Short Communication

Influence of Surface Taper and Shape of Pile on Ultimate Bearing and Uplift Capacities

by

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Introduction

We find wide application of piles in foundations of tall buildings, industrial structures, heavy machineries, etc. particularly in locations where hard load bearing stratum is not available at a shallow depth. For structures bearing heavy loads, piles remain always under compression. However, for tall and slender structures, like transmission line towers, conveyor supporting trestles, moments due to lateral loads may cause uplift in some of the legs and thus piles are also subjected to uplift. It had been observed by Nordlund (1963), Bakholdin (1971), *D*'Appolonia and Hribar (1963), Tavenas (1971), Das (1983) and others that the bearing and uplift capacities of piles in soils are functions of many variables—which are taper, roughness and shape of pile and volume of soil displaced by it.

The present paper deals with bearing and uplift tests conducted on six different types of model piles having same length, same tip area and same volume of materials but with various shapes of cross-section and taper of surface.

Description of Model Piles

Tests were conducted on six different types of model piles in dry sand viz. circular, square, triangular, circular-taper, square-taper and step-taper, volume, length and tip area of all piles were same and these were 3772 cm^3, 80 cm & 7.069 cm^2, respectively. These piles are shown in Figure 1.

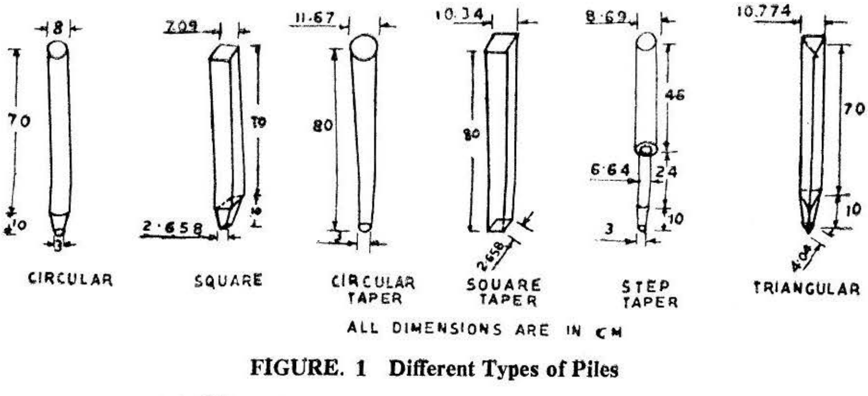

FIGURE. 1 Different Types of Piles

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The ratio of length to average diameter were chosen nearly equal to 10 on the basis of the findings of Touma and Reese (1974) who observed that in loose sand, the ultimate tip resistance increases with depth but trends asymptotically to a critical depth to diameter ratio of 10. For casting the piles, moulds of sheet metal were made according to the shape of piles. Piles were constructed in M-20 grade of concrete and main reinforcements were provided as 1.25 per cent of gross concrete area. 6 mm diameter rods as main reinforcement and 2.5 mm diameter wires as lateral reinforcement were provided. The spacing of lateral reinforcement were guided by the least lateral dimensions of piles. At the top of each pile a '*U*' shaped hook was provided for lifting.

Experimental Set-Up

In bearing capacity test, a wooden tank of length, breadth and height 70 cm, 70 cm and 110 cm was used. For removing the sand after the test, a small door was provided at the bottom of the tank. The tank was placed on the base of loading frame. The base of screw-jack was fixed with the top plate of frame by means of two C-clamps.

