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BATTER PILES UNDER INCLINED COMPRESSIVE LOADS

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ABSTRACT

The behaviour of batter piles under inclined compressive loads is of considerable importance, yet, not enough information is available in literature on the subject. The tests carried out in this paper were performed on a single inclined pile under various load inclinations in sand. The results indicate that the highest ultimate compressive load for vertical pile occurs at (30°) load inclination. At small load inclinations, a positive batter pile has greater ultimate compressive load than that of a negative batter pile. The trend changes at higher load inclinations. The slip surface analysis is recognised to be too complicated to have a definite solution.

الخلاصة

يعتبر سلوك الركائز المائلة المعرضة لأحمال انضغاط مائلة موضوعا ذا أهمية كبيرة، و لهذا الوقت لا تتوفر معلومات كافية في الأدبيات حول الموضوع. في هذا البحث أجري عدد من الفحوص على ركيزة منفردة مائلة و معرضة الى أحمال مائلة بزوايا مختلفة في الرمل. و قد بينت النتائج أن أقصى حمل انضغاط على الركيزة الشاقولية يحدث عندما تكون زاوية الحمل (30°). و تحت تأثير زوايا ميل قليلة للحمل، تظهر الركائز المائلة الموجبة مقاومة انضغاط قصوى أعلى من الركائز المائلة السالبة. و هذا السلوك يتغير عندما تكون زوايا الميل للحمل عالية. و قد تبين أن سطح الأنزلاق المتولد معقد كثيرا و لا يمكن إيجاد حل محدد له.

KEY WORD

Pile, Batter, Inclined loading, Compression

INTRODUCTION

In addition to vertical loads, structures are often subjected to horizontal forces, which result in inclined loading on the foundations. Since the resistance against horizontal displacement offered by vertical piles is small, batter or inclined piles are usually employed when the lateral forces exceed the allowable limit (Peck et al., 1974).

If the horizontal loads imported to the pile foundation are large, a foundation consisting solely of vertical piles may not possess sufficient lateral resistance. In such circumstances, battered (inclined) piles are installed to permit the horizontal foundation load to be supported by a component of the axial pile-soil resistance in addition to the lateral resistance, (Mosher and Dawkins, 2000).

A review of literature on single piles showed that a number of experimental works have been carried out for single vertical piles under inclined loads, (Petrasovit and Awad, 1968, Meyerhof and Ranjan, 1972a, Meyerhof, 1981, Meyerhof et al., 1981, Meyerhof et al., 1983and Chari and Meyerhof, 1983). Meanwhile, only limited attempts have been made in the literature to study the behaviour of single batter piles under inclined loads (Petrasovit and Awad 1968, Ranjan, 1970 and Meyerhof and Ranjan, 1972b). The present investigation is based primarily on model tests on rigid piles and attention has been paid to the evaluation of the ultimate compressive loads. The investigation deals with the behaviour of single batter piles.

TEST APPARATUS

The apparatus layout is shown in **Fig. (1).** The model piles used were made of steel. The pile used consists mainly of two parts: The first main part is the 30 cm one which is made rough by sandpaper glued on its surface. The second is the upper portable part screwed in the first main part and hollowed at a distance 3 cm above the surface for load application. A rotary shaft was screwed in the upper portable part to give the inclination of pile using two nuts tightened around the upper portable part.

The sand bed was prepared by pouring dry sand from a fixed height to give a unit weight of 17.2 kN/m^3. The sand of specific gravity 2.65 has minimum and maximum relative densities of 66 % and 78 %, respectively, and is of medium gradation with a particle size distribution shown in **Fig. (2).** The angle of shearing resistance is 38°. More details about the experimental work are given by (Kashat, 1990).

TESTING PROGRAM

The testing program consisted of the following tests:

1- Seven compressive tests were conducted on a vertical pile with varying load inclinations from vertical ($\alpha = 0^o$) to horizontal ($\alpha = 90^o$) in increments of (15^o) as shown in **Fig. (3-a).**

2- Fourteen compressive tests were conducted on a positive batter pile with varying load inclinations from vertical ($\alpha = 0^o$) to horizontal ($\alpha = 90^o$) in increments of (15^o) and varrying batter angles β from (15^o) to (30^o) as shown in **Fig. (3b).**

3- Fourteen compressive tests were conducted on negative batter piles with varying load inclinations from vertical ($\alpha = 0^o$) to horizontal ($\alpha = 90^o$) in increments of (15^o) and varying batter angles β from (-15^o to -30^o) as shown in **Fig. (3c).**

Semi-spacial tests are carried out on a batter pile (positive batter and negative batter, see **Fig. (3)** under various load inclinations to investigate the slip surface layout around some selected tests using photographs.

