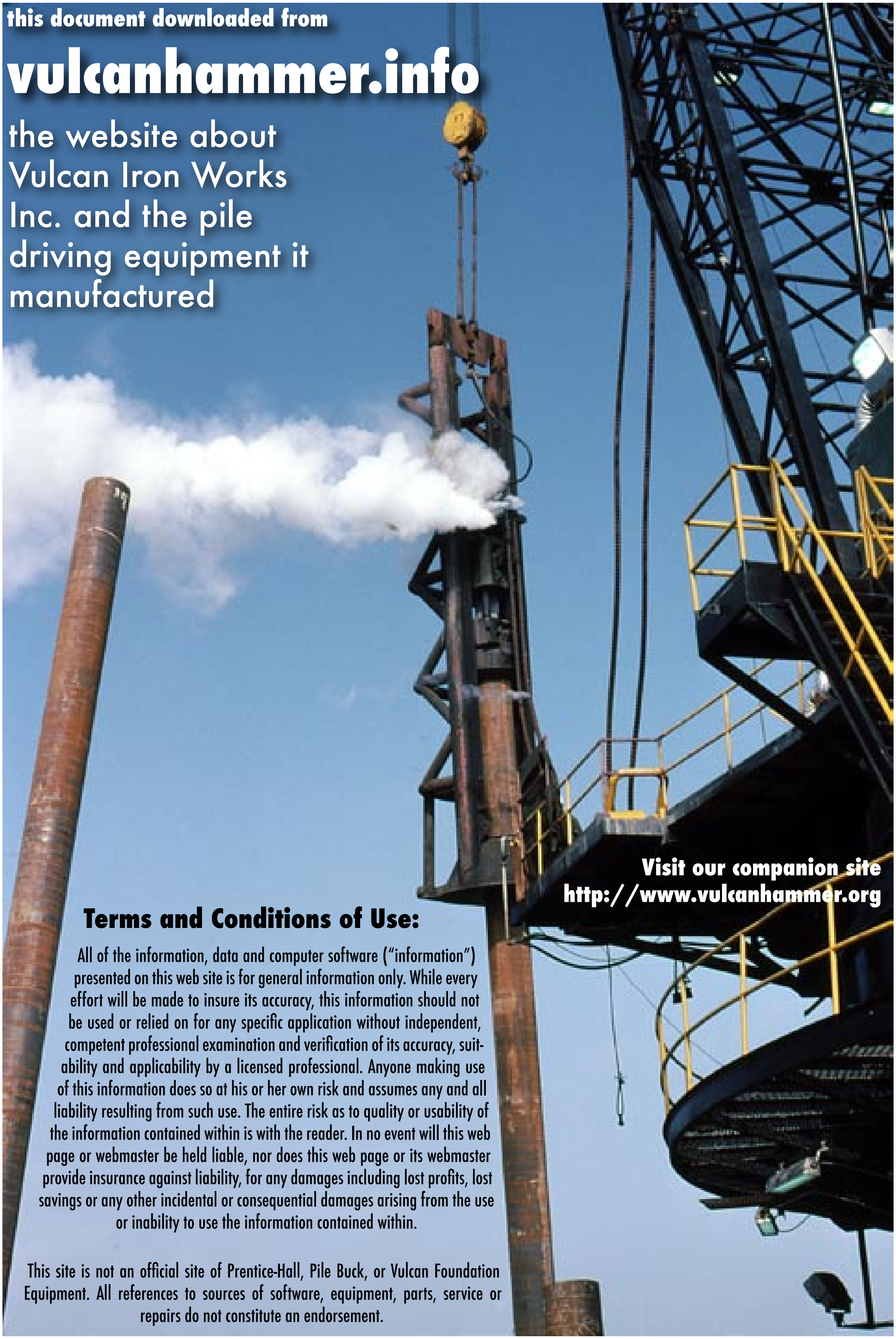

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UWEX-Madison, Wisconsin, Oct. 8-8, 1980

The Bearing Capacity of Rigid Piles Under Inclined Loads in Sand. II: Batter Piles

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Received June 28, 1972

Accepted September 12, 1972

Following the previous investigation reported in the first part on vertical piles, this second part of the paper presents an analysis of the results of loading tests on rigid batter piles under inclined load in sand. The bearing capacity of axially loaded batter piles is discussed by comparing experimental results and theoretical estimates. The theory for ultimate resistance of rigid vertical piles under horizontal loads is extended to that of laterally loaded batter piles. Model test results are compared with those of theoretical estimates and good agreement is found. Methods of analysis of vertical piles under inclined loads are extended to those of rigid batter piles under inclined loads in sand and the analysis is compared with some test results.