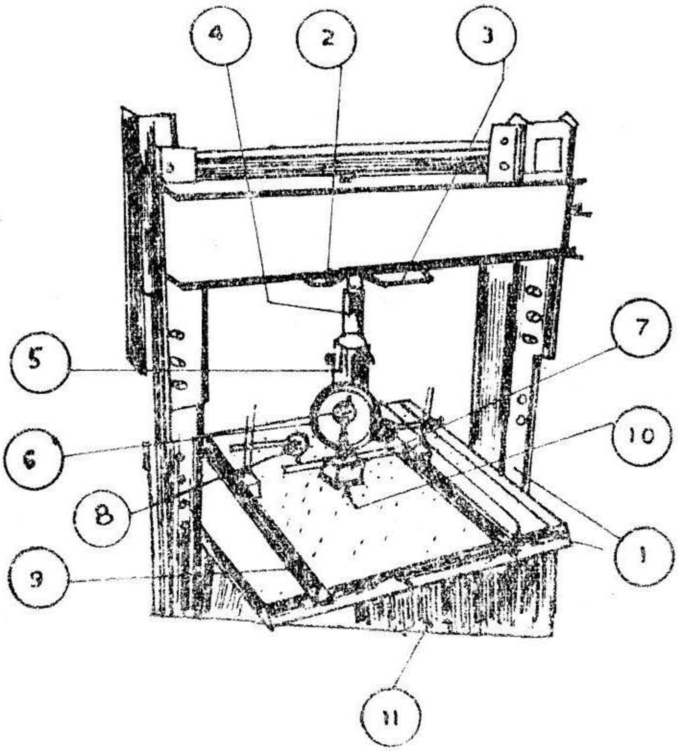
The other end of screw-jack was further fixed with a clamping rod. At the bottom of this clamping device, a threaded rod was fixed for fixing the proving ring. It was then further placed on a wooden base. The wooden base was finally kept on pile head. A small hole was provided in the central portion of base for keeping the *U*-shaped hook of pile. Two steel plates were fixed on both the sides of the wooden base. Two deflection gauges were placed on the plates. The least count of the gauges was 0.001". The base of dial gauges were placed on angle sections. The test set-up is shown in Fig. 2.

In uplift test, the same tank was used. Two bearing pulleys were fixed on the top plate of loading frame. A steel wire was joined with the hook of pile and other end was passed around the central and then the front pulley and terminated at the loading pan. Two steel plates were fixed on both sides of the top of pile by proper adhesive. The deflection gauges were kept on these plates. The test set-up is shown in Fig. 3.

Test Procedure

The tests presented here were performed on sand with a placement density of 1.59 gm/cm^3. Angle of internal friction of sand was 38°56' and angle of sliding friction of concrete on sand was 31°13'. The uniformity co-efficient of sand was 2.4. In bearing test, the tip of the model pile was placed freely on sand in the tank. The whole tank was filled by spraying sand from a hopper freely from 30 cm height above the bottom level of sand in each time, for getting a uniform density.

The bearing capacity tests were done by applying static vertical load by screw jack. The load was applied through proving ring in steps by means of the screw-jack till failure of pile which was evident from a sudden large increase in the rate of settlement. The actual failure load was determined from the intersection of initial and final tangents of the load settlement curve, as shown in Fig. 4.



(1) Loading Frame (2) C-Clamp (3) Top Plate (4) Screw-Jack (5) Clamping Rod (6) Proving Ring (7) Base of Proving Ring (8) Dialgauge (9) Angle (10) Pile (11) Wooden Tank

