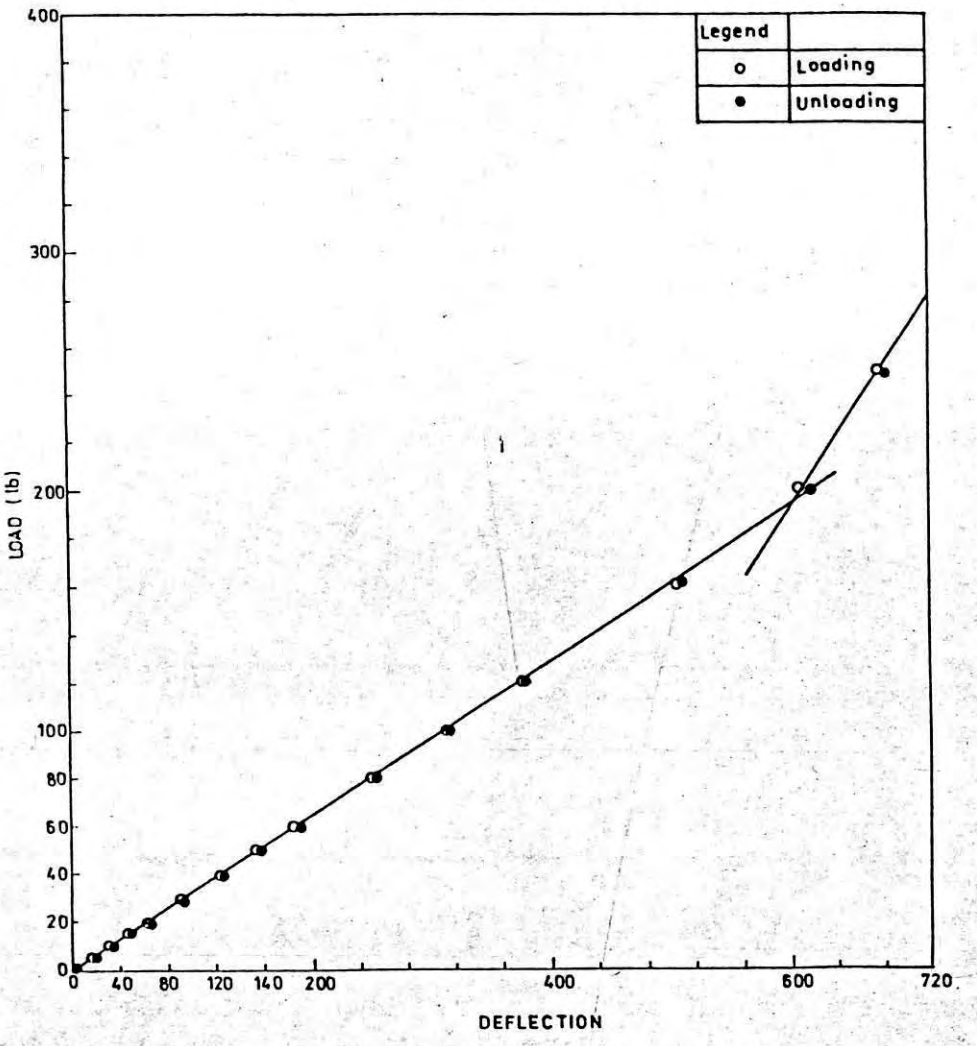


Fig. 5.8 Calibration curve for proving ring used in the measurement of uplift load.

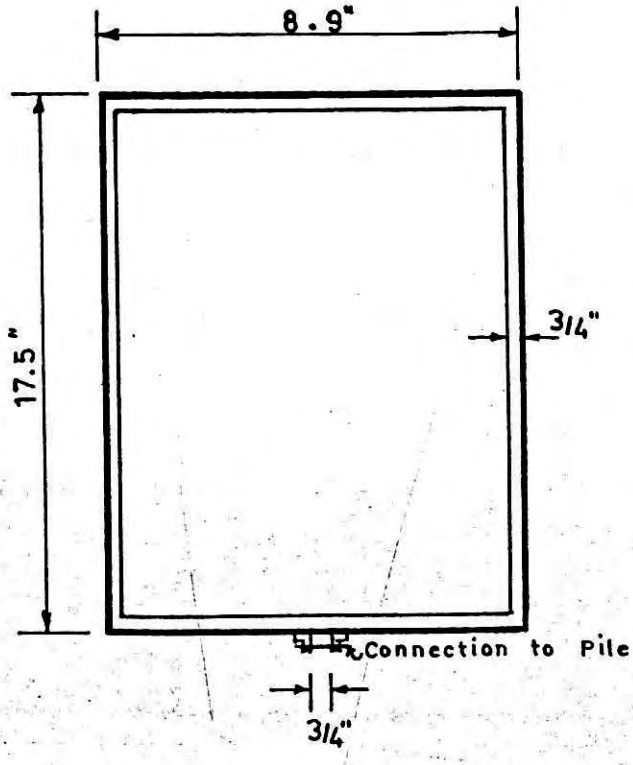


Fig. 5.9 Rectangular frame used for applying uplift load on pile.

5.6 Measurement of Upward Movement of Pile

After installation of piles in sand bed the uplift load is applied on them to measure the uplift capacity. The uplift load application arrangement is shown in photograph of Fig. 5.11. As uplift load is applied to the embedded pile it moved upward. This upward movement of pile is measured by a magnetic dial gauge as shown in Fig. 5.11. dial gauge is placed in such a way that the measuring tip of the gauge rests on the large circular plate "a" of the torque meter as shown in Fig. 5.5a. Following are the steps followed for measuring uplift load capacity of the screw-piles.

i) The proving ring arrangements are made above the torque meter. As shown in Fig. 5.11.

ii) The steel frame is attached with the torque meter head by a pin.

iii) A magnetic dial gauge is placed in such a way that its measuring tip rests on the large circular plate "a" of the torque meter.

iv) The lever arm of the proving ring is rotated in such a way that the steel frame pulls the torque meter with the pile.

v) The pile is lifted at a uniform rate of one division of dial gauge reading per second. So that, both dial gauge and proving ring dial reading can be taken easily.

Fig. 5.10 Fully installed screw pile with torque meter on top.

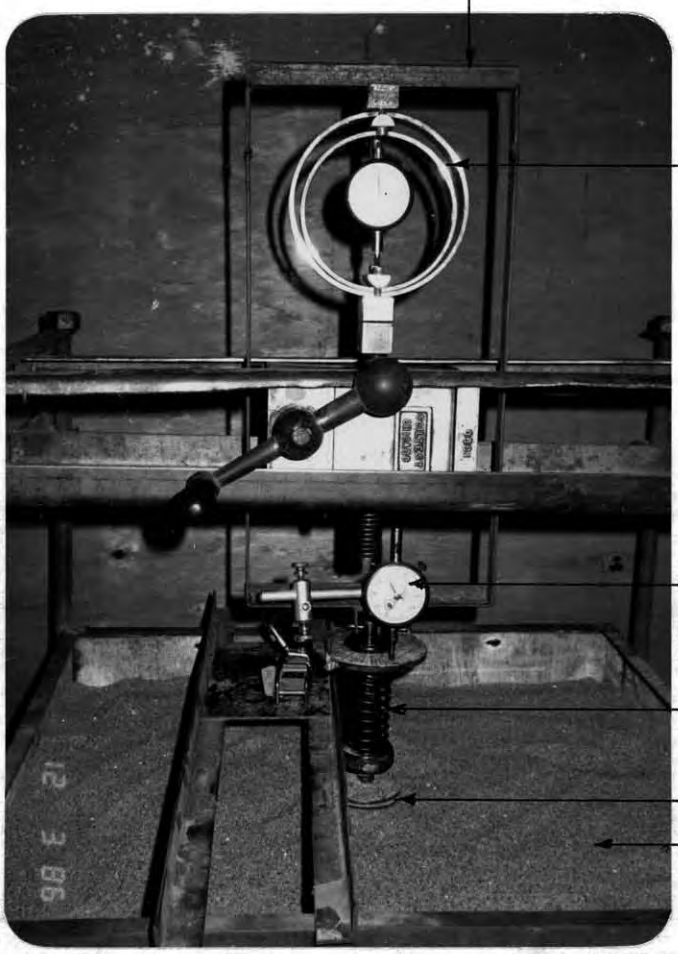


Fig. 5.11 Arrangements for uplift loading of pile and measurement of displacement by a dial gauge.

vi) Proving ring dial readings are recorded corresponding to dial gauge readings 10,20,30,40,50,60,70,80,90, 100,120,140,160 ... divisions upto failure.

vii) From Fig. 5.7 uplift loads are found for the respective deflection in proving ring.

When the pile is uplifted then density of the sand bed is measured to know the condition at which the pile is installed. For this purpose a layer of sand is removed from the box and five cans are kept at that layer in upside down position. Then the cans are carefully taken out with sand in it, and weight is measured. In a similar way density is measured at top, middle and bottom of the box.

Here exact density is not found as the sand in the box is disturbed due to the installation and uplifting of the piles.

CHAPTER 6

RESULTS OF LABORATORY INVESTIGATION

6.1 General

As stated earlier, the experiments performed are aimed at studying the effects of shaft dimension, blade dimension, number of blades per unit length and blade arrangement on driving torque. Also the effect of above factors on uplift are to be studied.

Twenty one different screw piles are used in these experiments. Detailed dimensions of these model piles are presented in Table 6.1 and each pile is designated by a number shown in column 1 of the Table 6.1. This table also shows shaft radius of each pile, blade spacing and torque required to drive 14 inches into soil bed of a specified density. Table 6.1 shows the theoretical driving torque required to drive the piles to a depth of 14 inches, calculated from equations 4.8 and 4.9. The use of equation 4.8 and 4.9 required an assumption of normal soil pressure on the cylindrical surface which is twisted during application of the torque. This normal pressure may be due to soil being at either earth pressure at rest (k_o) condition or at active condition (k_a) or passive condition (k_p). In Table 6.1, the theoretical values of torque calculated are shown in column 10,11 and 12 on the basis of soil pressure normal to the cylindrical surface being at k_a, k_o and k_p conditions respectively.

Table 6.1 Driving torque for verious pile types at differnt driving conditions

1	2	3	4	5	6	7	8	9	10	11	12	13	14
Piles	Symbol	Pile type				Soil density (lb/ft^3)	Relative density D_r %	Angle of internal friction	Total theoretical torque required to drive 14 in. (lb-in)			Total measured torque (lb-in)	Measured torque (lb-in/ft)
		R_p in.	$\frac{R_B}{R_p}$	No. of blades	Blade spacing in.				k_a	k_o	k_p		
1	○	0.125	3	3	4	84.49	4.61	27.0	0.057	0.083	0.049	1.75	1.50
1a	●	0.125	3	5	2	84.14	3.08	27.0	0.075	0.110	0.539	2.70	2.31
2	△	0.125	5	3	4	83.67	0.67	26.5	0.157	0.225	1.075	6.10	5.22
2a	▲	0.125	5	5	2	83.67	0.67	26.5	0.626	0.908	4.286	8.30	7.11
3	▽	0.125	7	3	4	94.10	2.87	26.0	0.382	0.549	2.514	7.30	6.25
3a	▼	0.125	7	5	2	84.10	2.87	26.0	1.669	2.402	8.059	12.50	10.71
4	□	0.250	3	3	4	84.32	4.01	27.2	0.346	0.505	6.507	16.50	14.14
4a	■	0.250	3	5	2	84.02	2.46	27.2	0.176	1.719	12.527	17.75	15.21
5	◺	0.250	5	3	4	83.89	1.80	26.5	1.148	1.640	7.841	20.75	17.78
5a	◣	0.250	5	5	2	83.89	1.80	26.5	8.502	12.105	15.806	35.00	30.00

R_p = radius of pile shaft

R_B = radius of screw blade

k_o = coefficient of earth pressure at rest

k_a = coefficient of active earth pressure

k_p = coefficient of passive earth pressure

Table 6.1 Contd...

1	2	3	4	5	6	7	8	9	10	11	12	13	14
6	⧖	0.250	7	3	4	84.20	4.68	27.0	3.082	4.453	18.897	51.50	44.14
6a	⧗	0.250	7	5	2	84.20	4.62	27.0	13.81	20.000	33.330	68,50	58.71
7	◇	0.125		3	3	83.92	1.82	26.5	1.26	1.837	8.661	12.50	10.71
7a	◆	0.125		3	4	83.92	1.82	26.5	15.460	30.460	40.406	48.00	41.14
8	⬡	0.125		3	4	84.60	4.92	28.0	2.141	3.187	16.868	15.00	12.85
8a	⬢	0.125		3	4	84.60	4.92	28.0	20.200	41.620	53.293	53.25	45.64
9	☆	0.125		3	4	83.93	1.83	26.5	2.956	4.282	20.185	20.50	17.75
9a	★	0.125		3	4	83.93	1.83	26.5	30.420	52.410	62.451	58.00	49.71
10	✳	0.375	3	3	4	83.73	0.71	26.0	0.963	1.401	8.401	20.10	17.22
11	+	0.375	4	3	4	83.73	0.71	26.0	2.695	2.885	13.185	38.00	32.57
12	×	0.375	5	3	4	83.73	0.71	26.0	4.373	5.330	24.369	68.50	58.71

Column 13 represents the measured torque required to drive the pile same distance as above for each pile.