En suite de l'investigation antérieure présentée dans la première partie sur des pieux verticales cette deuxième partie de l'article donne l'analyse des résultats des essais sur des pieux rigides inclinés soumis aux charges inclinées dans le sable. La force portante observée pour des pieux inclinés soumis aux charges axiales est comparée avec les estimations théoriques. La théorie de la résistance limite des pieux rigides verticales soumis aux charges horizontales est étendue à la résistance latérale des pieux inclinés. Les résultats des essais en modèles sont comparés avec les estimations théoriques et ils sont raisonablement d'accord. Les méthodes d'analyses des pieux verticales soumis aux charges inclinées sont étendues aux pieux rigides inclinés et l'analyse est comparée avec les résultats des essais dans le sable.

Introduction

As shown in the first part of the paper (Meyerhof and Ranjan 1972) vertical piles have only a relatively small resistance against lateral loads. Batter piles are usually employed when the lateral load exceeds the allowable limit for vertical piles (Peck *et al.* 1953; McNulty 1956). Single batter piles under horizontal loads have been studied (Tschebotarioff 1953; Murthy 1964). However no attempts seem to have been made in the past to study batter piles under inclined loads. Though it is rare that batter piles are driven singly, because they are usually employed in groups with vertical piles, it is of interest to study a single batter pile under inclined load to gain a better understanding of group behavior.

Batter Piles Under Axial Load

Figure 1 shows alternative theoretical failure zones below an axially loaded inclined deep strip foundation. The failure zones in Fig. 1(*a*) are similar to those of an axially loaded vertical strip foundation with a vertical free surface. Substituting the proper values for the smooth shaft, the angle of the radial shear zone is:

[1] $$\theta = 180° - \alpha$$

Using a similar approach as for the free standing vertical strip, the bearing capacity factors, N'_q, can be obtained. This approach shows that N'_q values decrease with increasing batter angle β to that of the bearing capacity factor for a surface footing at $\beta = 90°$. This seems to be a very conservative approach.

For small batter angles of deep foundations when the slip surfaces do not reach the ground surface, the failure zones below an axially loaded strip foundation can be assumed to be as shown in Fig. 1(*b*). This suggests that θ remains constant and that the bearing ca-