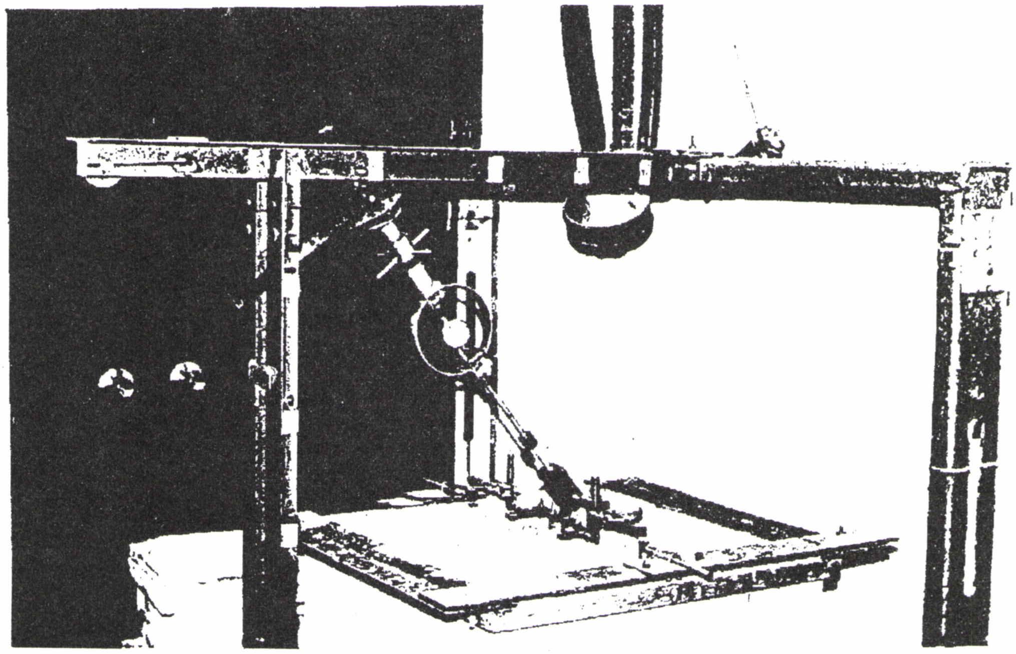


Fig. (1) Testing apparatus.

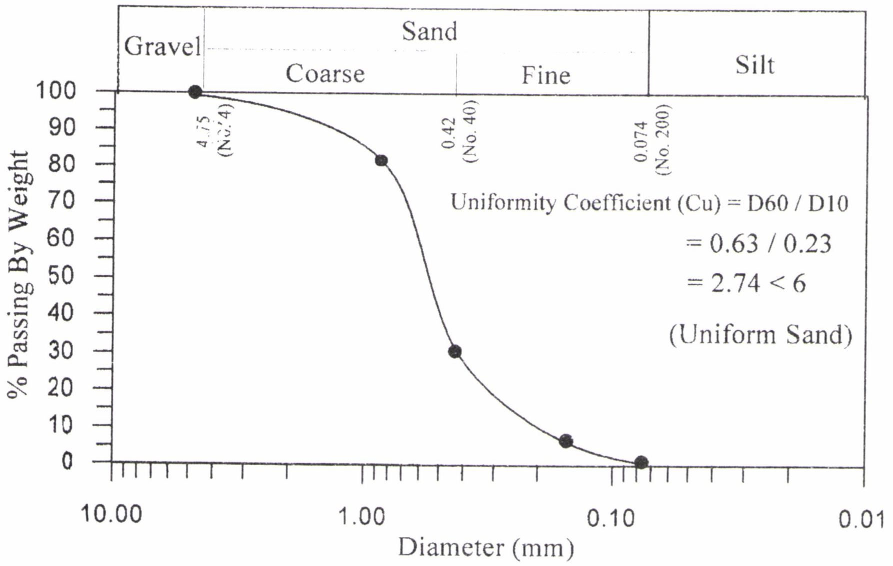


Fig. (2) Particle size distribution for the sand tested.