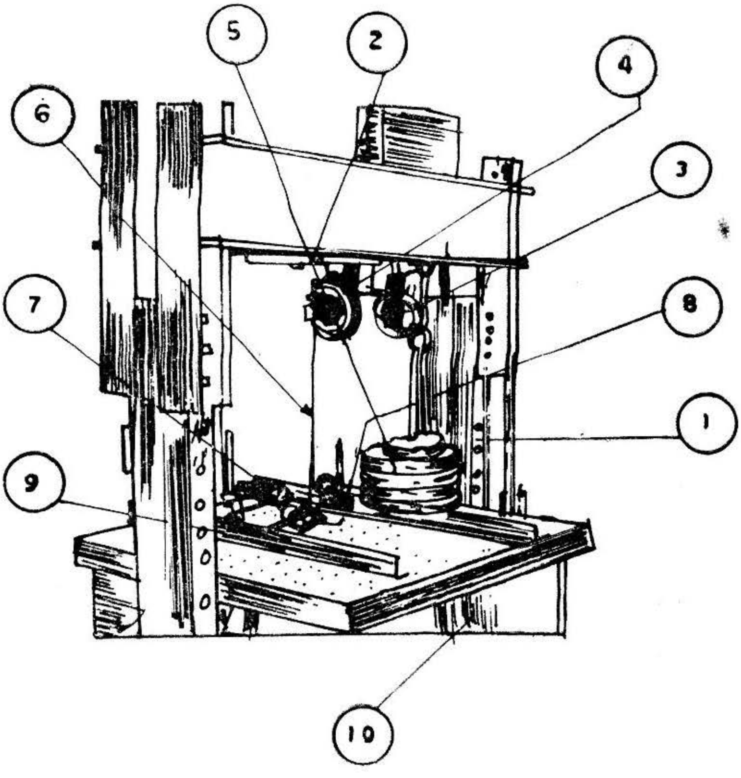
FIGURE 2 Bearing Capacity Test Set-Up

In case of uplift test, same method as above was adopted for embedding the pile in sand. Load was applied by increasing the load in steps in the load pan. The pile fails suddenly when it reaches the ultimate load. *Load displacement curve is shown in Fig. 5.*

For each pile, both the bearing and uplift tests were done. Each test was repeated a few times to find the most consistent result.

Theoretical Analysis and Discussion of Experimental Results

The conventional approach to the analysis of the bearing capacity of deep foundation consists of separating the resistance of the pile into the tip resistance, Q_t and side resistance, Q_s.



(1) Loading Frame (2) Top Plate (3) Front Pulley (4) Central Pulley (5) Loads (6) Wire (7) Dial Gauge (8) Pile (9) Angle (10) Wooden Tank

FIGURE 3 Uplift Capacity Test Set-Up

Tip resistance is, $Q_t = N_q.$ A. q.

and side resistance is $Q_s = C \int_0^h$ K.p. tan δ dh.

Two distinct zones develop around the tip of the pile as a result of the downward movement—the flow zone and the arching zone. The deformation occurs, due to downward movement, of a horizontal plane, through tip and some distance above the tip as shown in Fig. 6. In side resistance, as in Fig. 7 the non linear increase of the shear transfer with depth reflects the load tranfer from the pile and of the arching of the sand near the tip of the pile. It was stated by Touma and Reese (1974) that the hatched area under the curve of Fig. 7 is related to the area under the line p tan δ. It is convenient to define α_{avg} as the ratio of these areas.