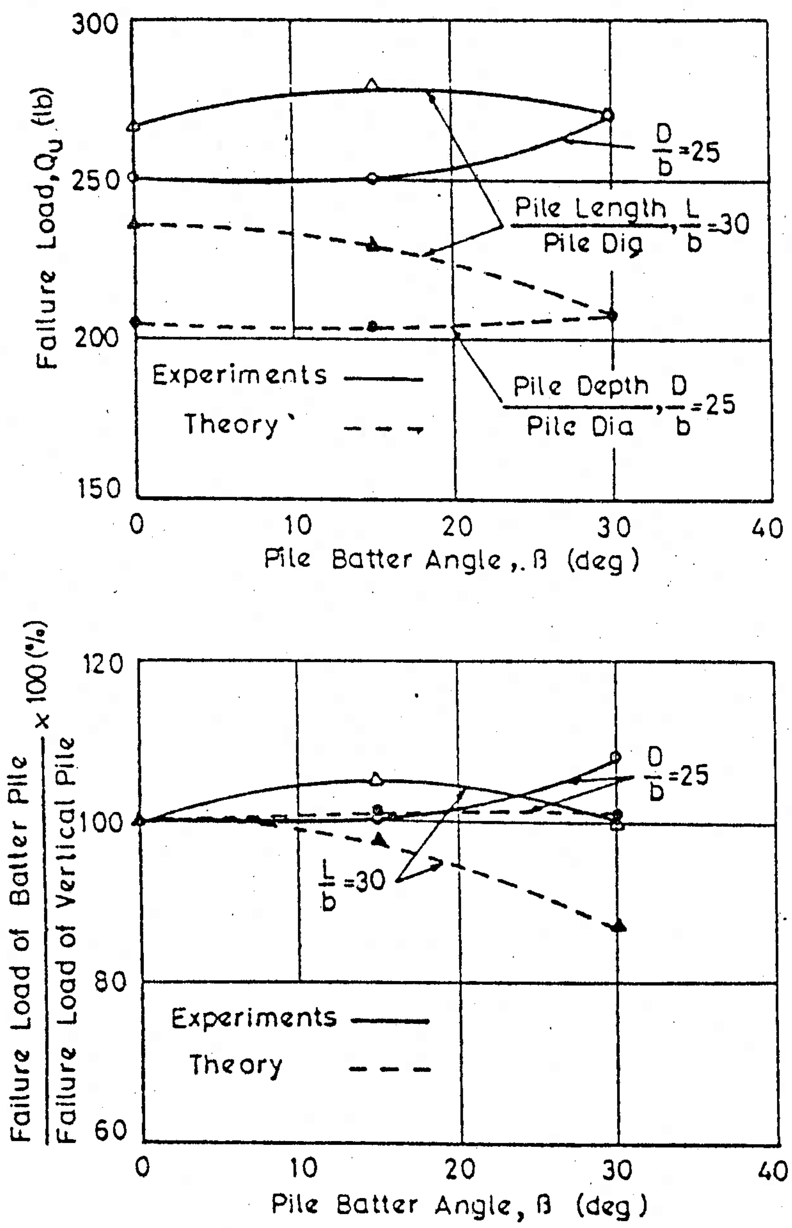

FIG. 2. Axially loaded batter piles in dense sand.

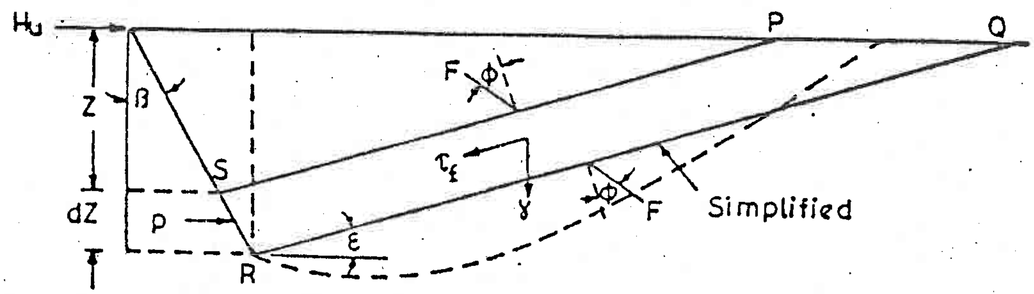

Fig. 4. Earth wedge in positive batter pile analysis.