It should be mentioned that in the calculation of torque, the effects of vibration and disturbance of soil around the blades during installation is not considered. Table 6.2 shows the theoretical uplift load calculated by using equations 4.13 and 4.14, for each pile driven to 14 inch depth. During uplifting shear failure in a cylindrical surface is considered. This is described in Art. 4.2. The shear on the cylindrical surface would depend on the normal pressure on it. The normal pressure would again vary depending upon the soil being at k_a, k_o or k_p condition. Column 8, 9 and 10 in Table 6.2 shows theoretical uplift loads calculated on the assumptions that soil surrounding the pile is at k_a, k_o and k_p state respectively at the time of uplift. The effects of any disturbance during installation is not considered in the above calculations.

6.2 Density of Uniform Sand Bed

A uniform sand bed is prepared for the laboratory tests which is detailed in Chapter 5. The densities of different sand beds prepared by different heights of fall are presented in Fig. 5.4. For 4 inches height of fall of sand, average sand densities were found to be 85, 86 and 88 pcf at top middle and bottom of the box respectively. At this height of fall average density is 86.5 pcf.

Table 6.2 Theoretical and Measured Uplift Loads Resisted by Screw Piles

1	2	3	4	5	6	7	8	9	10
Piles	Legend	R_B/R_p	No. of blade	Soil density (pcf)	Angle of internal friction (degree)	Total theoretical uplift load (lb)			Measured uplift load upto failure (lb)
						k_a	k_o	k_p	
1	○	3	3	84.49	27.00	4.65	4.83	7.07	8.5
1a	●	3	5	84.14	27.00	5.37	5.87	12.08	11.0
2	△	5	3	83.67	26.50	4.91	5.29	9.00	14.0
2a	▲	5	5	83.67	26.50	6.54	7.30	16.48	17.5
3	▽	7	3	84.10	26.00	6.46	6.86	11.55	16.5
3a	▼	7	5	84.1	26.00	8.21	9.33	22.36	20.5
4	□	3	3	84.32	27.25	6.30	6.66	11.23	20.5
4a	■	3	5	84.02	27.25	7.89	8.90	21.59	25.0
5	◺	5	3	83.89	26.50	8.89	9.48	16.51	23.0
5a	◣	5	5	83.89	26.5	11.54	13.17	32.71	28.0
6	⧖	7	3	84.20	27.00	21.311	22.15	32.56	37.5
6a	⧗	7	5	84.20	27.00	24.95	27.29	56.21	50.0

Table 6.2 (Contd...)

1	2	3	4	5	6	7	8	9	10
10	*	3	3	83.73	26.00	7.78	8.30	14.30	24.5
11	+	4	3	83.73	26.00	11.21	11.89	19.90	34.25
12	×	5	3	83.73	26.00	14.04	14.90	24.91	47.5
7	◇		3	83.92	26.50	9.54	10.46	22.66	16.5
7a	◆		3	83.92	26.50	19.13	21.14	44.32	43.0
8	⬡		3	84.60	28.00	11.38	12.70	30.28	19.0
8a	⬢		3	84.60	28.00	20.12	22.14	52.21	50.0
9	☆		3	83.93	26.50	12.52	13.82	39.50	21.25
9a	★		3	83.93	26.50	21.34	23.21	63.14	57.0

In a similar way for 8 inches height of fall, average densities are found to be 86, 87 and 89 pcf at top, middle and bottom of the box respectively. At this height of fall the average density was 87 pcf.

Similarly it is found that for 12 inches height of fall, average densities obtained at top, middle, and bottom are 88, 89 and 92 pcf respectively. The average density is found, to be 90 pcf.

From above it is observed that with the increase in height of fall of sand from 4 to 12 inches the average density increased from 86.5 to 90 pcf.

From a measurement of sand density of various locations within the sand bed, range of variation in density within two feet of sand is found to be 3.3 percent for 4 inches fall, 3.4 percent for 8 inches fall and 4.6 percent for 12 inch fall.

6.3 Factors Affecting Driving Torque of Screw Pile

A number of factors affect driving torque in a sand bed. It is difficult to isolate the affect of each factor separately. From the test results the effect of shaft diameter, blade diameter and blade spacing, are tried to be isolated. A possible contribution of each of the above factors in the driving torque requirement is discussed in this article. The

Arts. 6.3.1, 6.3.2 and 6.3.3, describes results obtained for piles whose all the blades are of same diameter while that in which 6.3.4 describe cases in which the pile blades are unequal. A good co-efficient of correlation (r = 0.997) has been observed between measured torque and theoretical torque which may be related by

$$T_m = 2.378\ T_t \qquad (6.1)$$

where T_m = measured torque

T_t = theoretical torque by equation 4.8

This relation is shown in Fig. 6.1. This is only for the piles containing blades of equal diameter, where experiments are performed in loose sand.

6.3.1 Effect of Shaft Diameter on Driving Torque

For a given center to center spacing of blades, Fig.6.2 shows the value of torque required per foot of length (T/ft) of the pile for a particular radius of screw blade (R_B). This figure is plotted from data shown in Table 6.1. The firm line in Fig. 6.2 show torque required for driving one foot of pile for three different shaft diameters in loose sand. The results are for sandy soils where relative density was less than 10%. The figure within parenthesis in Fig. 6.2 indicate shaft diameter. From the driving records for three shaft diameters of piles. It can be observed that the piles with larger shaft diameter (0.75 inch) required larger torque compared to smaller shaft diameter

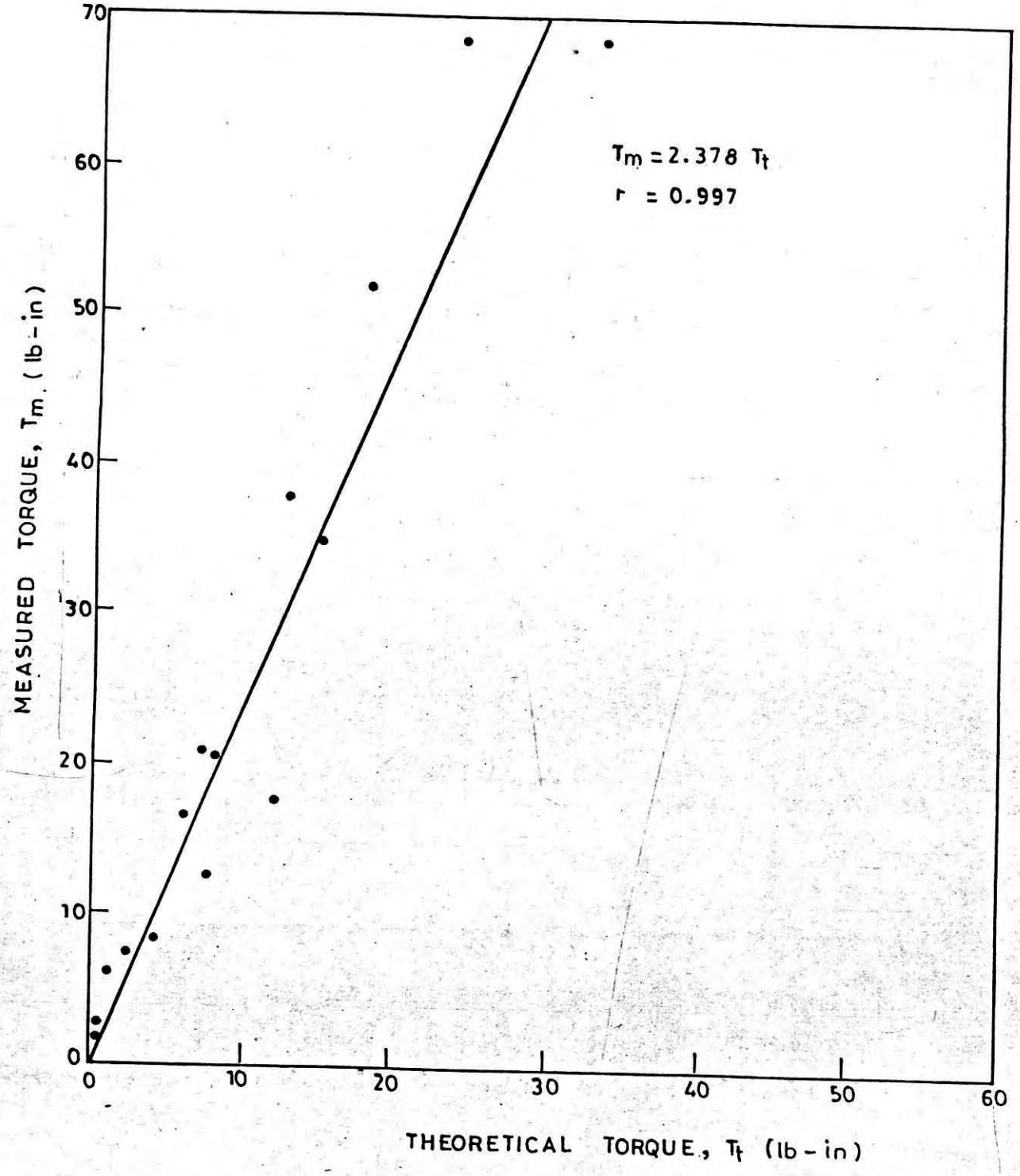


Fig. 6.1 Measured torque versus theoretical torque.

(0.25 inch), for the same blade size. This is due to the increase in shaft perimeter resulting in increase in frictional area as the shaft radius is increased. Three diameters of pile shaft 0.25 inches, 0.5 inches and 0.75 inches are used. And all this piles are driven upto a fixed depth of 14 inches. It is evident that the torque required to drive a pile did not increase significantly with change in shaft diameters.

The dash lines in Fig. 6.2 show theoretical driving torque required to drive a pile one foot into soil. The theoretical calculations assumed that passive earth pressure (k_p) is acting on the cylindrical surface on soil on which torque is applied. In the above calculations equations 4.8 and 4.9 are used. It can be seen that theoretical values are less than measured values. This is probably because, in the calculation of theoretical driving torque, conditions such as compaction of soil around the pile blades are not considered and soil density after the application of torque could not be ascertained. It is expected that soil surrounding the pile would densify due to penetration of pile and also due to some vibration during driving.

From Fig. 6.2 it can be seen that although shaft diameter increases the torque requirement for driving a pile into sand, the increase is not very significant. For example for a blade radius of 0.75 inches, torque per foot of length increased from 6 lb-in/ft to 14.5 lb-in/ft, when shaft diameter is increased

from 0.25 inches to 0.5 inches respectively. For larger blade dimensions effect of shaft diameter is insignificant and for smaller blade dimensions this effect is significant.

6.3.2 Effect of Blade Radius on Driving Torque

Blade radius has important effect on torque required to drive a pile. From Fig. 6.2 it can be observed that torque required to drive a pile one foot in soil increases with the increase in radius of screw blade (R_B). Blade radius is varied from 0.375 inches to 1.875 inches. The details of piles used are shown in Fig. 3.2. Each pile type can be identified from its symbol presented in Table 6.1. As the radius of screw blade increases, the frictional area increases, and more driving torque is required to overcome the frictional forces. Blade radii are varied with the shaft radius in such a way that the ratio of radius of screw blade to radius of pile shaft (R_B/R_p) are 3,5 and 7 respectively. Each pile is driven upto a depth of 14 inches within soil. From Fig.6.2 it can be observed that with increase in radius of screw blade (R_B) from 0.375 inches to 1.875 inches, the torque/ft increased from 1.5 lb-in/ft to 58.71 lb-in/ft.