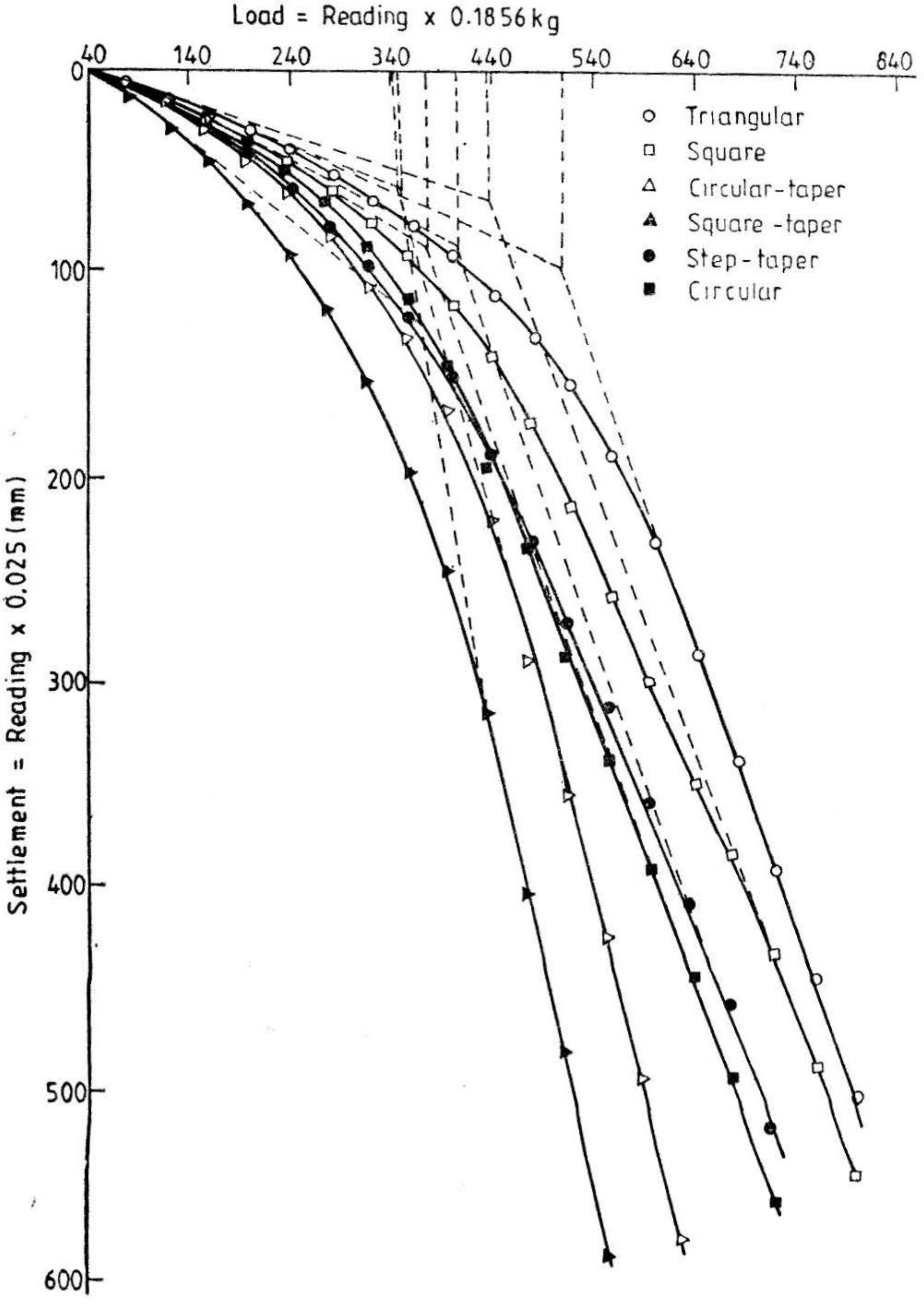


FIGURE 4 Load Versus Settlement Curve of Pile

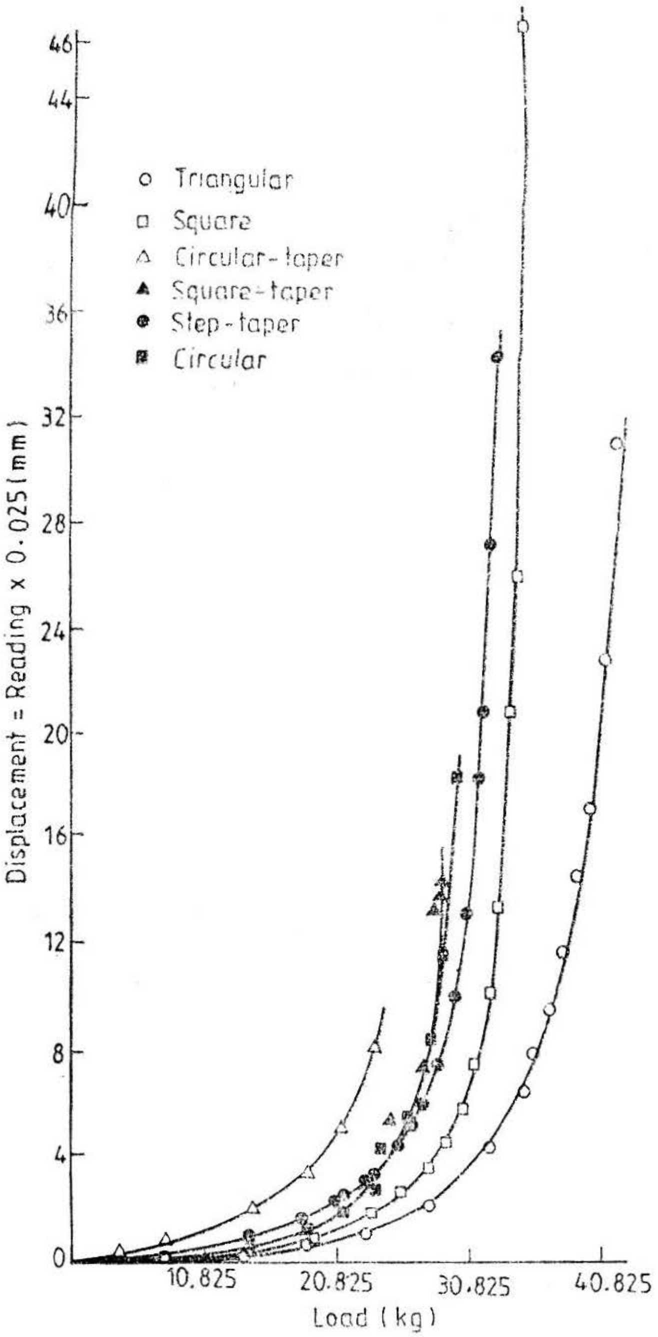


FIGURE 5 Uplift Load Versus Displacement Curve of Pile

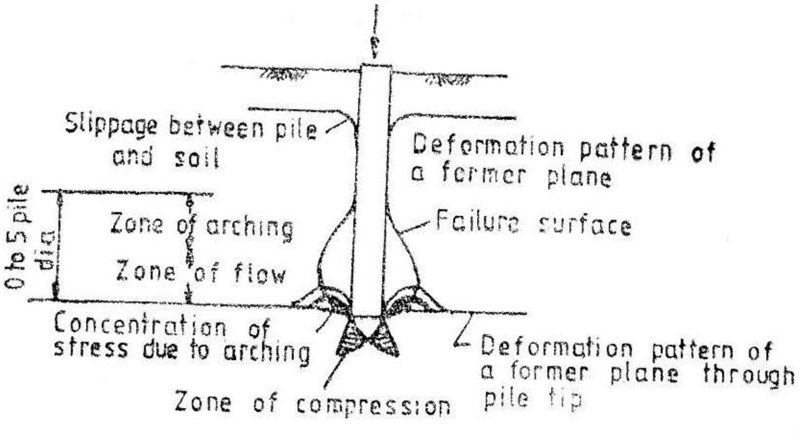


FIGURE 6 Zones Around Tip of Pile (After Touma and Reese, 1974)

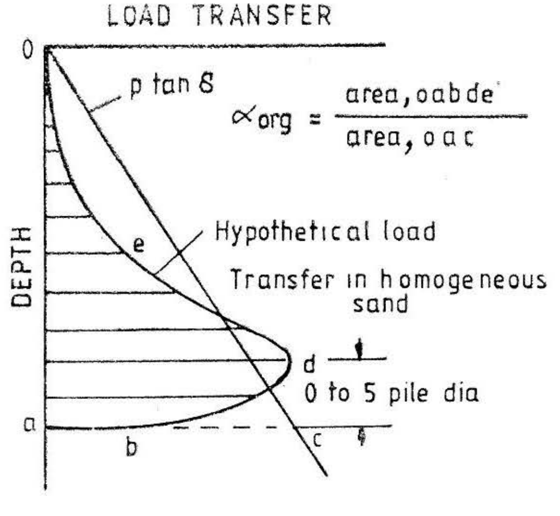


FIGURE 7 Typical Load Transfer vs Depth in Sand (After Touma and Reese, 1974)

As the space around the pile was filled by spraying sand from certain height after placing the tip of pile on sand, bored pile theory is applied. α avg values are taken from the results obtained by Touma and Reese on test with bored piles.

