Comparative Behaviour of Tapered and Uniform Diameter Piles in Loose Sands

by

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Introduction

Load carrying capacity of a tapered pile is calculated using approaches suggested by Nordlund (1963), Bakholdin (1971) and Trofimenkoy *et al* (1973). Of these, Nordlund's approach is fairly rigorous and widely used. But like any other theoretical approach, it requires assessment of bearing capacity factor N_q, dimensionless factor $K\delta$ (which represents the ratio of effective normal and shear stresses at any point on the pile surface) and angle of friction (δ) on the pile-soil interface, apart from the effective vertical stress distribution along the pile depth and the angle of shearing resistance of soil subsequent to pile driving. Calculated pile capacities, which are often based on assessed factors without firm basis, may therefor not be reliable. The Paper reports a study undertaken expressly to examine (*a*) degree of dependability of N_q and $K\delta$ values recommended in the literature (*b*) performance of tapered piles visa-a-vis piles of corresponding average diameter and uniform cross-section. Load tests on tapered and uniform diameter piles were conducted at a site where subsoil consisted of fairly homogeneous loose sand deposit above water table. From the observed pile capacities, values of N_q and $K\delta$ were computed by *back analysis* and compared with those which would have been otherwise assumed in making a theoretical estimate of pile capacity. The difference which have come to focus is discussed.

Test Piles

Three pyramidal timber piles, all of 3.5m length and 20cm × 20cm top having square tips of 16cm × 16cm; 12cm × 12cm and 8cm × 8cm and taper angles of 0.3°, 0.7° and 1° were load tested. These piles will be hereafter designated as $P_{3\cdot5} : \frac{20}{16}$, $P_{3\cdot5} : \frac{20}{12}$ and $P_{3\cdot5} : \frac{20}{8}$ respectively. Two piles of average diameter and uniform cross section were also tested. These will be designated as $P_{3\cdot5} : \frac{18}{18}$ and $P_{3\cdot5} : \frac{16}{16}$.

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Sub-Soil Characteristics

A typical bore log of the test site and the results of standard penetration test, dynamic cone test and static cone test are presented in Figure 1. The strata was of 'loose' relative density having angle of shearing