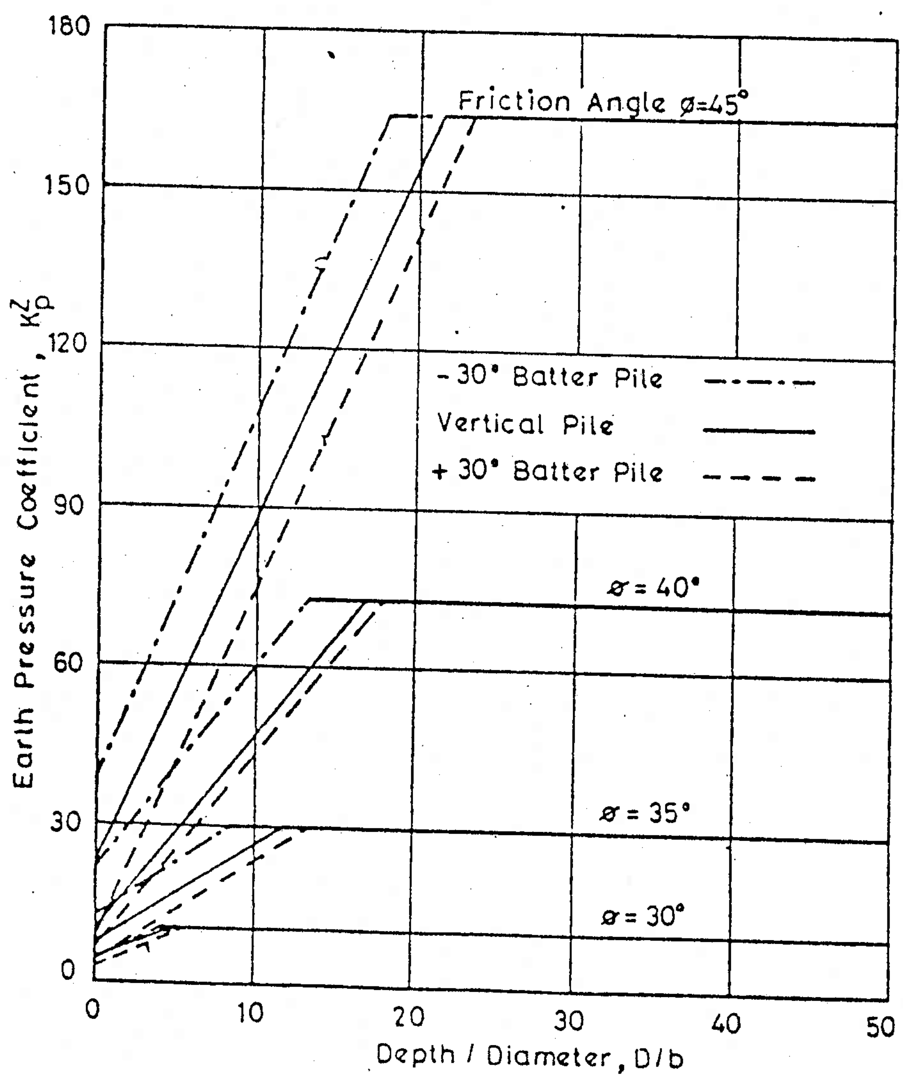

Fig. 5. Earth pressure coefficients for 30° rough batter piles.

TABLE 1. Comparison of theoretical and experimental ultimate horizontal loads for 30° batter piles

Test number	Depth/Diameter (D/b)	Batter angle (β) (degrees)	Exp. ult. hor. load H_{ue} (lb)	Theo. ult. load H_{ut} (lb)	Deduced friction angle (Φ_d) (degrees)	Ratio Φ_e/Φ_d
Compact sand (triaxial friction angle, Φ_e = 40.0°)						
A-7	15	−30	13.5	13.0	40.2	1.00
B-33	25	−30	49.0	44.0	40.6	0.99
A-23	15	+30	8.0	8.3	39.6	1.01
B-69	25	+30	32.5	38.8	39.0	1.03
Dense sand (triaxial friction angle, Φ_e = 46.0°)						
D-85	15	−30	35.0	28.1	47.7	0.96
E-111	25	−30	130.0	105.0	47.7	0.96
D-102	15	+30	15.0	17.3	44.6	1.03
E-147	25	+30	75.0	86.5	44.8	1.02

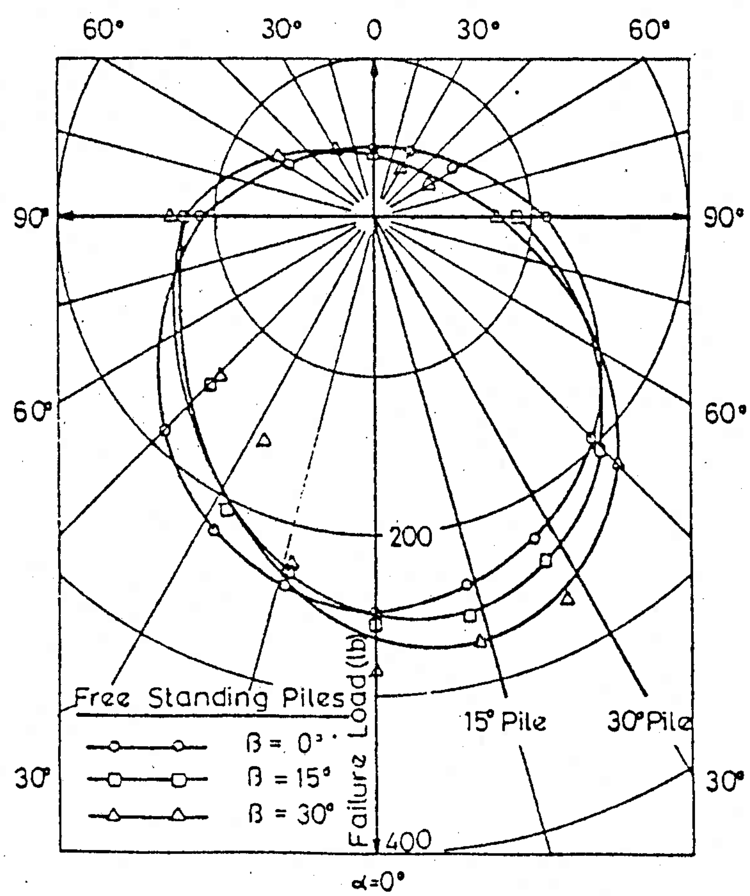

FIG. 7. Polar bearing capacity diagram for free standing vertical and batter piles (D/b = 25) in dense sand.