For all the cases K values are assumed as 0.50. Nordlund (1963) established some graphs which show the variation of K with the taper angle (w) for driven piles only. Here as the bored piles theory is taken into consideration, these values are not used. More detailed analysis is to be done to find the actual K value.

Now, the ultimate side resistance is,

$$Q_s = C \int_0^h \alpha_{avg} \text{ k.p. } \tan \delta \text{ dh.}$$

This equation holds good for straight edge of pile.

In case of slant side edge,

$$Q_{s1} = \int_0^h K \; C_h \; \alpha_{avg} \; p. \; \frac{\text{Sin}\,(w+\delta)}{\text{Cos}\; w} dh$$

The αavg value is taken as 0.7, as obtained by Touma and Reese (1974). The effective overburden is taken as 0.7 of total overburden at the tip. In the case of step-taper pile the α_{avg} is taken as 0.35 due to arching phenomenon at two points.

In bearing capacity test the tip rtsistance is computed by Q_t = Nq.A.q. No correction terms are applicable for circular or square base in this equation.

In the uplift test the total resistance is offered only by slde friction. Here the uplift capacity equation is written based on the cylindrical model i.e. the model of linear increase of earth pressure with depth.

So uplift capacity, $Q_n = C \int_0^h$ k.p. tan δ dh.

But Das (1983) found from test with rough pile, that unit skin friction at the soil-pile interface increases with depth ratio upto a critical embedment ratio. But the above uplift equation was developed on linear increase of pressure, due to that a correction factor $\alpha_{avg\,1}$ is applied. $\alpha_{avg\,1}$ represents the ratio of pressure diagram areas of triangular upto critical depth and then rectangular, to linear triangular upto the tip of pile. Here $\alpha_{avg\,1}$ is assumed as 0.7.

So in straight portion, $Q_n = \int_0^h C\alpha_{avg\,1}\,\gamma$.k.h. tan δ

In slant side the frictional resistance against uplift is calculated as,

$$Q_{n1} = \int_0^h K\,\alpha_{avg\,1}\,\gamma\,h \;\; \frac{\sin\,(\delta - w)}{\text{Cos}\; w}\; C_h \;\text{dh}.$$

In bearing and uplift tests, the frictional resistance was offered by upper straight 70 cm and between truncated conical 10 cm portion of circular, triangular and square piles. In addition to that middle portion also offered the resistance for step-taper pile and for other piles, resistance is due to only the 80 cm slant edge. In bearing test, tip resistance also acted in addition to the above resistances.

Here the α_{avg} and $\alpha_{avg\,1}$ values are assumed only, according to previous experimental results. More detailed analysis is to be done for finding their actual values.

From the results presented in Table 1 it is evident that out of three factors—surface area, shape and taper, the surface area is the most dominant factor in increasing the bearing and uplift capacity of piles

TABLE 1

Specific Load Bearing and Uplift Capacity from Test Results

Item		Different types of pile						Remarks
		Circular Taper	Square-Taper	Step-Tape	Circular	Square	Triangular	
Surface area	cm²	1876.75	2082.07	1861.75	1874.49	2115.17	2410.68	
	per cent	100.83	111.87	100	100.72	113.65	129.53	Volume of Concrete base areas and total length same for all piles
Bearing Capacity	kg	70.07	65.437	75.183	64.50	81.21	94.21	
	per cent	108.63	101.45	116.56	100	125.96	146.06	
Uplift capacity	Gross in kg	24.97	29.27	33.652	30.835	35.506	42.786	
	Net in kg	14.37	18.27	25.002	22.21	26.706	32.285	
	per cent	100	127.13	173.987	154.55	185.845	224.66	