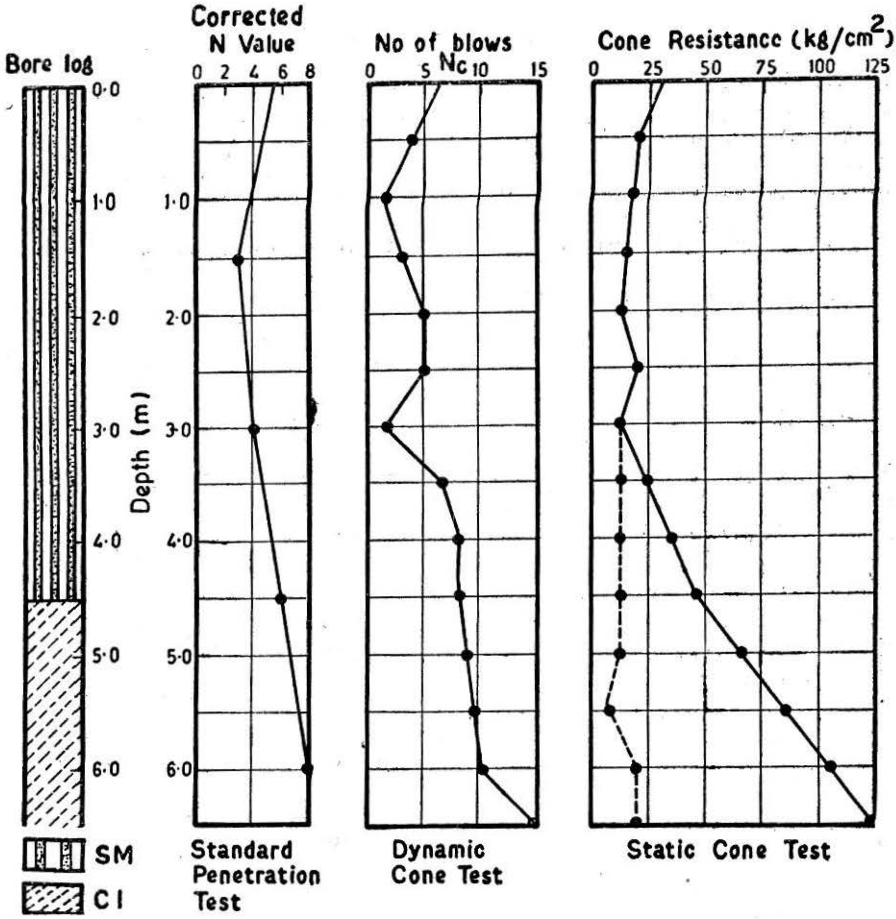

FIGURE 1 Sub-soil profile and penetration record

resistance, equal to 29° as inferred from the penetration record. The consolidated drained triaxial tests were performed on 38 mm diameter 114 mm high undisturbed cylindrical specimens. These specimens were prepared out of undisturbed block samples. The shear strength parameters so determined corroborated well with the above reported value of the angle of shearing resistance obtained from penetration testing. The ground water table, at the time of pile driving and load testing was about 0.5m below the pile tip. The water content varied marginally with depth and its average value was 10 per cent, giving a degree of saturation of about 40 per cent. At 4.5m depth, the soil strata was found to change from *SM* to *CI*.

Driving of Piles and Load Tests

The piles were driven by a winch operated 250 kg hammer under a free fall of 75cm. The pile driving record is shown in Figure 2. The penetration resistance encountered during driving of the pile $P_{3\cdot5} : \frac{20}{16}$ ought to have been higher than that for the pile $P_{3\cdot5} : \frac{20}{12}$ The reverse behaviour obtained in acutal driving appear to be due to local variations of soil density. The load tests were conducted using maintained load method. Load increments were applied and vertical pile displacement corresponding to each load increment was recorded using four dial gauges measuring 0.001mm.

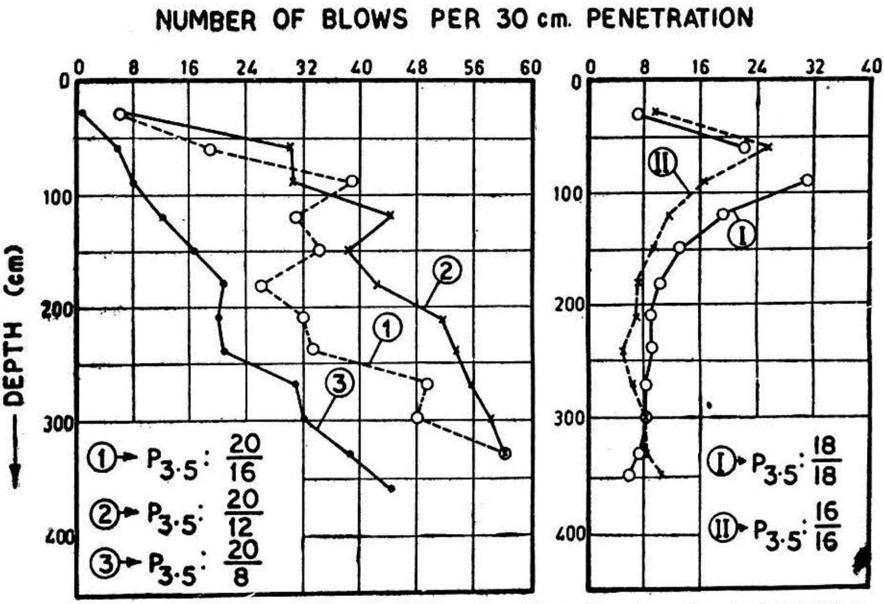

FIGURE 2 Penetration record of tapered and uniform diameter piles during driving

Load-displacement curves for all the the piles are presented in Figure 3 and the ultimate pile capacities computed from (a) $\frac{\epsilon}{P}$ versus ϵ relationship, Chin (1970), where P denotes load and ϵ, the corresponding settlement (b) load-displacement relationship on a double logarithmic scale are reported in Table 1.