Also shown in Fig. 6.2 by dashed line is the theoretically computed driving torque. The theoretical calculation also show that torque required to drive a pile increases with the increase in blade radius. However, the theoretical value is less than the

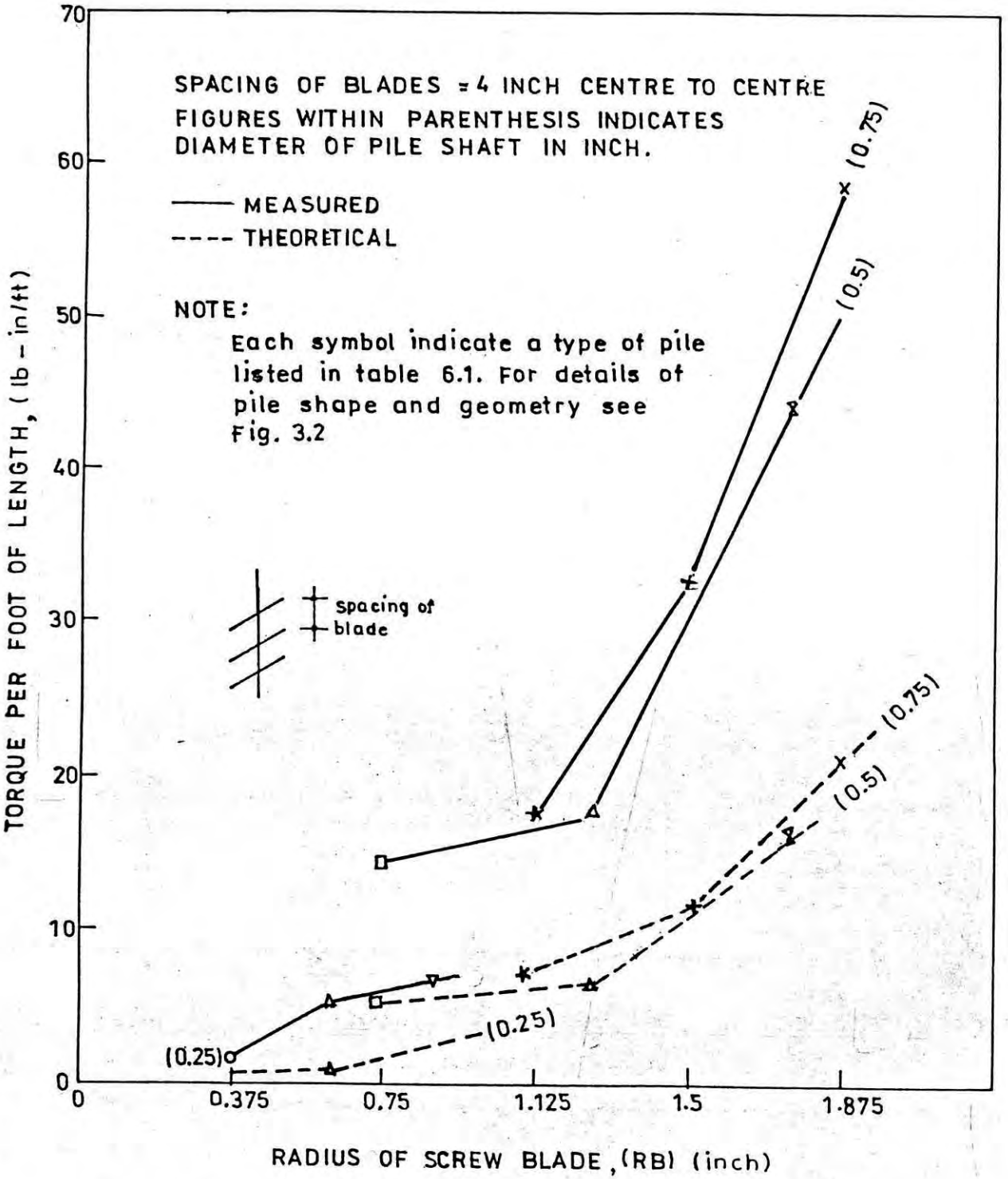


Fig. 6.2 Torque per foot of length versus radius of screw blade.

measured value. This difference can be attributed to omission of the effects of increased soil density due to driving of pile in loose soil in the theoretical analysis.

6.3.3 Effect of Blade Spacing on Driving Torque

Fig. 6.3(a) shows relation between driving torque and spacing of blades. In this figure lines designated by "a" are for the piles whose shaft radius is 0.125 inches and lines designated by "b" are for the piles whose shaft radius is 0.25 inches. The blade radius of each pile is indicated by the figure written within parenthesis. It can be observed that torque/ft decreases with the increase in spacing of blades. This is reasonable, with increase in the number of screw blades the frictional area also increases, and as a result more driving torque is required.

It can be observed from Fig. 6.3a that, the larger the radius of the screw blade, the larger is the difference in torque for change in blade spacing. For example, for blades of 1.75 inch radius the difference in torque due to change in blade spacing from 2 inch to 4 inch, the driving torque required decreased from 58.7 lb-in/ft to 44.1 lb-in/ft. while that for screw blades of 0.375 inch radius, the driving torque decreased from 2.31 lb-in/ft to 1.5 lb-in/ft. Fig. 6.3b shows relation between blade radius and increase in torque due to change in spacing from 4 inches to 2 inches. It can be observed

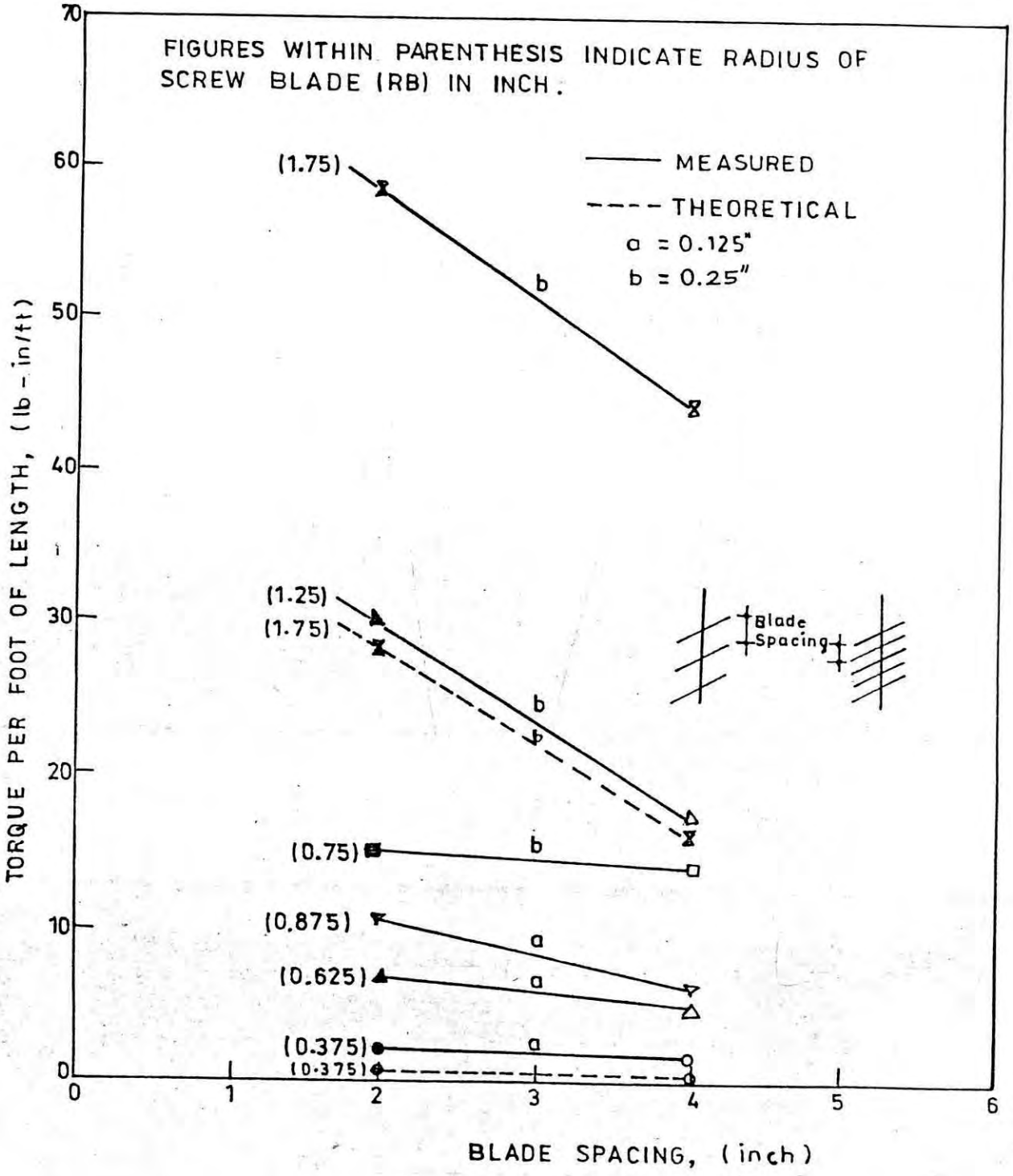


Fig. 6.3a Torque per foot of length versus blade spacing.

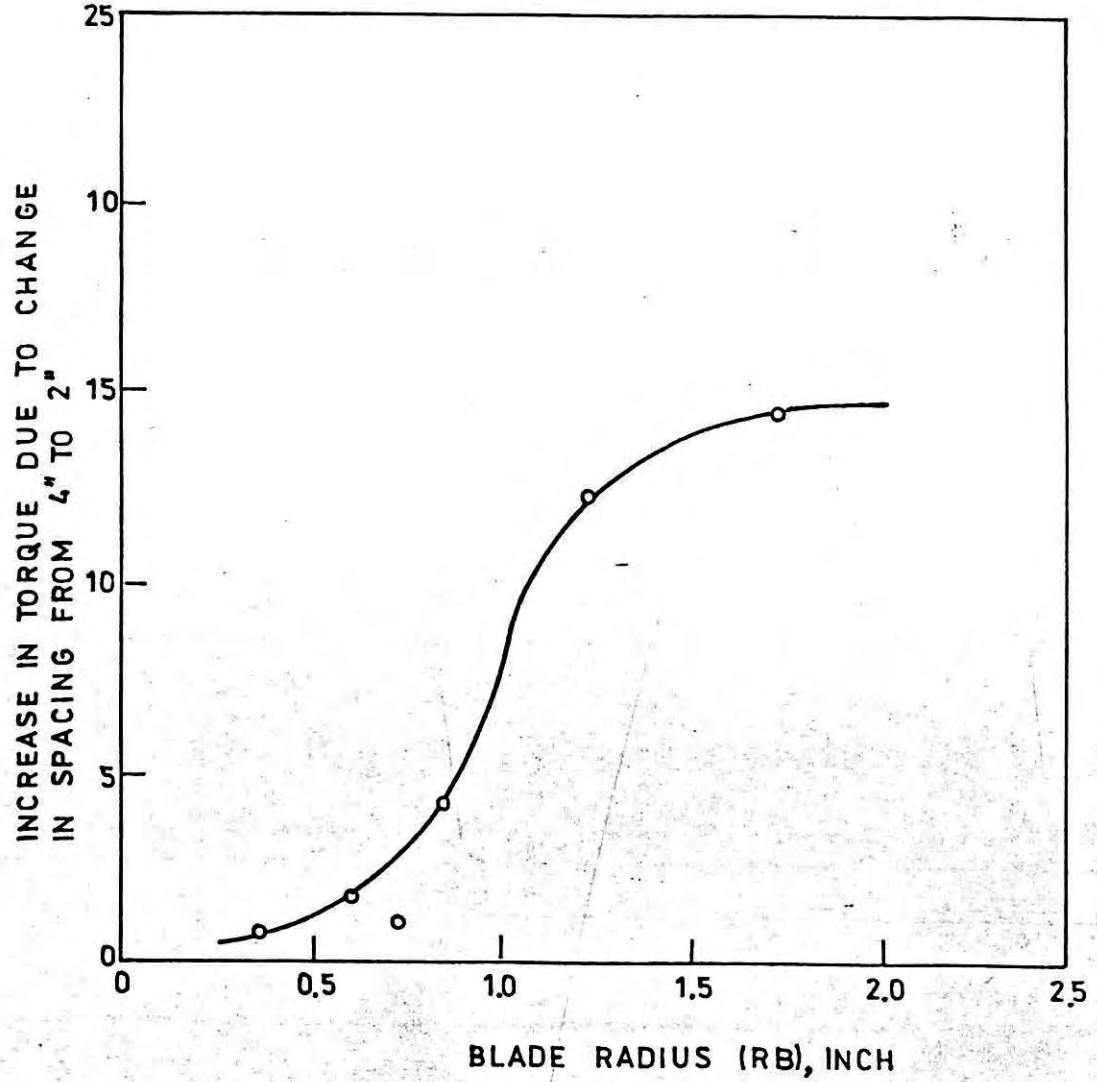


Fig. 6.3b Increase in torque due to change in spacing from 4" to 2" versus blade radius.

that, torque increases with blade radius but the rate of increase changes for different radius. This suggests that there is a relation between blade size and spacing for a optimum torque developed due to driving.

6.3.4 Effect of Arrangement of Screw Blades in a Pile on Driving Torque

Six piles whose blades are unequal and grouped as D_3 and E_3 shown in Fig. 3.2b are used in the laboratory for studying the effects of blade arrangement on torque. Table 6.3 shows the torque required by each of the piles to drive them to one foot in soil. In Table 6.3 the column 1 shows schematic arrangement of each blades, Col. 2 shows pile designation, Col. 3, 4 and 5 show radius of each blade, Col. 6, torque required to drive one foot into soil and Col. 7 the theoretically required torque to drive each pile one foot into soil. The theoretical estimate is made using equation 4.9. Piles with larger blades at the bottom and smaller blades at the top (i.e. group E_3) required a driving torque of three to four times than that of piles with smaller blades at the bottom and larger blades at the top (i.e. group D_3). Among other reasons this is probably because the density of sand increased with depth, as found in the uniform sand bed.