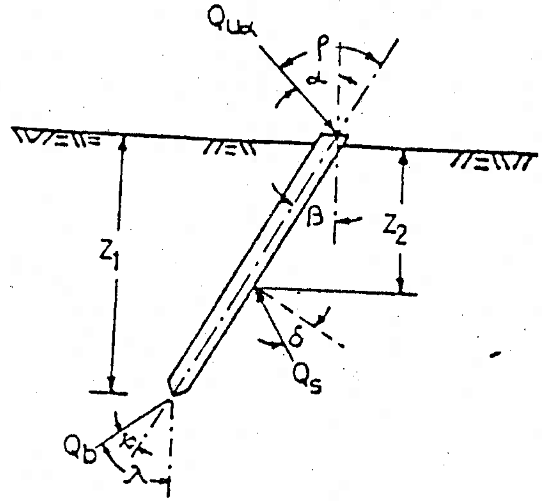

FIG. 9. Free standing (negative) batter pile under inclined load.

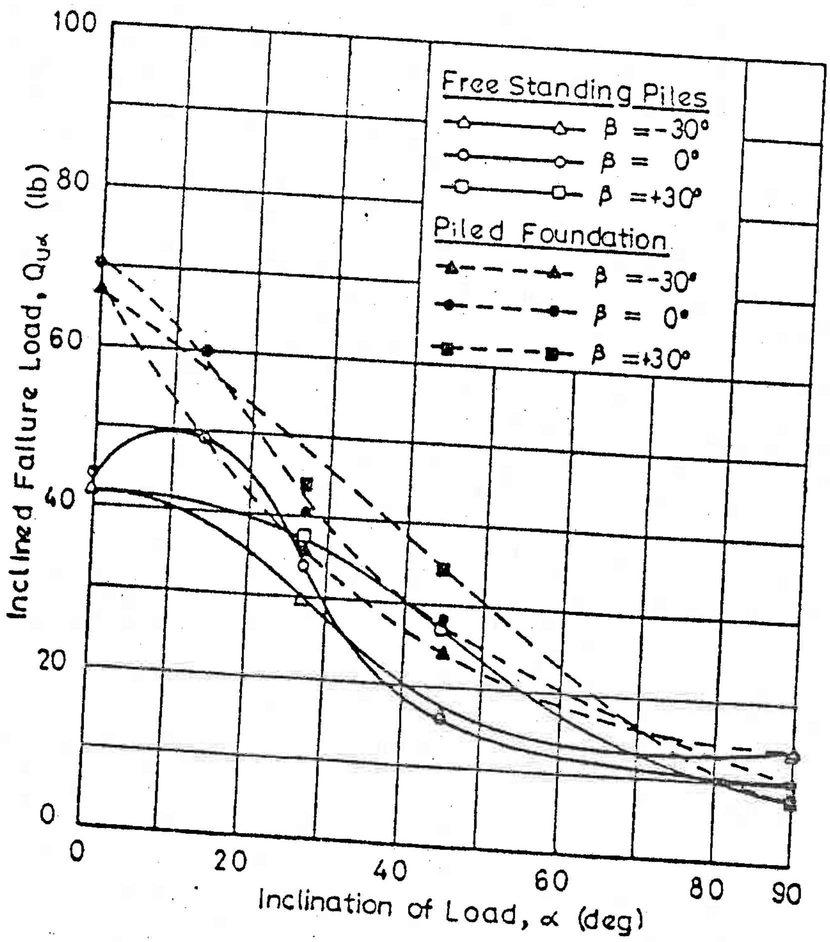

FIG. 10. Inclination of load *vs.* resultant failure load for vertical and batter piles (D/b = 15) in compact sand. A-series.