Theoretical Computation

The ultimate bearing capacity of a tapered pile in cohesionless soil is given by the following general equation (Refer Figure 4).

$$P_u = N_q\, A_b\, q_D + \sum_{d=o}^{d=D} K\delta\; q_d \sin(w+\delta)\sec(w)\; S.\triangle d \ldots\ldots (1)$$

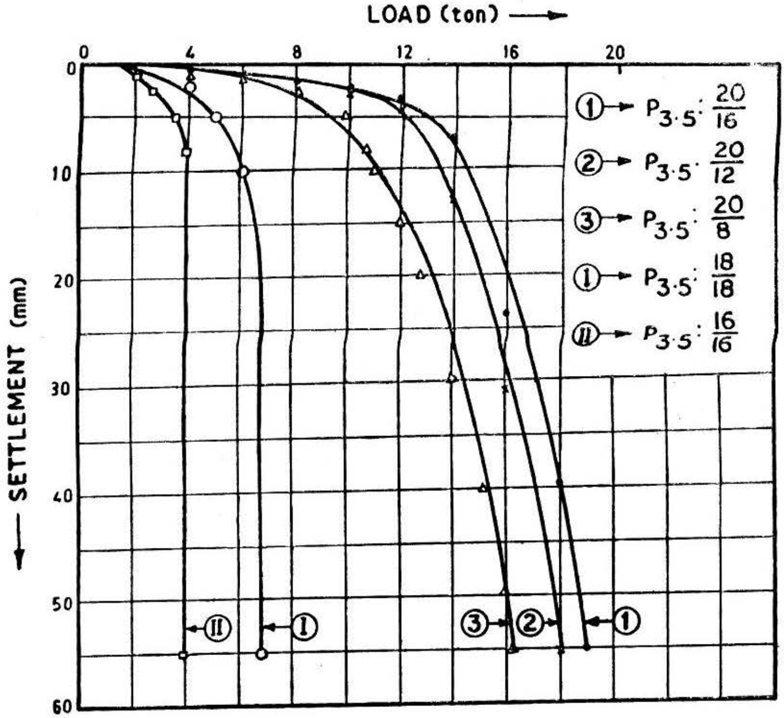

FIGURE 3 Load-displacement curves of tapered and uniform diameter piles

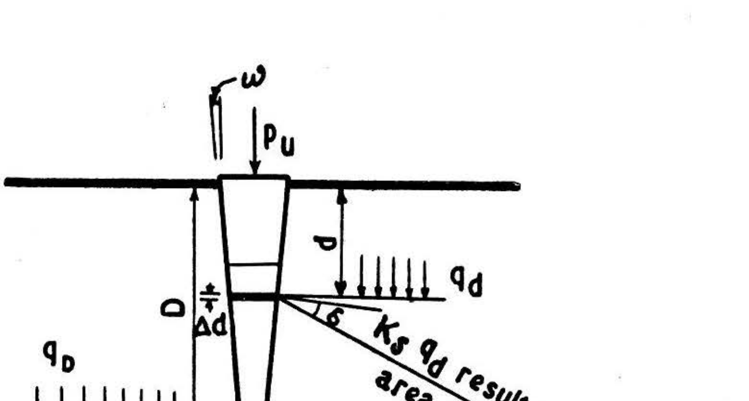

FIGURE 4 Illustration of terms used in general equation of ultimate bearing capacity

TABLE 1 **Observed and predicted ultimate bearing capacity of tapered and uniform diameter piles**

Pile	End bearing capacity (ton)				Shaft resistance (Nordlund 1963) ton	Ultimate bearing capacity (ton)					
						Computed				Observed	
	Berezantsev (1961)	Terzaghi (1943)	Vesic (1963)	Nordlund (1963)	$\phi=\delta=29°$ (1963)	Terzaghi (1943)	Vesic (1963)	Berzantsev (1961)	Nordlund (1963)	$\frac{\varepsilon}{P}$ Versus-ε	P Versus-ε on log-log scale
$P_{3\cdot5}\,\frac{20}{16}$	5.06	4.66	4.50	3.37	6.59	11.25	11.09	11.65	9.96	14.2	15.0
$P_{3\cdot5}\,\frac{20}{12}$	2.84	2.62	2.53	1.90	11.09	13.71	13.62	13.93	12.99	13.3	13.0
$P_{3\cdot5}\,\frac{20}{8}$	1.26	1.16	1.12	0.76	13.76	14.92	14.88	15.02	14.52	10.7	11.0
$P_{3\cdot5}\,\frac{18}{18}$	6.40	5.90	5.70	4.27	2.16	8.06	7.86	8.56	6.43	5.0	6.0
$P_{3\cdot5}\,\frac{16}{16}$	5.06	4.66	4.50	3.38	1.92	6.58	6.42	6.98	5.30	3.0	4.0

in which

P_u = ultimate bearing capacity

N_q = dimensionless bearing capactiy factor for tip resistance

A_b = bearing area of pile tip

q_d and q_D = effective over burden pressure at depths d and D respectively

w = taper angle

δ = friction angle on the surface of sliding

$K\delta$ = dimensionless factor which represents the ratio of effective normal and shear stresses at any point on the pile surface