In Fig. 6.4 the area within the dotted line is the area of soil that is disturbed by the piles during driving. Piles of group E_3 has larger screw blades at the bottom of the piles.

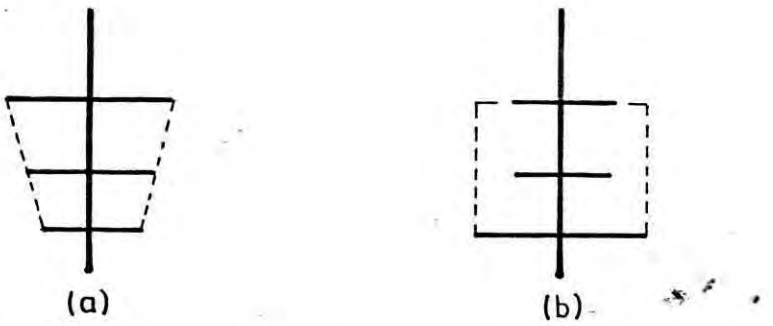
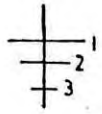
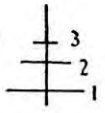
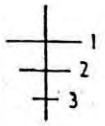
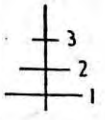
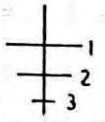
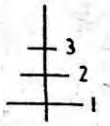


Fig. 6.4 Showing the area disturbed by piles.
(a) Piles of group-D_3 (b) Piles of group E_3.

And this larger blade is likely to compact the sand in larger area than those of piles of group D_3. Due to this compaction density of sand around the piles of group E_3 should increase, and more driving torque would be required.

From Table 6.3 it is observed that, there is some measure of agreement between the theoretically estimated value of torque and the measured value, for the piles of group D_3, i.e. piles 7, 8 and 9. This is probably due to sands of smaller area is disturbed as smaller blades are at the bottom of piles. And in theoretical calculation affect of compaction and disturbance around the pile blade during driving is not considered. From the above table it is observed that piles of group E_3 required driving torque of three to five times than that of theoretical value predicted by equation 4.9. The larger blades at the bottom is likely to compact and disturb a larger area, as a result density of sand during driving increases and this increase in density is not considered in Eqn. 4.9.

Table 6.3 Torque Per Feet of Depth for Piles of Different Blade Geometry

1	2	3	4	5	6	7
Legend	Piles	Radius of blades (inches)			Measured torque/ ft(lb-in/ ft)	Theoretical (T/ft)
		1	2	3		
	7	1.78	1.08	0.375	10.71	7.42
	7a	1.78	1.08	0.375	41.14	7.42
	8	2.03	1.33	0.625	12.85	14.30
	8a	2.03	1.33	0.625	45.64	14.30
	9	2.28	1.58	0.875	17.57	17.30
	9a	2.28	1.58	0.875	49.71	17.30

6.4 Factors Affecting Uplift Capacity of Screw Pile

A number of factors affect uplift capacity in a sand bed. It is difficult to isolate the affect of each factor separately. From the test results the effect of shaft diameter, blade diameter and blade spacings are tried to be isolated. A possible contribution of each of the above factors in the uplift capacity is discussed in this article. The articles 6.4.1, 6.4.2 and 6.4.3 describes results obtained for piles whose all the blades are of equal diameter while that in which 6.4.4 describe cases in which the pile blades are unequal. A good correlation (r = 0.82) has been observed between measured uplift load and theoretical uplift load which may be related by

$$U_m = 8.626 + 0.807\, U_t \qquad (6.2)$$

where

U_m = measured uplift load

U_t = theoretical uplift load by equation 4.13

This relation is shown in Fig. 6.5. This is only for the piles containing blades of equal diameter, where experiments were performed in loose sand.

6.4.1 Effect of Shaft Diameter on Uplift Load

For a given center to center spacing of blades, Fig.6.6 shows the value of uplift load required for a particular radius of screw blade (R_B). This figure is plotted from data shown in

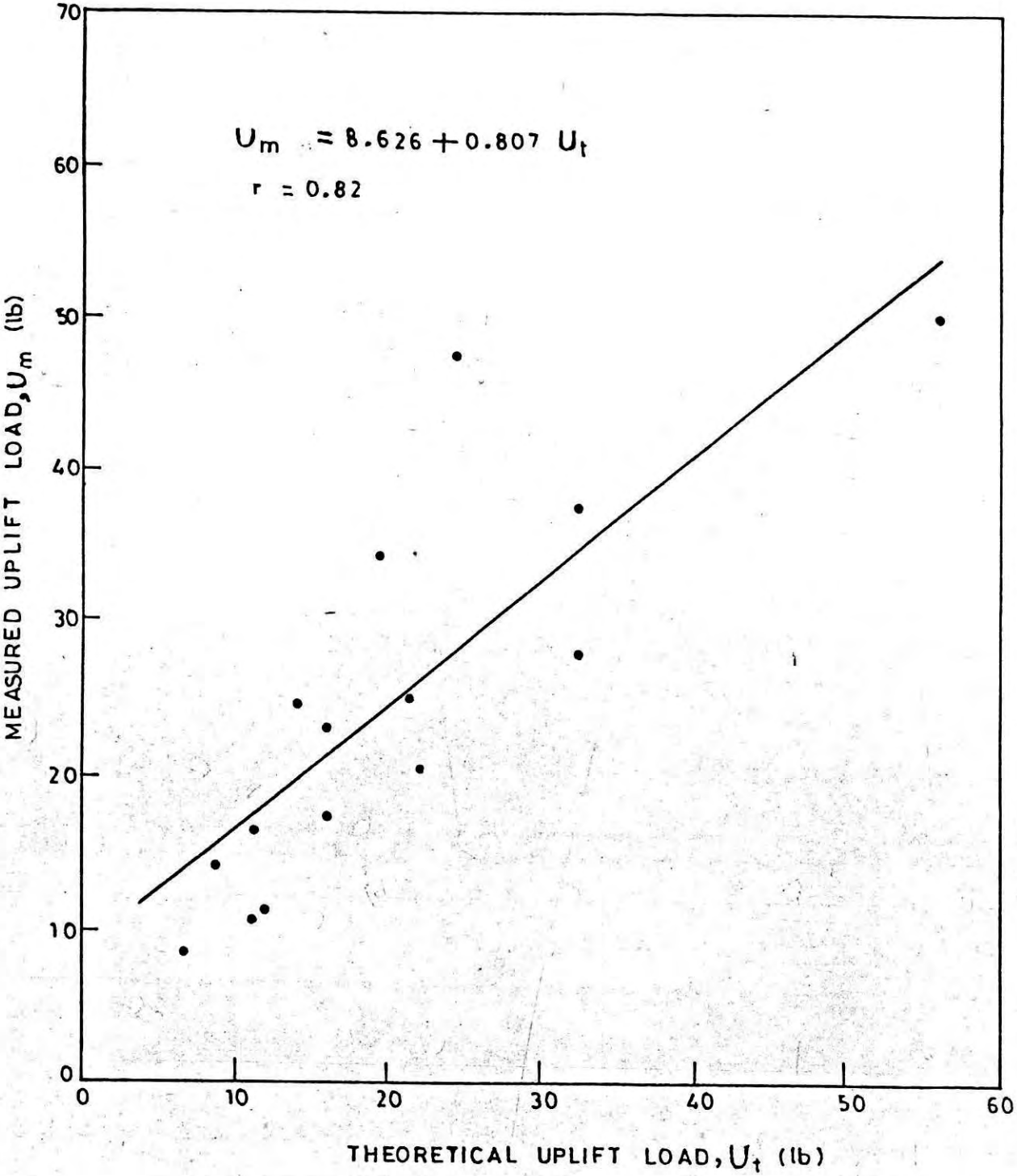


Fig. 6.5 Measured uplift load versus theoretical uplift load.

Table 6.2. The firm line in Fig. 6.6 show uplift load for uplifting the piles for three different shaft diameter in loose sand. The results are for sandy soils where relative density was less than 10%. The figure within prenthesis in Fig. 6.6 indicate shaft diameter. From the uplift records for three shaft diameters of piles it can be observed that the piles with larger shaft diameters (0.75 inch), required large uplift load compared to smaller shaft diameter (0.50 inch) for the same blade size. This is due to the increase in shaft perimeter resulting in the increase in sand density around the shaft. Three diameters of pile shaft 0.25 inches, 0.5 inches and 0.75 inches are used. And all this piles are driven upto a fixed depth of 14 inches. It is evident that the uplift load required for uplifting a pile did not increase significantly with change in shaft diameters.

The dash lines in Fig. 6.6 show theoretical uplift load required for uplifting a pile upto failure. The theoretical calculations assumed that passive earth pressure (k_p) is acting on the cylinderical surface on soil on which uplift load is applied. In the above calculations equation 4.13 is used. It can be seen that theoretical values are less than measured values. This is probably because, in the calculation of theoretical uplift load, conditions such sand density during driving is likely to have increased which affect is not included in the calculation.

6.4.2 Effect of Blade Radius on Uplift Load

Blade radius has important effect on uplift load required for uplifting a pile. From Fig. 6.6 it can be observed that uplift load increases with the increase in radius of screw blade (R_B). Blade radius is varied from 0.375 inches to 1.875 inches. As the radius of screw blade increases the frictional area and uplift resistance increases. From Fig. 6.6 it can be observed that with increase in radius of screw blade from 0.375 inches to 1.875 inches, the uplift load increased from 8.5 lb to 47.5 lb.

Also shown in Fig. 6.6 by dashed line is the theoretically computed uplift load. The theoretical calculation also show that uplift load required increases with increase in blade radius. However, the theoretical value is less than the measured value. This difference can be attributed to omission of the effects of increased soil density due to driving of pile in loose soil in the theoretical analysis.

6.4.3 Effect of Blade Spacing on Uplift Load

Fig. 6.7a show relation between uplift load and spacing of blades. In this figure lines designated by 'a' are for the piles whose shaft radius is 0.125 inch and lines designated by 'b' are for the piles whose shaft radius is 0.25 inches. The blade radius of each pile indicated by the figure written within parenthesis. It can be observed that uplift load decreases with the increase in spacing of blades. This is

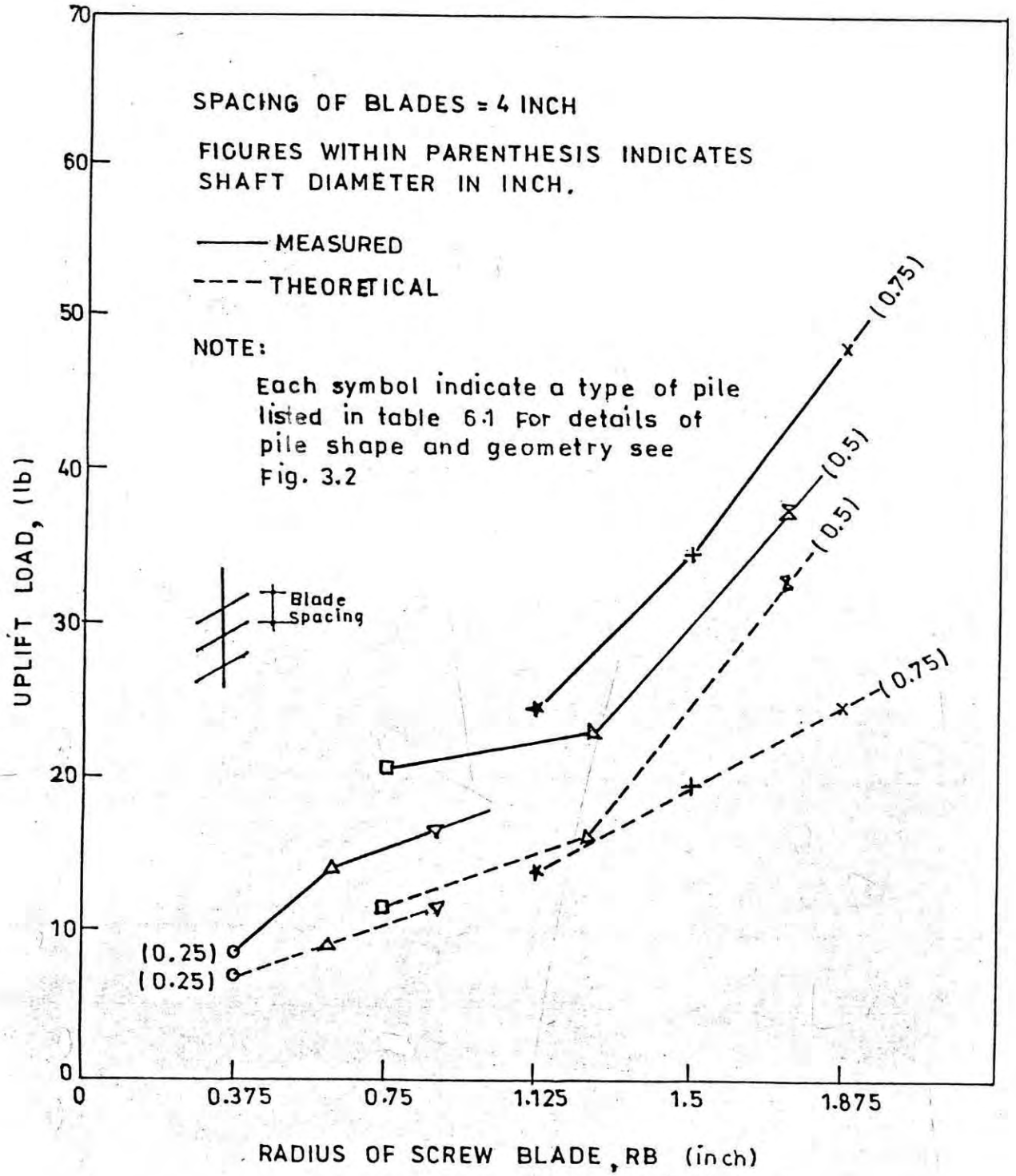


Fig. 6.6 Uplift load versus radius of screw blade.

reasonable as with the increase in number of screw blades density of larger area also changes during driving of pile, and as a result more driving torque is required.