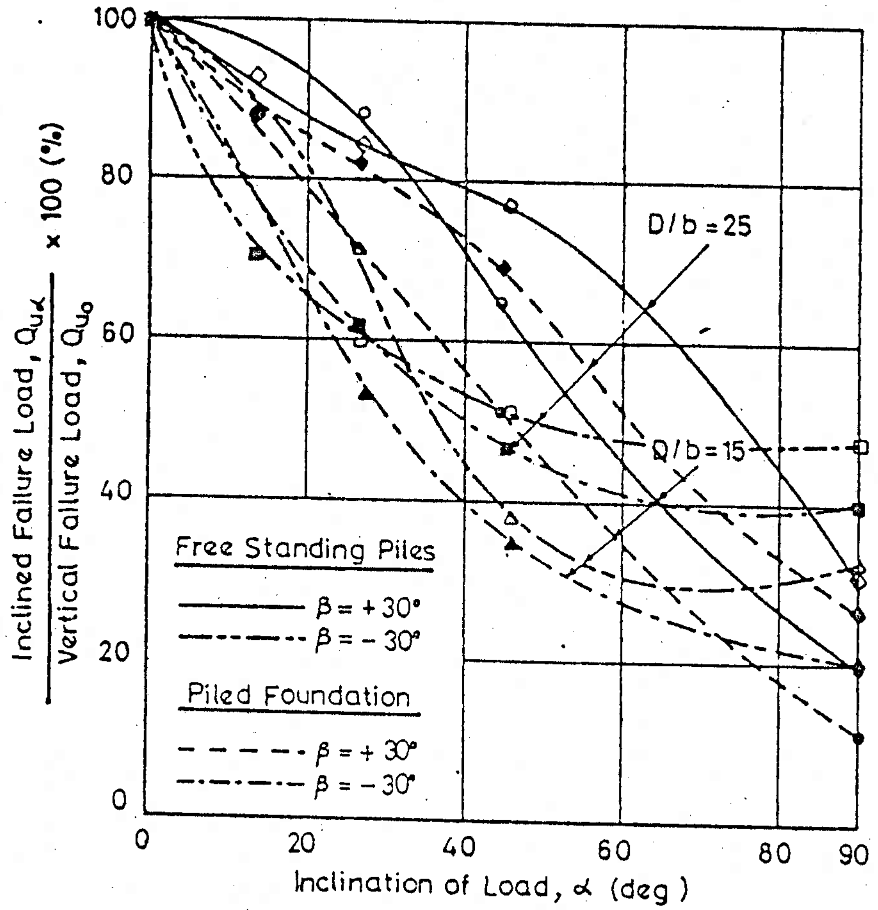

FIG. 13. Inclination of load *vs.* ratio of resultant failure load to vertical failure load for batter piles in compact sand. A- and B-series.

deposit of cohesionless material. The pile is subjected to a central foundation load, $Q_{u\alpha}$, inclined at an angle α to the vertical (or at an angle ρ to the pile axis such that $\rho = \alpha \pm \beta$ depending upon the negative or positive pile batter). The load $Q_{u\alpha}$ is transmitted through a base load Q_b inclined at an angle λ to the vertical (or at an angle $\kappa = \lambda \mp \beta$ to the pile axis) and a shaft load, Q_s inclined at an angle δ to the normal of the pile. Considering the conditions of static equilibrium, Eqs. [5*a*, *b*, *c*] are obtained.

For $\Sigma H = 0$,

[5*a*]
$$Q_{u\alpha} \sin\alpha - Q_s \cos(\beta + \delta) + Q_b \sin\lambda = 0$$

For $\Sigma V = 0$,

[5*b*]
$$Q_{u\alpha} \cos\alpha - Q_s \sin(\beta + \delta) - Q_b \cos\lambda = 0$$

For $\Sigma M = 0$,

[5*c*]
$$Q_b \sin\lambda\, Z_1 = Q_b \cos\lambda\, Z_1 \tan\beta + Q_s \cos(\beta + \delta) Z_2 + Q_s \sin(\beta + \delta) Z_2 \tan\beta$$

Considering the proper directions of the earth pressure, similar types of equations could be obtained for positive batter piles.