S = minimum perimeter encompassing the pile

$\triangle d$ = depth of pile element

For pile without taper, the Equation 1 can be written as the well known formula

$$P_u = N_q A_b q_D + \sum_{d=o}^{d=D} K q_D \tan(\delta) S\triangle d \ldots(2)$$

in which

K = ratio of effective horizontal stress to effective overburden stress

Theoretical estimates of pile capacities using above equations are presented in Table 1. A comparison with actual pile capacities will reveal that (*a*) the observed pile capacities decrease with increasing taper angle contrary to theoretical predictions, (*b*) the observed capacity of average diameter uniform piles are lower than those calculated and (*c*) tapered piles yield higher capacities than corresponing average diameter uniform piles. The first two observations deserve disussion. The third observation confirms the findings of Peck (1958), Trofimenkov *et al* (1973) etc.

Discussion

The theoretically predicted and the observed pile capacities corresponding to different taper angles are presented in Figure 5. Respective shaft friction components are also shown. The observed trend is clearly reverse of what was theoretically predicted. In order to examine the reasons for the difference, N_q and $K\delta$ sin (δ) values were computed by back analysis using the observed pile capacities and pile geometries. The results are presented in Figure 6 and Figure 7 respectively. Two observations are : (*a*) Actual N_q value operative seem to be much lower than that recommended by Berezantsev (1961), Vesic (1963) Terzaghi (1943) and Nordlund (1963). (*b*) $K\delta$ *sin*δ values do not increase sharply with taper angle as one would conclude from the recommendations by Nordlund.

Ultimate pile capacity is sum total of ultimate point bearing and ultimate shaft friction. Keeping pile length and its top dimensions unaltered, if the taper angle is increased, point bearing must decrease. If the ultimate pile capacity was to increase with increasing taper angle, it would mean that the rate of decrease of point bearing