It can be observed from Fig. 6.7a that, the larger the radius of the screw blade, the larger is the difference in uplift load for change in blade spacing. For example for blades of 1.75 inch radius the difference in uplift load due to change in blade spacing from 2 inches to 4 inches, the uplift load decreased from 50 lb to 37.5 lb. While that for screw blades of 0.375 inch radius the uplift load decreased from 11.0 lb to 8.5 lb. Fig. 6.7b show relation between blade radius and increase in uplift load due to change in spacing from 4 inches to 2 inches. It can be observed that, uplift load increases with blade radius, but the rate of increase changes for different radius.

This is because, spacing of blade decrease and soil around the blades changes in density. Consequently the blades act in group with very little increase in uplift load for the blades of smaller radius. It may be mentioned that the tests were performed on sand beds having small values of relative density. Such beds increase in density easily by penetration of screws of the pile. As the local increase in densities could not be measured, no definite conclusion could be made regarding the effects of spacing of blades on uplift capacity of piles.

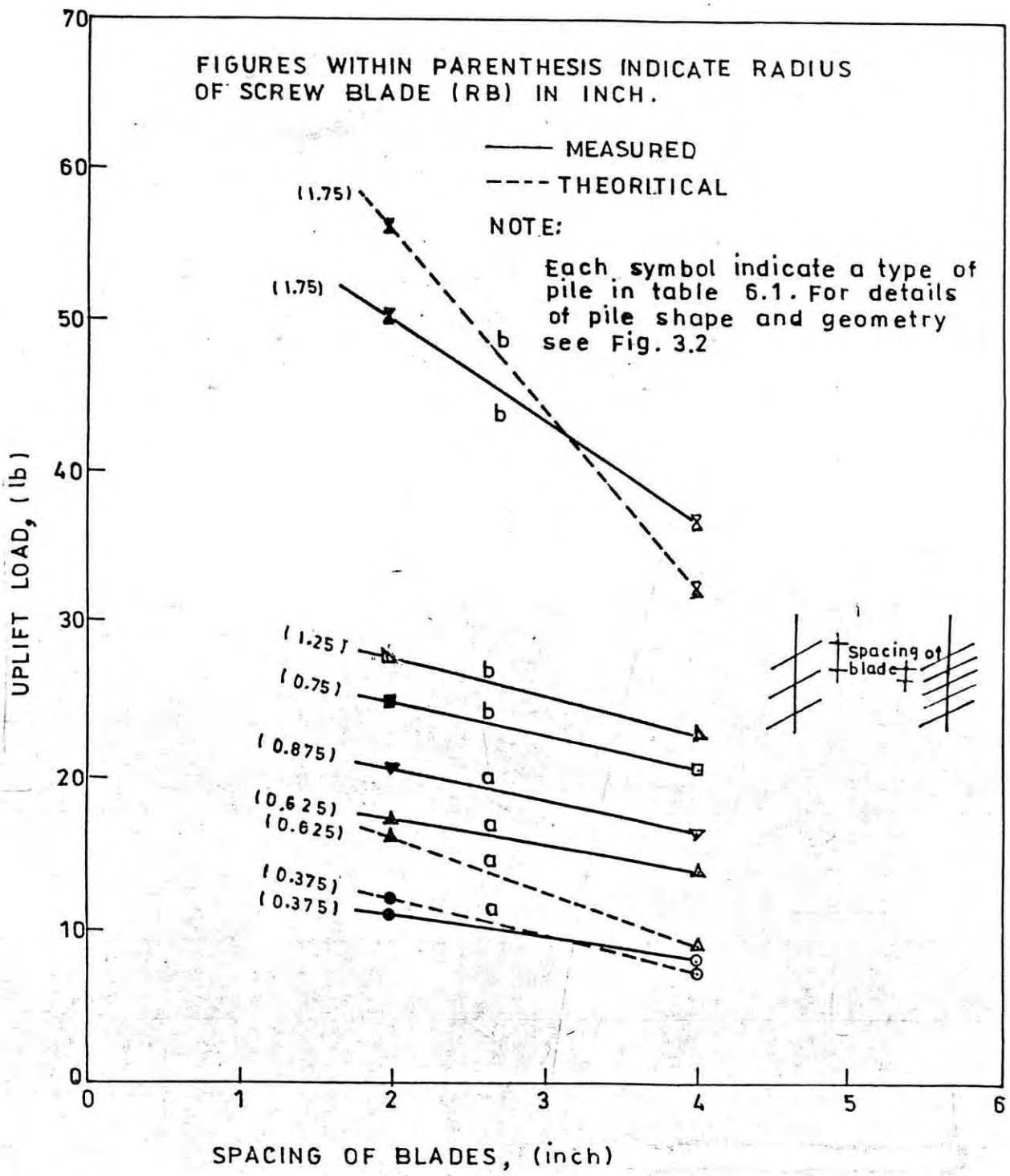


Fig. 6.7a Uplift load versus spacing of blades.-

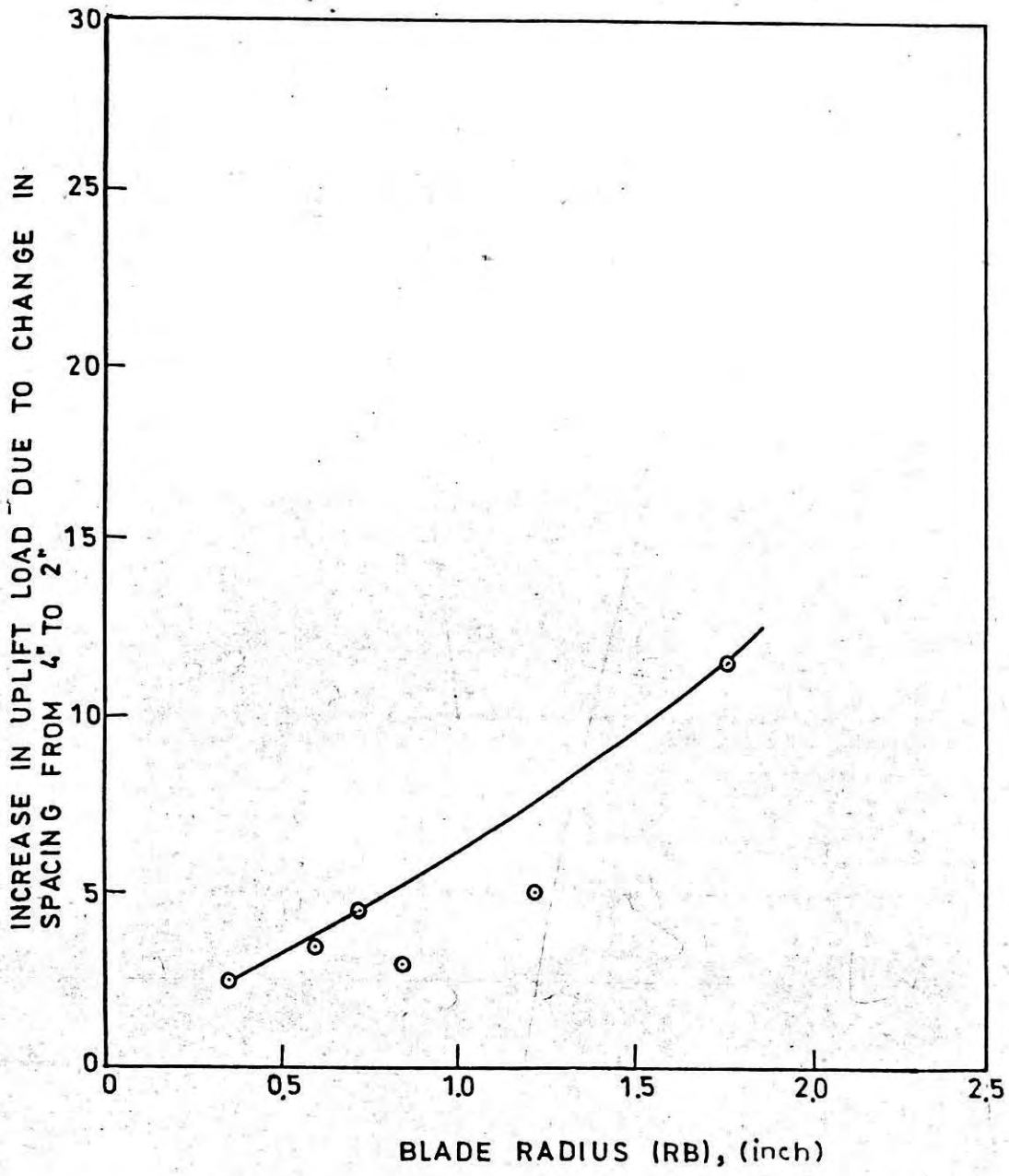


Fig. 6.7b Increase in uplift load due to change in spacing from 4" to 2" versus blade radius.-

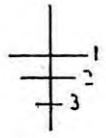
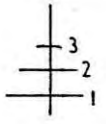
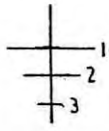
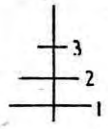
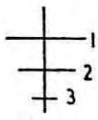
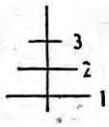
6.4.4 Effect of Arrangement of Screw Blades in a Pile on Uplifting

Six piles whose blades are unequal and grouped as D_3 and E_3 shown in Fig. 3.2b are used in the laboratory for studying the effects of blade arrangement on uplift load. Table 6.5 shows the uplift load required for uplifting and in Col. 5, the measured uplift load for each pile. The theoretical estimate is made using equation 4.14. Piles with larger blades at the bottom and smaller blades at the top (i.e group E_3) required uplift uplift load of nearly 2.6 times than that of piles with smaller blades at the bottom and larger blades at the top (i.e group D_3). This is because when larger blades are kept at the bottom then the volume of sand participating in uplifting increases significantly. And densification of loose sand also occurs during driving.

Fig. 6.4 shows the area of sand disturbed by the piles during driving. Piles of group E_3 has larger screw blades at the bottom of the pile. And this larger blades compact the sand in larger area than those of piles of group D_3. Due to this compaction more volume of dense sand participate in uplifting, as a result uplift load increases.

From Table 6.4 it is observed that there is some measure of agreement between the theoretically estimated value of uplift load and measured value.