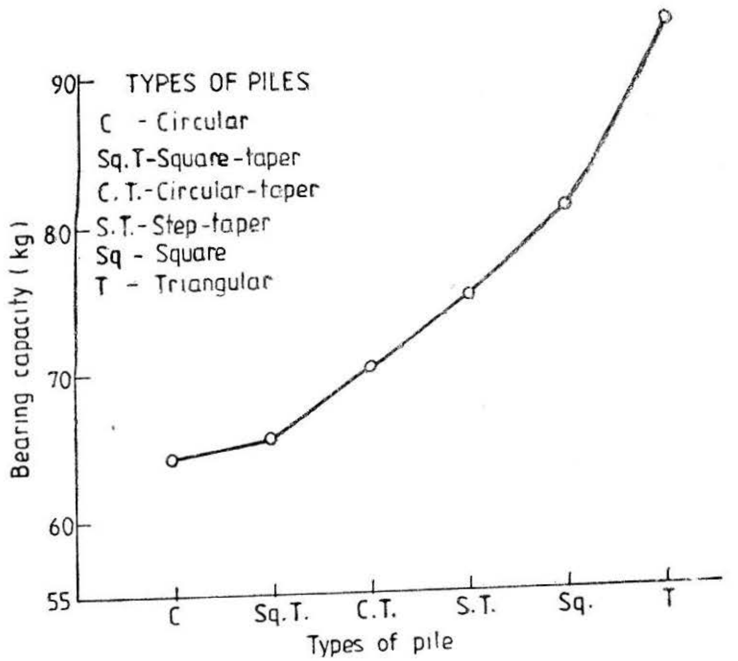


FIGURE 8 Variation of Bearing Capacity with Type of Pile

having same tip area and same volume, and same length. The variation of bearing capacity with the type of pile is shown in Fig. 8.

The procedure of filling up of the tank with soil after placing the pile in position does not simulate the actual soil behaviour corresponding to field installation of a tapered pile. But here the test is conducted just to find the effect of shape and taper, so in all the cases same condition is maintained to evaluate these effects.

From Table 1, it is observed that in bearing capacity test, increase of surface area leads to increase in bearing capacity. Again it is found that in step-taper pile, the bearing capacity is more than circular taper and circular pile whereas their surface area is same—effect of shape is observed here. In uplift capacity tests, circular taper and square-taper has minimum uplift load resisting capacity. Here also, increase of surface area leads to higher uplift resistance capacity, which is found considerable in square and triangular pile. Triangular pile has 29 per cent more surface area than circular taper pile, but it has 124 per cent more uplift capacity than the circular-taper pile. The variation of uplift capacity with the type of pile is shown in Fig. 9.