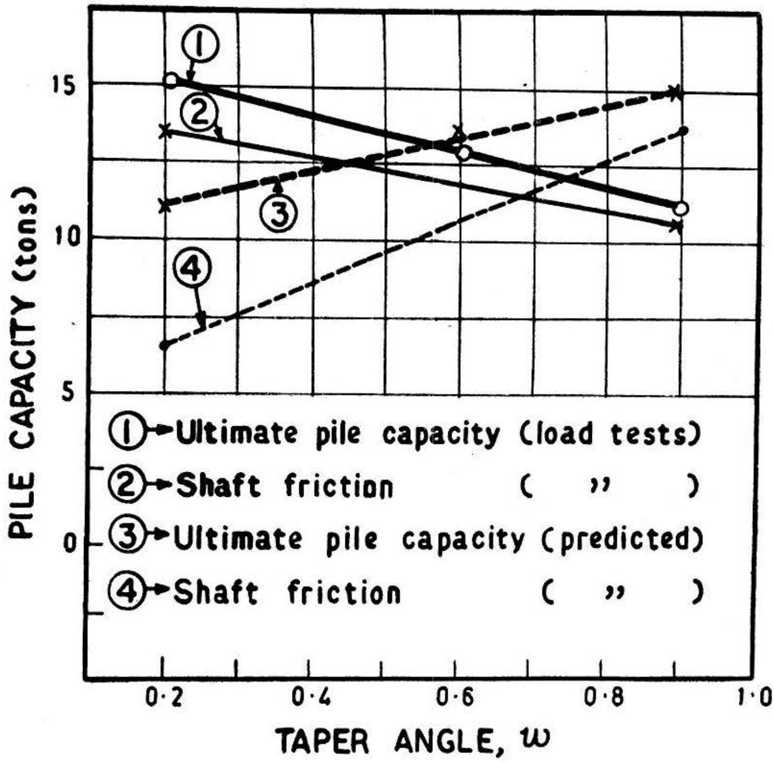

FIGURE 5 Predicted and observed ultimate pile capacities *versus* taper angle

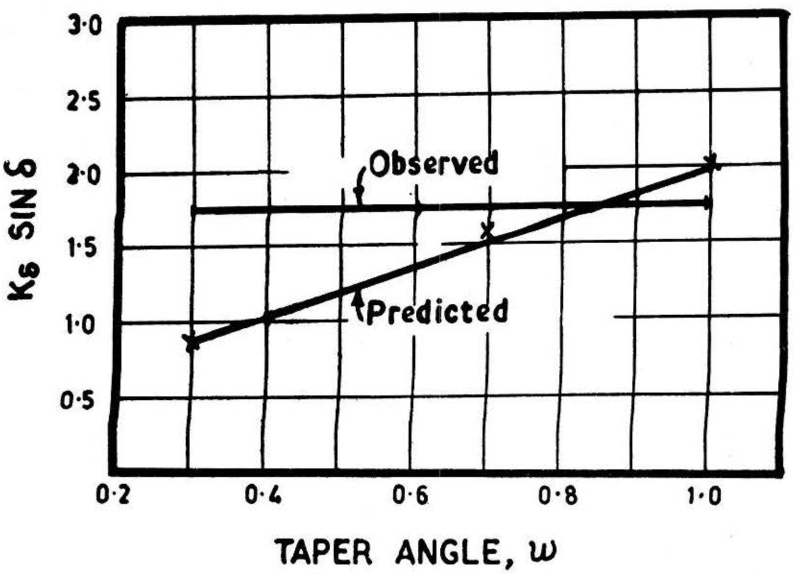

FIGURE 6 Relationship between bearing capacity factor *w* and K_δ *sin* δ

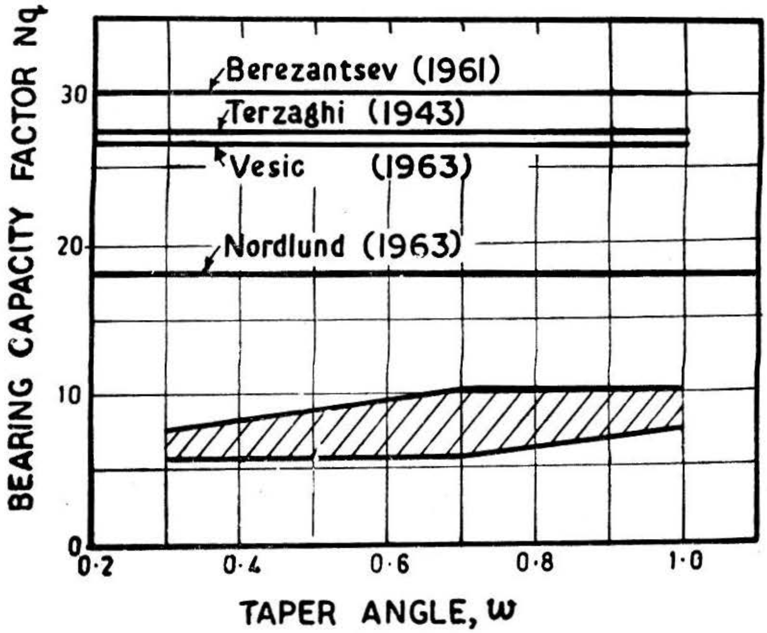

FIGURE 6 Relationship between bearing capacity fector N_q and taper angle, w

with increase of taper angle should lag behind the rate of increase of shaft friction. In the field study reported, shaft friction of tapered piles did not increase at the theoretically predicted rate. Also, the point bearing was found to be lower than theoretical values due of (*a*) reduced tip area with increasing taper angle (*b*) lower actual N_q values than those recommended in the literature. The combined effect therefor explains the observed trend of decreasing pile capacities with increasing taper angle. The N_q and $K \tan(\delta)$ values obtained by substituting results of uniform diametes piles in Equation 2 are respectively 20.7 and 0.074. The recommended N_q values for uniform diameter piles, therefore seem to be in agreement with those computed from load test results. The lower observed capacities of uniform diameter piles may therefore be attributed to relatively lower values of $K \tan(\delta)$

Conclusion

The choice of bearing capacity factor N_q and dimensionless factor $K\delta$ in calculating ultimate bearing capacity of tapered piles deserve reconsideration in view of the findings reported. The findings open up a question if the N_q values for tapered piles also depend on the taper angle ?

Acknowledgement

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