Table 6.4 Uplift Load for Piles of Different Blade Geometry

1	2	3	4	5	6	7
Legend	Piles	Radius of blades (inches)			Theoretical uplift load (lb)	Measured uplift load (lb)
		1	2	3		
	7	1.78	1.08	0.375	22.66	16.50
	7a	1.78	1.08	0.375	44.32	43.00
	8	2.03	1.33	0.625	30.28	19.00
	8a	2.03	1.33	0.625	52.21	50.00
	9	2.28	1.58	0.875	39.50	21.25
	9a	2.28	1.58	0.875	63.14	57.00

6.5 Relation between Uplift and Driving Torque

Fig. 6.8 shows the relationship between maximum uplift load and driving torque for piles containing equal diameter blades. Here a linear correlation is found between uplift load and driving torque. A good correlation ($r = 0.984$) has been observed between uplift load and driving torque, which may be related by

$$U_m = 11.656 + 0.5422\ T_m \qquad (6.3)$$

Fig. 6.9 shows the relationship between maximum uplift load and driving torque for piles containing taper arranged blades. Here also a linear correlation is found. A strong correlation ($r = 0.994$) has been observed between uplift load and driving torque which may be related by

$$U_m = 5.18 + 0.847\ T_m \qquad (6.4)$$

The relationship shown in Fig. 6.8 is independent of blade dimension. In order to see the effect of blade dimension on the relationship between T_m and U_m a plot of uplift load (U_m) and ratio of driving torque to radius of screw blade (T_m/R_B) is made in Fig. 6.10, for piles containing equal diameter blades. Here again a linear correlation with $r=0.958$ is observed. The relationship may be expressed by the equation:

$$U_m = 3.098 + 1.12\ T_m/R_B \qquad (6.5)$$

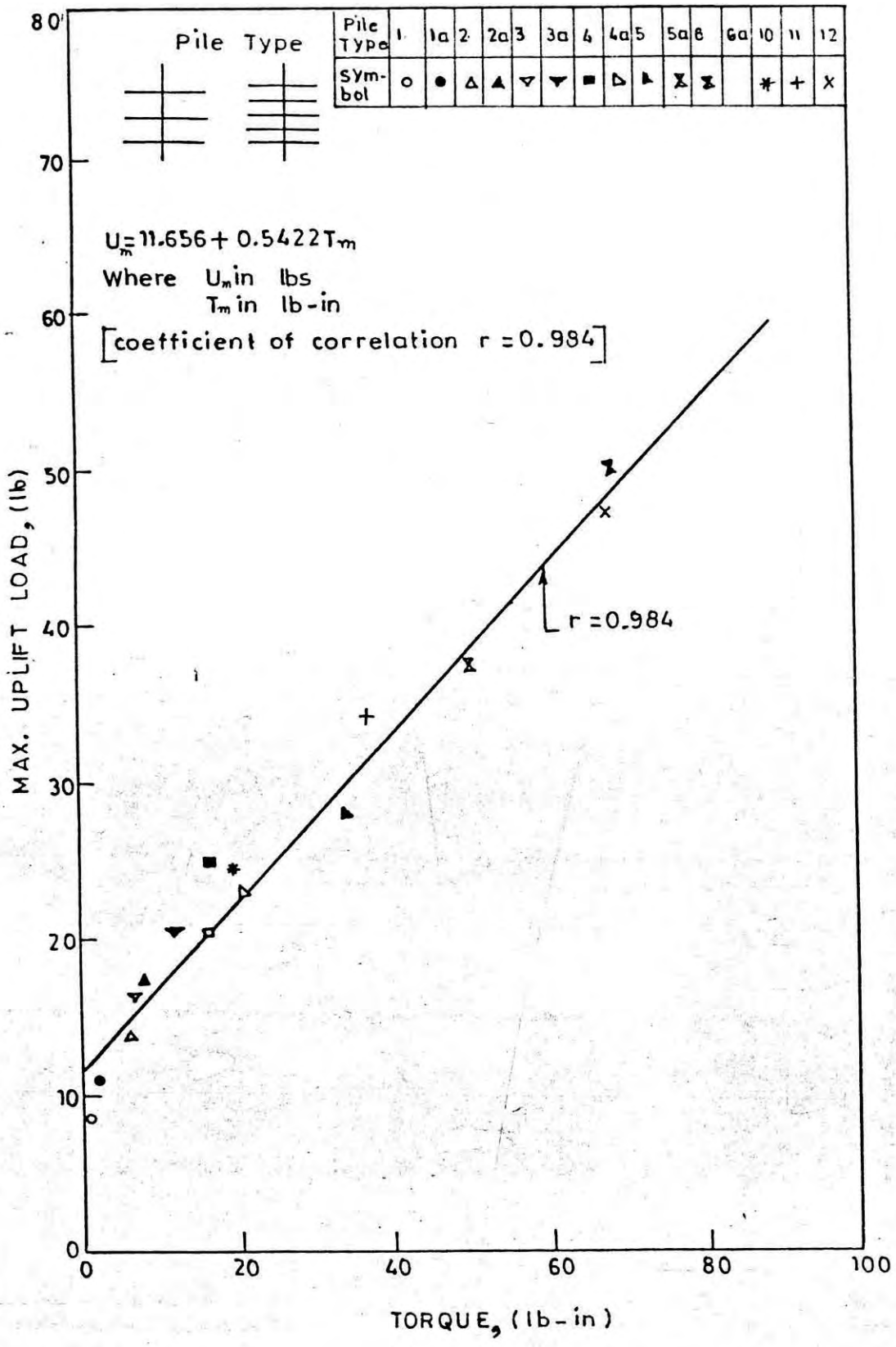


Fig. 6.8 Maximum uplift load versus torque.

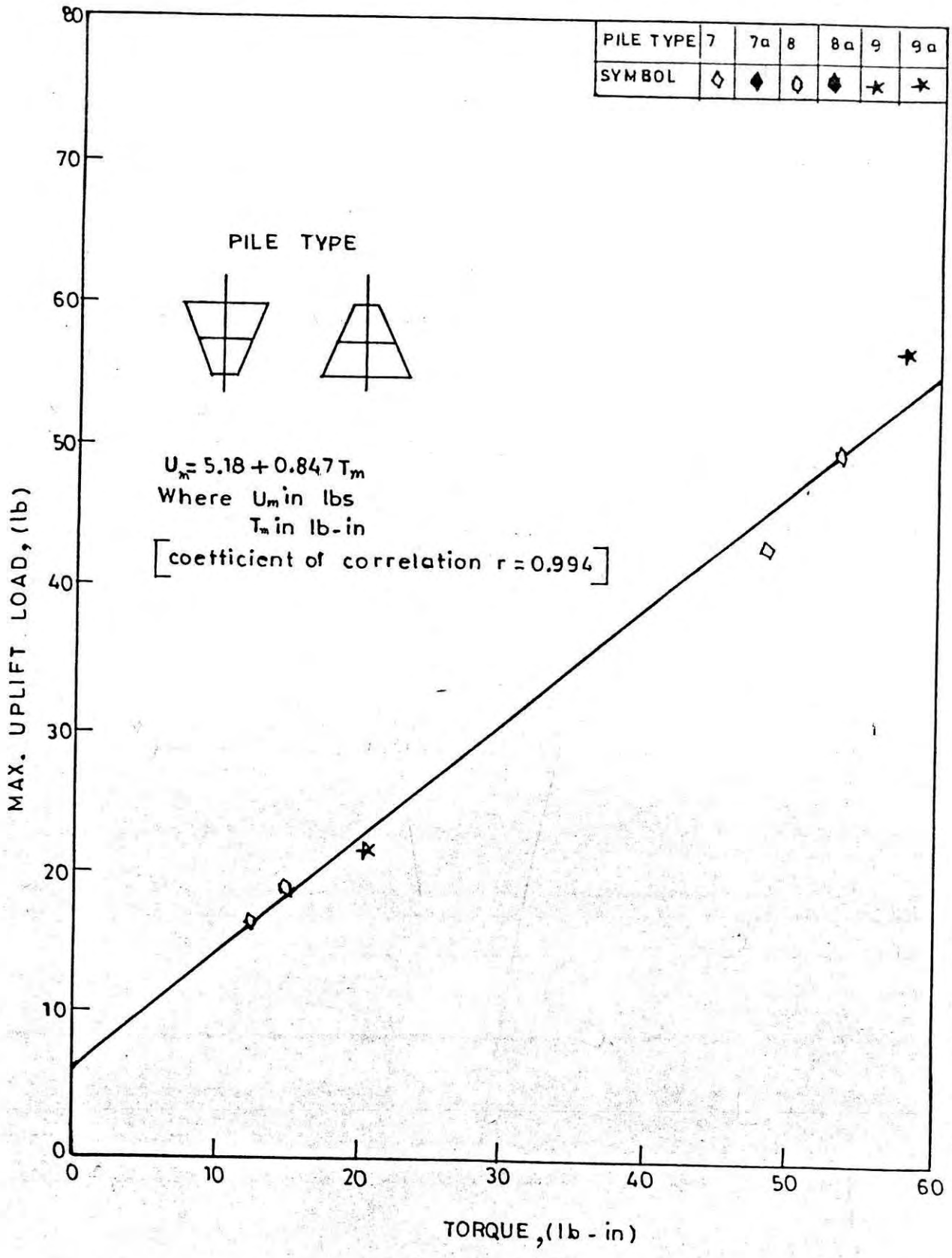


Fig. 6.9 Maximum uplift load versus torque.

This suggests that blade dimension has an important affect on this correlation, although other factor such as density of soil may affect the result.

Experiments are performed in loose sand and for this test conditions equation 6.3 is selected for piles containing equal diameter blades. Here coefficient of correlation r is 0.984.

6.6 Upward Movement of Piles During Uplifting

In Fig. 6.10 uplift load has been plotted against upward movement of pile types 1, 1a, 2, 2a and 3, 3a. From this figure it is evident that for same upward movement, piles with larger blade will carry more upward load. This is because the shearing area for the larger blades is more and also a greater volume of sand above the blade participate in resisting the uplift. Fig. 6.11 also shows that for same upward movement, piles with closer spacing of blades carries larger upward load. This is expected because with decrease in blade spacing sand surrounding the pile is densified as a result the shear strength of the soil surrounding the pile is likely to increase and therefore increase in upward load capacity of the pile.

Fig. 6.12 shows plottings of uplift load versus upward movement for pile types 7, 7a, 8,8a and 9,9a. From this figure it is evident that for a particular upward movement, piles

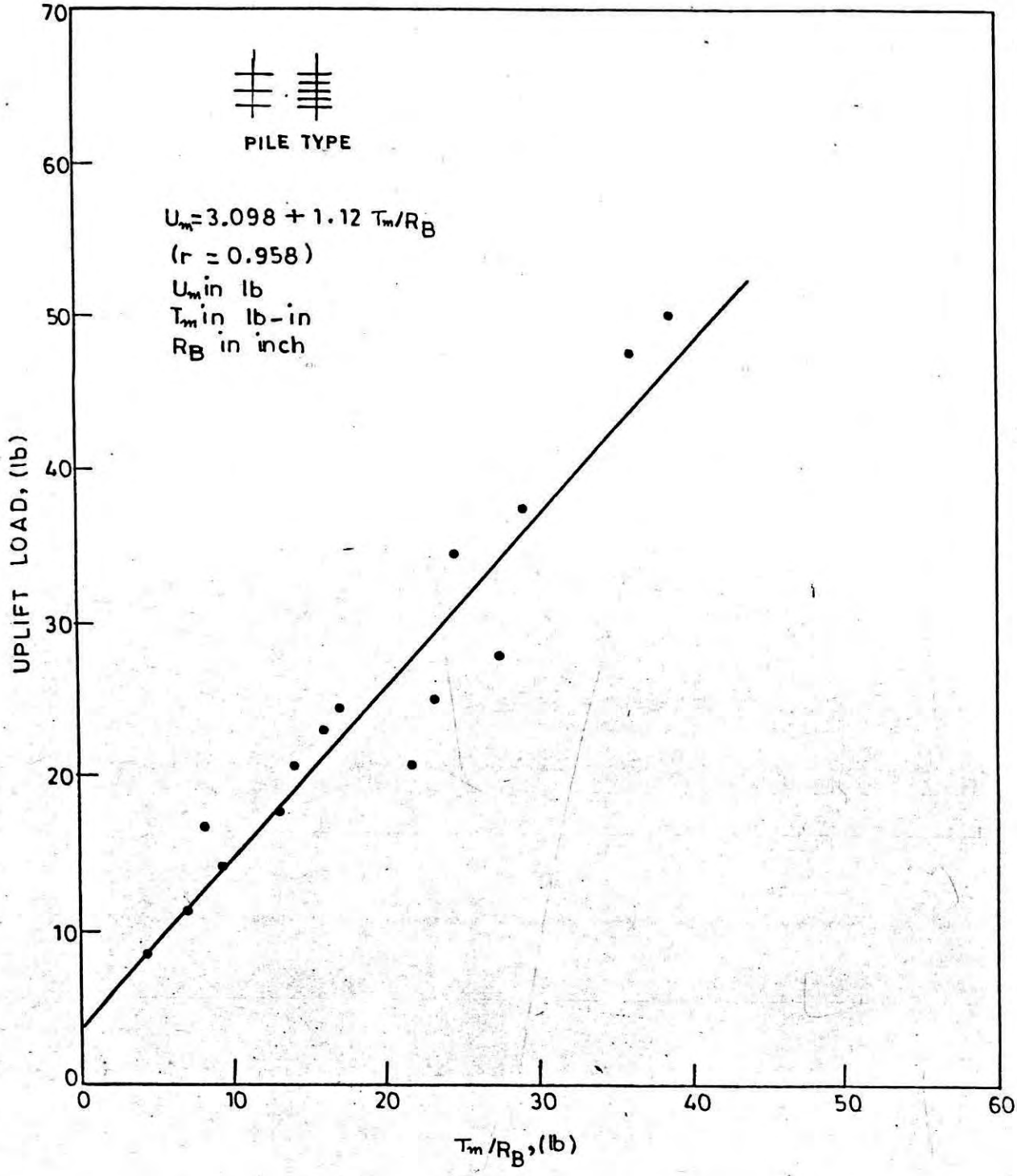


Fig. 6.10 Maximum uplift load versus torque/blade radius.