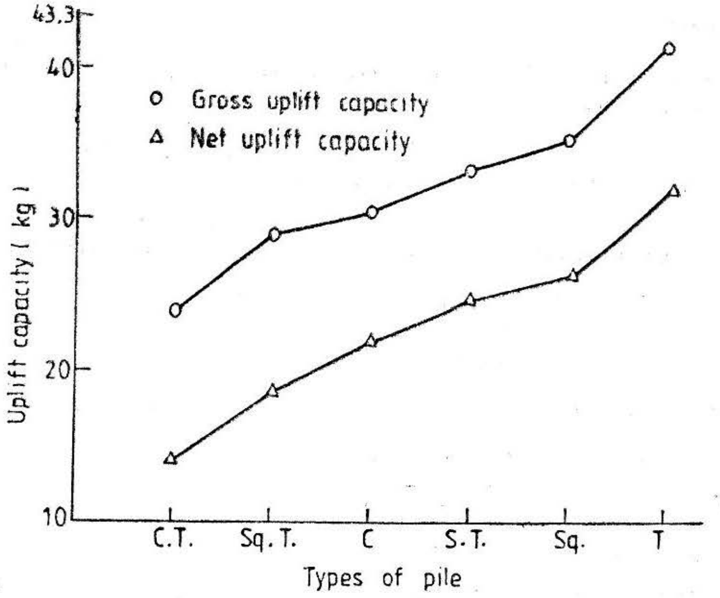


FIGURE 9 Variation of Uplift Capacity with Type of Pile

TABLE 2

Comparison of Theoretical and Experimental Values

Items	Method	Circular-taper	Square-taper	Step-taper	Circular	Square	Triangular
Bearing capacity in kg.	Analytical Top portion	18.87	20.88	4.892	20.857	23.52	26.822
	Botom portion			2.0214	5.248	5.725	7.433
	Middle portion			4.80			
	Tip	46.01	45.98	45.21 *at step,* 23 0 at bottom	46.06	45.98	46.00
	Total	64.88	66.86	79.92	72.165	75.225	80.255
	Experimental	70.07	65.437	75.183	64.50	81.21	94.21
Uplift capacity in kg,	Analytical Top portion	15.619	17.82	9.784	20.86	23.52	26.82
	Bottom portion			2.28	2.182	2.658	2.214
	Middle portion			9.914			
	Total	15.619	17.82	21.97	24.04	26.178	28.947
	Experimental	14.37	18.27	25.002	22.21	26.706	32.286

In Table 2 the experimental values are compared with analytical solution and it is observed that they are quite matching.

Conclusions

From the analysis of load tests reported herein, the following conclusions may be drawn :

1. The shape and taper of pile have significant effect in bearing capacity as well as in uplift capacity.
2. For same volume of concrete, the triangular piles have maximum compressive load bearing and uplift load resistance capacity.
3. Driven or bored triangular pile will be effective in sandy soil.

Appendix-I

Sample Calculations

Bearing Capacity of Circular Pile

Length of upper cylindrical portion	= 70 cm
Length of bottom conical portion	= 10 cm
Tapering angle of conical portion	= 14°2′10.4″
Top diameter	= 8 cm
Bottom diameter	= 3 cm
Angle of friction	= 31°13′
Terzaghi's Bearing capacity factor N_q	= 72.788

$$K = 0.5$$

Frictional side resistance from top cylindrical portion.

$$Q_{s1} = C \int_0^h a_{avg} \times P_h \times \tan\delta \times dh$$

$$= \pi \times 8 \times \int_0^{70} \times 0.70 \times Kx\gamma \times h \times \tan\delta\, dh$$

$$= \pi \times 8 \times \int_0^{70} 0.70 \times 0.5 \times 0.001597 \times \tan 31°13' \times h dh$$

$$= 20.857 \text{ Kg.}$$

Frictional side resistance from the conical bottom portion.

$$Q_{S_2} = K\,(pv + po)\ \frac{\sin\,(w+\delta)}{\cos W}\ C_h\, dh$$

$$Po = \alpha_{avg} \times \gamma \times 70$$

$$pv = \alpha_{avg} \times h \div \gamma$$

$$C_h = \pi\,(8 - 0.5\,h)$$

$$Q_{S_2} = \int_0^{10} K(0.70\times\gamma\times 70+0.70\times\gamma\times h)$$

$$\frac{\sin(31°13'+14°2'10.4'')}{\cos 14°2'10''.4}\times\pi(8-0.5\,h)\,dh$$

$$= 5.248 \text{ Kg.}$$

Tip resistance, Q_t $= A\times N_q\times q_e$

$= \pi \times(1.5)^2\times 72.788\times 0.70\times 001597\times 80$

$= 46.06$ Kg.

Ultimate bearing capacity $= 20.857+5.248+46.06$

$= 72.165$ Kg.

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Notations

A : Bearing area of pile base

C : Minimum perimeter

C_h : Circumference at depth h

K : Co-efficient of Earth pressure

P : Over burden pressure $= \gamma \times h$

N_q : Bearing capacity factor

h : Embedded length of pile

dh : Differential length along pile

Q_t : Tip resistance of pile

Q_s : Frictional resistance of straight edge in bearing capacity test

Q_{s4} : Frictional resistance of conical edge in bearing capacity test

Q_n : Frictional resistance of straight edge in uplift capacity test

R_{n1} : Frictional resistance of conical edge in uplift capacity test

γ : Angle of sliding friction between the pile surface and the surrounding soil

q : Effective pressure in soil at level of tip

w : Taper of the pile expressed as an angle

α_{avg} : Ratio of average load transfer to average value of product $p \tan \phi$ in bearing capacity test

γ : Unit weight of soil