Analysis of Results

Typical experimental results for loading tests on batter piles under inclined loads are

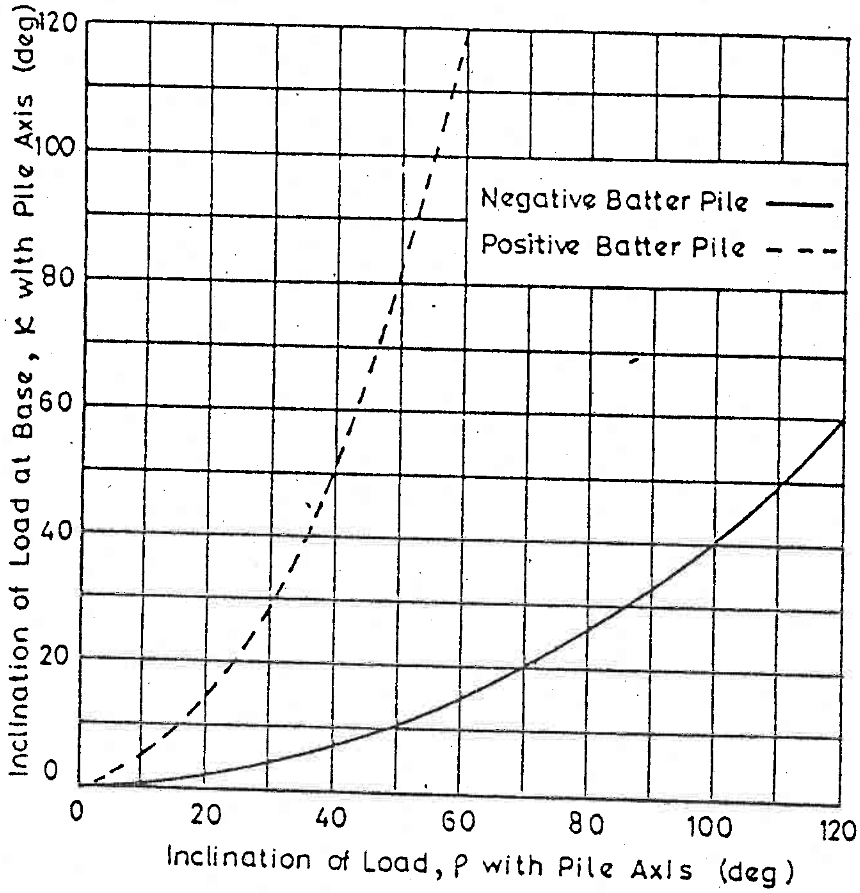

FIG. 15. Inclination of load at pile top vs. inclination of load at base for 30° batter piles.

from the pile axis, the axial base load, Q_{ba} is calculated from Eq. [12] (Meyerhof and Ranjan 1972) by substituting $Q_{ba} = Q_{b\alpha}$. In Eq. [12] the N_q' values are taken from Fig. 12 (Meyerhof and Ranjan 1972) for a certain value of base load, given κ and a known value of angle of internal friction Φ such that for an axially loaded pile ($\rho = 0°$) with $\kappa = 0°$ the base capacity is the same. The axial base load is then resolved into the horizontal and vertical components.

Knowing the experimental failure load $Q_{u\alpha}$ and the corresponding base load obtained as above, the horizontal load on the shaft is calculated from Eq. [5*a*]. Assuming full passive pressure mobilization under horizontal load ($\alpha = 90°$), the passive pressure mobilization factor, *m*, under different inclinations of load is obtained and plotted in Fig. 16.

For depth/diameter ratios of 15 and 25 the *m* values obtained for positive batter piles and moderate load inclinations are relatively higher than those corresponding to negative batter piles. The possible reason for this could be the difference between theoretical and experimental failure loads under full mobilization of passive pressure. However, it is of interest to note that *m* values for depth/diameter ratios of 15 and 25 for 30° negative batter piles are practically of the same order as the corresponding *m* values for vertical piles.

In the case of both negative and positive batter piles Fig. 16 indicates that for greater

However, at larger inclinations of load with the vertical, the trend changes and under horizontal load negative batter piles have greater ultimate loads than corresponding positive batter piles.

For small pile batter angles the behavior of free standing batter piles under inclined loads appears to be qualitatively similar to that of the free standing vertical piles. The batter piles under inclined loads can be analyzed in a manner similar to that of vertical piles under inclined loads by using the inclination of the load with respect to the pile axis in the two cases.

Acknowledgments

One author (Gopal Ranjan) acknowledges the Commonwealth Scholarship awarded by the Canadian Commonwealth Scholarship and Fellowship Administration. The tests were carried out with the financial assistance of the National Research Council of Canada.

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