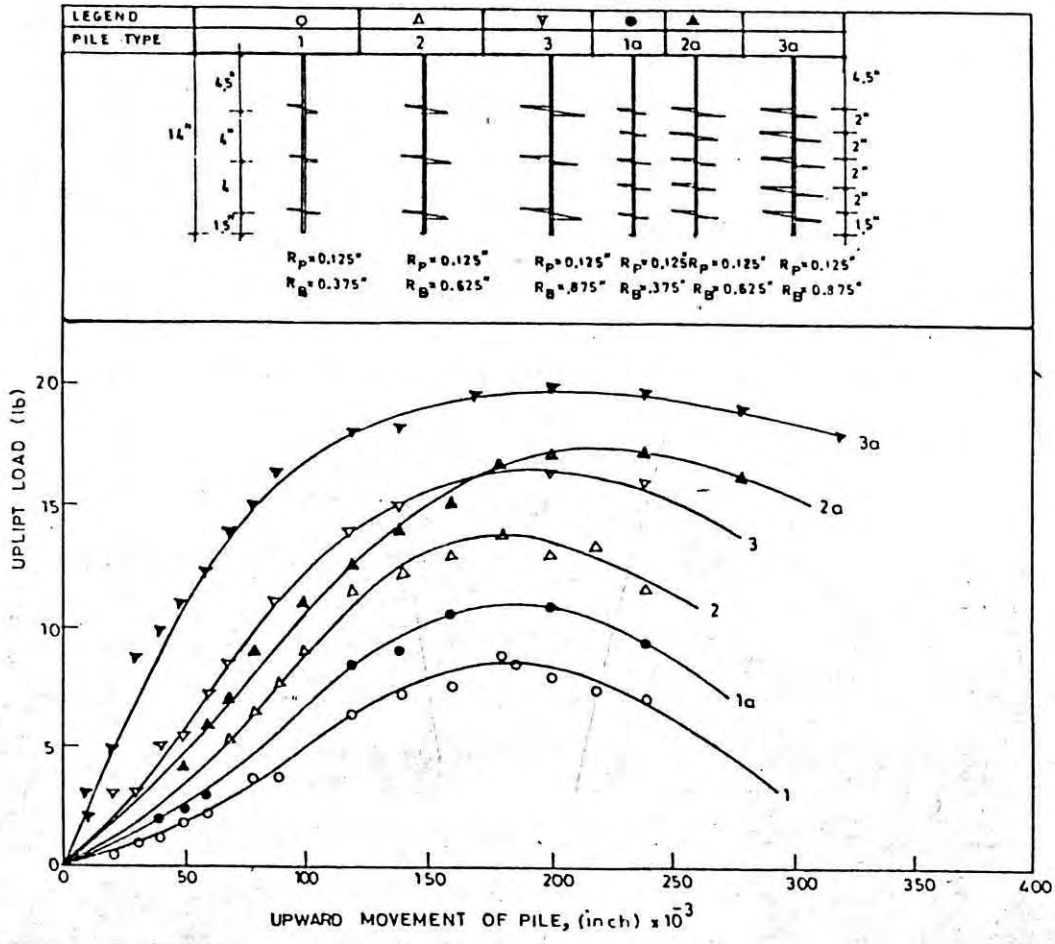


Fig. 6.11 Uplift load versus upward movement of the pile.

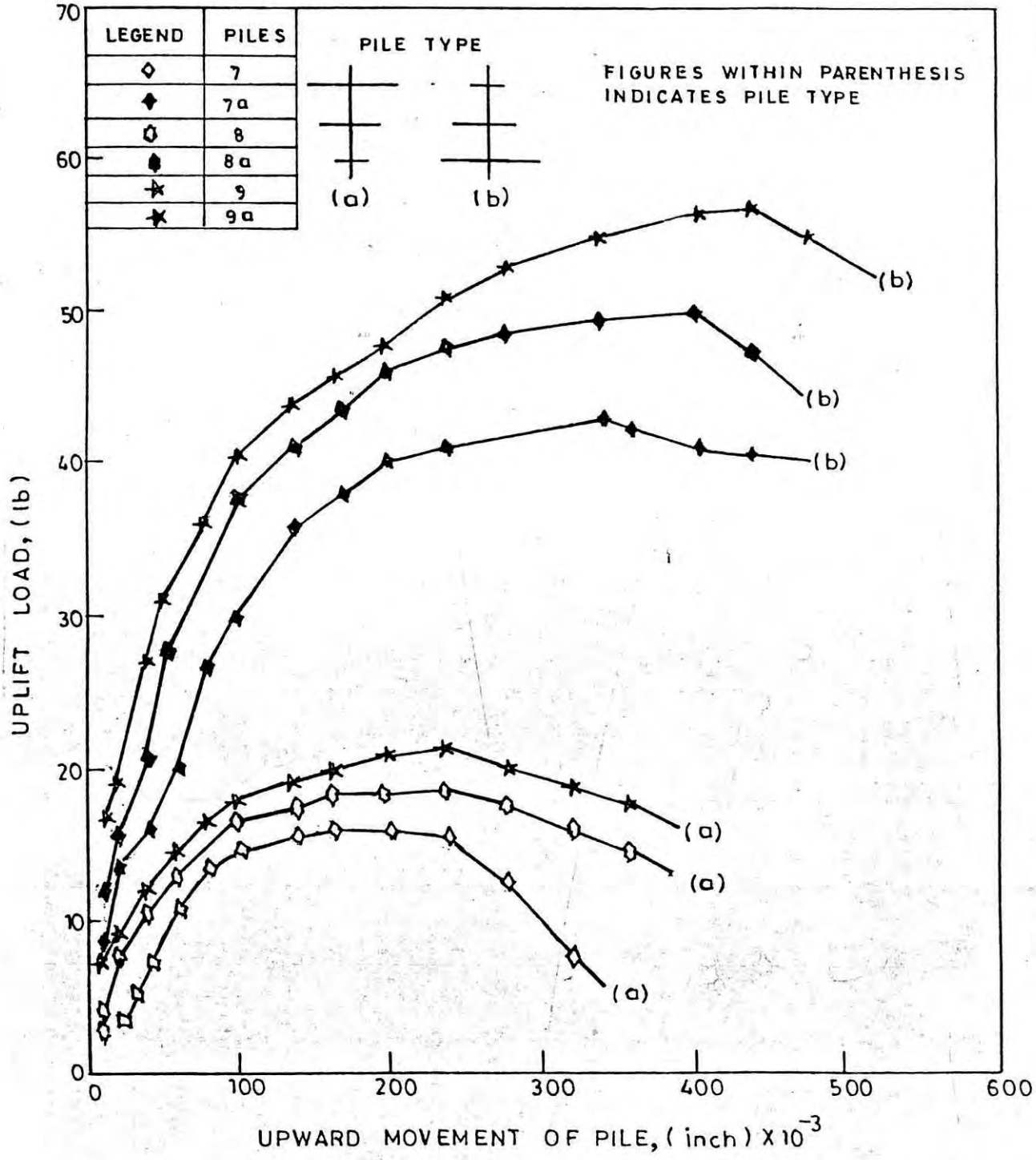


Fig. 6.12 Uplift load versus upward movement of pile.

with larger blades at the bottom (piles 7a, 8a and 9a) required more uplift load than the piles with smaller blades at the bottom (piles 7,8 and 9). This is because for piles with larger blades at the bottom a larger volume of sand is involved in resisting uplift load.

6.7 Summary of Test Results

Some of the important aspects of the experimental fundings are highlighted and summarized below.

1. This study required the preparation of a uniform sand bed in which model screw piles are installed. The density of sand bed depended on heights of fall of the sand and uniformity condition during poring. It is observed that with increase in height of fall from 4 to 12 inches the average density of sand increased from 86.5 to 90 lb/ft^3.

2. For the model piles tested it is possible to relate torque required to install a screw pile in a sand bed from a knowledge of the blade and shaft radius, spacing of blades and soil density. Torque for installing a pile predicted by equation 4.8 is found to be lower than torque measured in the model tests. A good correlation ($r=0.997$) however, is observed between the measured and the predicted values.

3. It is also possible to predict uplift load capacity of a screw pile using equation 4.13 from a knowledge of shaft

and blade radius, spacing of blades and soil density. A good correlation (r=0.82) has been observed between uplift load capacity predicted by equation 4.13 and uplift measured from model test.

4. It has been found that change in shaft diameter does not significantly effect the uplift load capacity or driving torque requirements of a screw pile, particularly so if the blade diameter is large in comparison to shaft diameter uplift load also does not increase significantly with change in shaft diameters.

5. Radius of screw blade has a significant influence on torque required to drive a pile in sand. For the model piles it is observed that with increase in radius of screw blade (R_B) from 0.375 inches to 1.875 inches, the torque/ft increased from 1.5 lb-in/ft to 58.71 lb-in/ft. It is also observed that the uplift load increased from 8.5 lb to 47.5 lb for the same increase in blade radius.

6. Piles with larger blades at the bottom and smaller blades at the top (i.e group E_3) required a driving torque of three to four times more than that of piles with smaller blades at the bottom and larger blades at the top (i.e group D_3) in the sand beds (which were initially in loose state) used in these experiments.

Piles of group E_3 also required an uplift load of nearly 2.6 times more than that of piles of group D_3. This is suggested as due to disturbance and densification of sand within a larger volume and during uplifting sand above this blades being of larger amount.

CHAPTER 7

CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE RESEARCH

7.1 Conclusions

The conclusions drawn on various aspects of this research may be summarized as follows.

1. For model screw piles a good correlation (r = 0.997) is found between measured torque (T_m) and theoretical torque (T_t) and is related by the equation:

$$T_m = 2.378\ T_t$$

where T_m and T_t are expressed in pound inch unit.

2. For model screw piles a good correlation (r = 0.82) is found between measured uplift load (U_m) and theoretical uplift load (U_t) and is related by

$$U_m = 8.626 + 0.807\ U_t$$

where U_m and U_t are expressed in pound force.

3. A good correlation (r = 0.984) exists between measured torque (T_m) and measured uplift capacity (U_m) in granular sand beds. For the types of pile used in this research and for the soil condition, the relation ship between torque and uplift capacity is expressed by the equation:

$$U_m = 11.66 + 0.54\ T_m$$

If the effect of blade dimension is included in the above relation between torque and uplift load, a linear correlation with r = 0.958 exists. The relation is expressed by the equation

$$U_m = 3.098 + 1.12\ T_m/R_B$$

where, R_B is the blade radius in inch.

4. For screw piles whose blades are unequal and increase or decrease in diameter from top to bottom of the embeded depth (i.e taper arranged blades), a strong correlation (r = 0.994) is found between uplift load and driving torque given by the equation

$$U_m = 5.18 + 0.847\ T_m$$

7.2 Recommendation for Future Research

This study was limited to a particular type of granular soil and three different types of piles. Therefore the applicability of the relations proposed in this thesis is limited to this particular type of pile geometry and soil condition. Any variations of dimensions of pile elements, soil type should require different statistical parameters for the mathematical relations of torque and uplift capacity. In order to develop a generalized model of screw pile behaviour, the following recommendations are made for future research.

1. In future studies the effect of soil density on the relationship between driving torque and uplift load should be determined. This may be done in the laboratory by varying the density of soil bed.

2. To investigate the geometry of the failure surface of the screw pile, against uplift loading by varying the diameter of the screw blade and the embedment depth of the blade. This can also be done in the laboratory models.

3. Also studies can be made regarding the effects of change in soil density around the screw blade during driving and uplifting of piles.

4. A more sensitive torque meter which can measure large driving torque for piles of larger shaft diameter can be prepared in the laboratory.

5. To find a consistent driving torque and uplift load, the experiment should be done in dense soil.

6. To find an optimum spacing of blade for optimum driving torque, the experiment should be done by piles of various spacing of blades.

REFERENCES

1. ABEDIN, ZOYNUL (1983) - 'Screw Pile in Alluvial Soils Driving Torque Uplift Capacity and Soil Strength Relations' M.Sc.Engg. (Civil) Thesis, BUET, Dhaka, Bangladesh.

2. BALLA, A. (1961) - 'The Resistance to Breaking out of Mushroom Foundations for Pylons', Proc. 5th. Int. Conf. S.M. & F.E., Vol. 1, pp. 569-576.

3. BEGEMANN, H.K.S. (1965) - 'The Maximum Pulling Force on a Single Tension Pile Calculated on the Basis of Results of the Adhesion Jacket Cone.', Proc. 6th. Int. Conf. S.M. & F.E., Vol. 2, pp. 229-233.

4. DAS, B.M., SEELEY, G.R., (1975) - 'Uplift Capacity of Buried Model Piles in Sand'. Jnl. Geotech. Engg. Divn. ASCE, Tech. Notes, October, 1975, pp. 1091-1094.

5. DAVIE, J.R., SUTHERLAND, H.B. (1977) - 'Uplift Resistance of Cohesive Soils'., Jnl. Geotech. Engg. Divn. ASCE, GT9, pp. 935-951.

6. DOWNS, D.I., CHIEURZZI, R. (1966) - 'Transmission Tower Foundations'. Jnl. Power Divn. ASCE, Vol. 92, PO2, pp. 91-114.

7. HITACHI CABLE CO. (1980a) - 'A Technical Note on Screw Pile'. Submitted to the Power Development Board, Dhaka, Bangladesh for the Construction of Tower Foundations in the East West Electrical Interconnector Project.

8. HITACHI CABLE CO. (1980b) - 'A Technical Specification on Swedish Sounding Test'. Submitted to the Power Development Board, Dhaka in Relation to the Construction of East-West Electrical Interconnector Project.

9. IRELAND, H.O. (1957) - 'Pulling Tests on Piles in Sand'. Proc. 4th. Int. Conf. S.M. & F.E., Vol. 2, pp. 43-54.

10. JOHNSTON, J. (1972) - 'Econometric Methods', 2nd Edition, Mc-Graw Hill Kogakusha Ltd., Tokyo, pp. 8-169.

11. KULHAWY, F.H., KOZERA, D.W., WITHIAM, J.L., (1979) - 'Uplift Testing of Model Drilled Shafts in Sand'., Jnl. Geotech. Engg. Divn. ASCE, GT1, pp. 31-47.

12. MEYERHOF, G.G., ADAMS, J.I. (1968) - 'The Ultimate Uplift Capacity of Foundations' - Can. Geotech. Jnl., Vol. 5, No.4, pp. 225-244.

13. PECK, R.B., HANSON, W.E., THORNBURN, T.H. (1974) - 'Foundation Engineering', 2nd Edition, John Wiley Inc., Newyork, pp. 20-114.

14. POULOS, H.G., DAVIS, E.H. (1980) - 'Pile Foundation Analysis and Design', John Wiley and Sons. Newyork, pp. 46-51.

15. ROBINSON, K.E., TAYLOR, H. (1969) - 'Selection and Performance of Anchors for Guyed Transmission Towers' Gan. Geotech. Jhn., Vol. 6, pp. 119-137.

16. SOWA, V.A. (1970)- 'Pulling Capacity of Concrete Cast-in-situ Bored Piles', Can, Geotech. Jnl. Vol. 7, pp. 482-493.

17. TOMLINSON, M.J. (1977)- 'Pile Design and Construction Practice', Cement and Concrete Association, 1977, pp. 210-216.

18. TROFIMENKOV, J.G., MARIUPOLSKI, I.G., (1965) - 'Screw Piles used for Mast and Tower Foundations', Proc. 6th Int. Conf. S.M. & F.E., pp. 328-332.

19. TURNER, E.A. (1962) - 'Uplift Resistance of Transmission Tower Footings.', Jnl. Power Divn. ASCE, Vol. 88, Paper 3187.

20. WHITAKER, T. (1976) - 'The Design of Piled Foundations.', Pergamon Press, Oxford. pp. 1-20.

APPENDIX-A

NUMERICAL EXAMPLES FOR THE THEORETICAL EQUATIONS

A-1 Numerical Example Illustrating Soil Strength-Driving Torque Relation

Driving torque for pile group A_3, A_5, B_3, B_5 and C_3 are computed by using the equation 4.8.

$$T = \frac{4}{3}\pi \text{Sec}\ \theta\ (R_B^3 - R_p^3) f_1\ N_2 + 2\pi R_p^2\ f_2 \qquad (4.8)$$

where $f_1 = k_a/2\ \gamma \tan \phi \tan \partial L^2$

$k_o = 1\text{-Sin}\ \phi$

$k_a = \frac{1\text{-Sin}\ \phi}{1+\text{Sin}\ \phi}, k_p = 1/k_a$

ϕ is found from the curve in Fig. A-1.

Theoretical driving torque for pile 2 of Group A_3 using the Equation 4.8.

$\theta = 20$

$R_p = 0.125$ inch

$R_B = 0.625$ inch

$N_2 = 3$

$\phi = 26.5^o$ (From Fig. A-1)

$\gamma = 0.0484\ lb/in^3$

For $\phi = 26.5^o$ (From Fig. A-1)

$k_o = 0.553$

$k_a = 0.382$

$k_p = 2.611$

for $k_o = 0.553$, $f_1 = 0.040$

for $k_a = 0.382$, $f_1 = 0.057$

for $k_p = 2.611$, $f_1 = 0.273$

For $k_a = 0.382$, f_2 becomes

$$f_2 = \frac{0.382}{2} (0.0484) \tan 26.5 \tan (2/3 \times 26.5)(14)^2$$

$$f_2 = 0.287,$$

Similarly for k_o and k_p, f_2 becomes 0.416 and 1.916 respectively.

Now putting the above values in equation 4.8, total driving torque is found.

For k_o condition total driving torque becomes

$$T_o = 4/3\,\pi \text{ Sec } 20(0.625^3 - 0.125^3)(0.040)3 + 2\pi(0.125)^2(0.287)$$

$T_o = 0.225$ lb-in and for k_p condition $T_p = 1.07$ lb-in.

Theoretical driving torque for piles of Group D_3 and E_3 are computed by using the equation 4.9.

$$T = 4/3\,\pi \text{ Sec } \theta\, f_1 (R_{B1}^3 + R_{B2}^3 + R_{B3}^3 - 3R_p^2) + 2\pi R_p^2 f_2 \qquad (4.9)$$

Considering the pile 7 of group D_3.

$\phi = 26.5^o$ then $k_o = 0.553$, $k_a = 0.382$ and $k_p = 2.611$

Then for k_o, k_a and k_p condition f_1 becomes 0.057, 0.039 and 0.271 respectively.

Similarly for k_o, k_a and k_p condition, f_2 becomes 0.44, 0.307 and 2.101 respectively.

Now for k_o condition driving torque becomes

$$T = 4/3\,\pi \text{ Sec } \theta\{0.375^3 + 1.08^3 + 1.785^3 - 3(0.125)^3\}0.553 + 2\pi(0.125)^2\ 0.44$$

$$T = 1.794 + 0.0435$$

$$T = 1.837 \text{ lb-in}$$

For k_a and k_p condition driving torque becomes 1.26 lb-in and 8.66 lb-in respectively.

A.2 Numerical Example Illustrating Soil Strength Uplift Load

Uplift load for pile group A_3, A_5, B_3, B_5 and C_3 are computed by using the equation 4.13.

$$P_u = \bar{W} + \pi(R_B^2 - R_p^2)\,\gamma H + N_1(N_2-1) + \pi R_B L^2\, k_p \gamma \tan \phi \qquad (4.13)$$

Theoretical uplift load for pile 2 of group A_3 using the above equation for k_o condition is

$$P_u = 4.02 + \pi(0.652^2 - 0.125^2)0.0484\{4.5+4(3-1)\} + 0.375(3x2)^2\ 0.553x0.0484 \tan 26.5$$

$$P_u = 4.02 + 0.712 + 0.565$$

$$P_u = 5.291 \text{ lb}$$

For k_a and k_p condition uplift load for this pile are 4.81 lb and 9.0 lb respectively.

Uplift load for piles of Group D_3 and E_3 are computed by using the equation 4.14

$$U_t = \bar{W} + \pi(R_{B3}^2 - R_p^2)\ \gamma H + \pi(R_{B2}^2 - R_p^2)\ \gamma N_1 + \pi(R_{B1}^2 - R_p^2)\gamma N_1 + \pi R_{B2}\ L^2\ K_p\ \gamma \tan \phi \qquad (4.14)$$

Theoretical uplift load for pile 7 of group D_3 using the equation 4.14.

$$U_t = \bar{W} + \pi(1.78^2 - 0.125^2)0.0485 \times 4.5 + \pi(1.08^2 - 0.125^2)$$

$$0.0485 \times 4 + \pi(0.375^2 - 0.125^2)0.0485 \times 4 + \pi(1.08)(8.5)^2$$

$$0.382 \times 0.0485 \tan 26.5$$

$$U_t = 4.31 + 2.173 + 0.701 + 0.076 + 2.264$$

$$U_t = 9.524 \text{ lb}$$

Similarly for k_o and k_p condition uplift loads are 10.46 lb and 22.601 lb respectively.

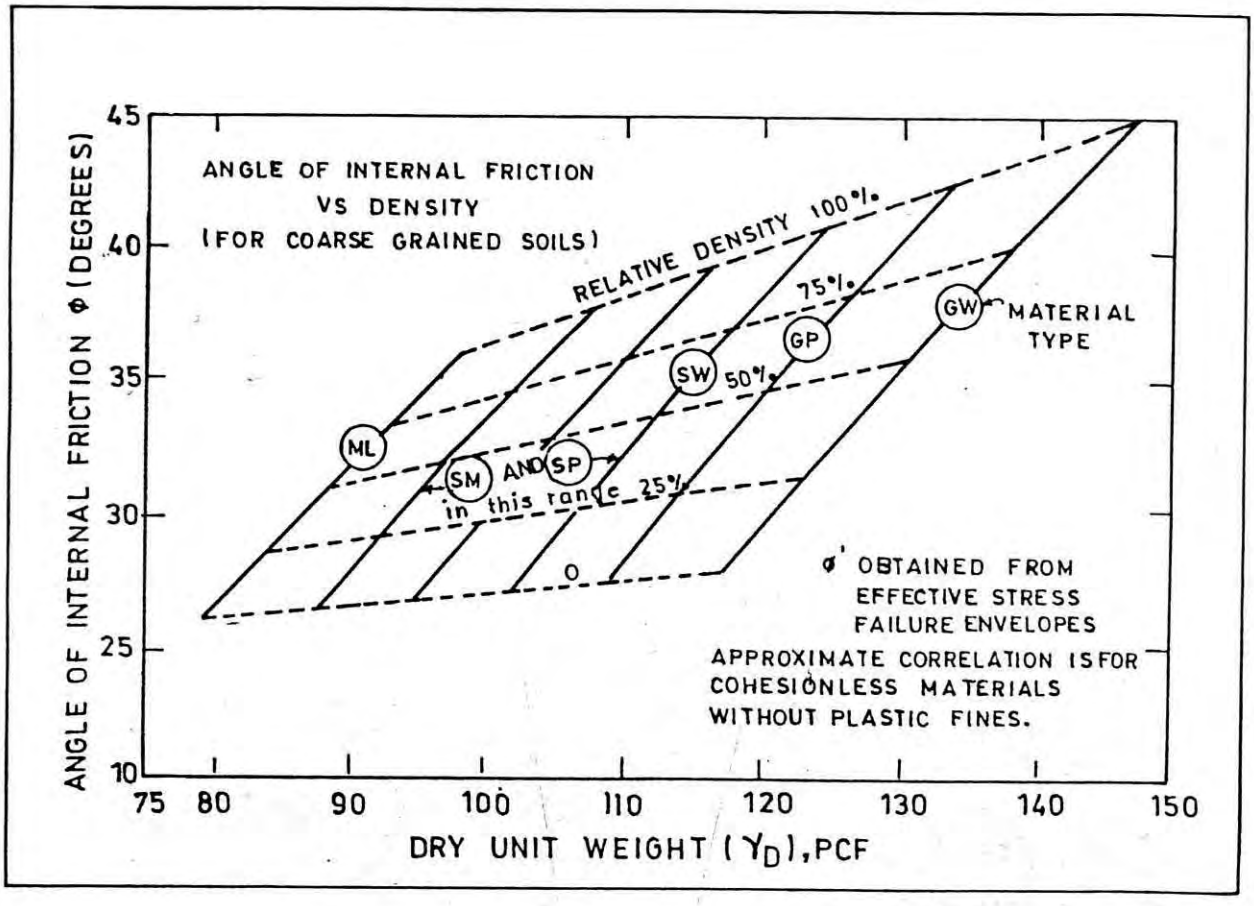


Fig. A.1 Angle of internal friction ϕ versus dry unit weight (after NAVFAC DM 7.1, May 1982).

APPENDIX-B

DETERMINATION OF RELATIVE DENSITY OF SAND IN LABORATORY

Relative density (D_r) is determined by using the equation

$$D_r = \left(\frac{\gamma_n - \gamma_{min}}{\gamma_{dense} - \gamma_{min}}\right) \frac{\gamma_{dense}}{\gamma_n} \times 100 \qquad (B.1)$$

where

γ_n = density of soil in its natural state (field value)

γ_{min} = loosest value of unit weight of soil obtained in the laboratory

γ_{dense} = densest value of unit weight of soil obtained in the laboratory.

Table B.1 shows the unit weight reading for loosest condition of sands in laboratory.

Table B.1 Unit weight reading for loosest state

Loosest state					
No. of obs.	Wt. of mold + soil in (lb)	Wt. of mold in (lb)	Wt. of soil in (lb)	Density (pcf)	Average density (pcf)
1	25.48	15.86	9.62	84.01	
2	25.48	15.86	9.62	84.91	83.58
3	25.43	15.86	9.57	83.58	

Calculation of Relative Density for a Particular Condition:

Pile No.1 is driven into sand of density 84.49 pcf, then at that condition relative density is found by using the quation (B.1)

where,

γ_n = 84.49 pcf

γ_{min} = 83.58 pcf

γ_{dense} = 109 pcf, from the curve in Fig. A-1.

Putting the above values in equation B.1

$$D_r = \left(\frac{84.49 - 83.58}{109.00-83.58}\right) \frac{109.00}{84.49} \times 100$$

$$D_r = 4.61\%$$