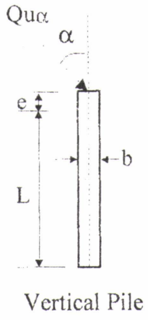
RESULTS AND DISCUSSION

The Failure Surface

The following results are obtained from the photographs taken to study the shape of the failure surface for single (vertical and batter) piles subjected to inclined compressive loads.

e/L = 0.1

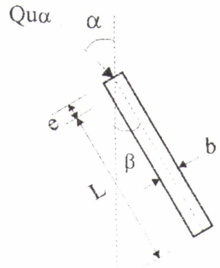
e = 3 cm
L = 30 cm
b = 1.5 cm
α= (0, 15, 30, 45, 60, 75, 90) deg.
γ = 17.2 kN/m^3



(a) - Single vertical pile undere compressive load.

e/L = 0.1

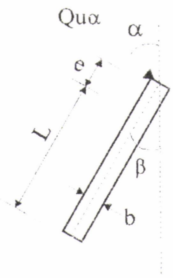
e = 3 cm
L = 30 cm
b = 1.5 cm
α= (0, 15, 30, 45, 60, 75, 90) deg.
β = (+15,+30) deg.
γ = 17.2 kN/m^3



(b) - Positive batter pile undere compressive load.

e/L = 0.1

e = 3 cm
L = 30 cm
b = 1.5 cm
α= (0, 15, 30, 45, 60, 75, 90) deg.
β = (-15,-30) deg.
γ = 17.2 kN/m^3



(c) - Negative batter pile undere compressive load.

Fig. (3) Single pile testing program under compressive load.

Plate (1) shows the observed failure surface for a single vertical pile under compressive load with depth of embedment (L = 30 cm) and under a load inclination α of (30^o) with the vertical (e/L = 0.3).

When the compressive load is increased, the sand layers nearby the pile shaft at the opposite side of the compressive load begin to move downwards. No movements of sand are observed at the side of loading and at the pile base. At higher loads, the sand layers at the side of load at a depth equals to (3/4) of the embeded depth of the pile are noticed to have clear movements downwards and with continuous movements of the sand layers at the opposite side.

Plate (2) shows the observed failure surface for (15^o) negative batter pile with length of embedment equals to (30 cm) and under (30^o) load inclination (e/L = 0.3).

When the compressive load is increased, the sand on the opposite side of loading begins to move at a rate higher than that of vertical piles. Also no movements of sand are observed at the side of loading as that happened in the vertical pile. At higher loading, the sand at the side of the load at a depth equals to (3/4) of the embeded depth of the pile begins to move upward. No movements are observed at the pile base during the stages of loading.

For a positive batter pile, under the same conditions as the negative batter pile above, the sand at either sides of the load begins to move downward. The rate of movement is higher at the opposite side than for the same side of load during all the stages of loading along the pile length. A cavity that nearly equals (1) to (2) times the pile diameter is formed below the pile base.

Single Pile Under Compressive Load

Definitions

A – Ultimate inclined compressive load $Q_{u\alpha}$:

According to Petrasovit and Awad (1968), the ultimate compressive load is the force pertaining to a vertical or horizontal displacement equals to pile diameter which of the two displacements first attained this arbitrary magnitude.

B – Normalized load ($Q_{u\alpha} / Q_{uo}$):

It is the ratio of the ultimate compressive load at any angle α to the ultimate compressive load at vertical angle ($\alpha = 0^o$).

C – Normalized load (Q_{uob} / Q_{uov}):

It is the ratio of the ultimate vertical compressive load of batter pile to the ultimate compressive load of vertical pile.

D – Normalized load (H_{ub} / H_{uv}):

It is the ratio of the ultimate horizontal compressive load of the batter pile to the ultimate horizontal compressive load of the vertical pile.

Settlement at Failure

Continuous records of vertical and horizontal displacements wee taken during the tests. The load – displacement curves are shown in **Figs (4) to (8).** The tests indicate that at small inclinations of load ($0 < \alpha < 30^o$), the vertical displacement governs the ultimate compressive load for both vertical and batter piles. It is found that for a positive batter pile, the governing vertical displacement exceeds the (30^o) load inclination. The horizontal displacement at these small inclinations of load is small. As the inclination of the load with the vertical increases, the vertical displacement at failure decreases and the horizontal displacement increases, and hence the horizontal displacement begins to take place instead of the vertical one in governing the ultimate compressive load.

The ultimate load is regarded for these reasons:

1 – At a range of displacement of (13 – 16) mm, any addition of small load makes the pile show a big increase in displacement which means that the surrounding soil failed and the ultimate compressive load is reached.

2 – Some of this work is similar to the work done by Petrasovit and Awad (1968). A similar manner to that described above is used in analyzing the results. The method is extended to be used in analyzing the results recorded for batter piles.

Fig. (4) shows clearly the load – displacement curves for a vertical pile and **Figs. (5) to (8)** show the load – displacement curves for batter piles with inclinations ($\pm 15^o$ and $\pm 30^o$).

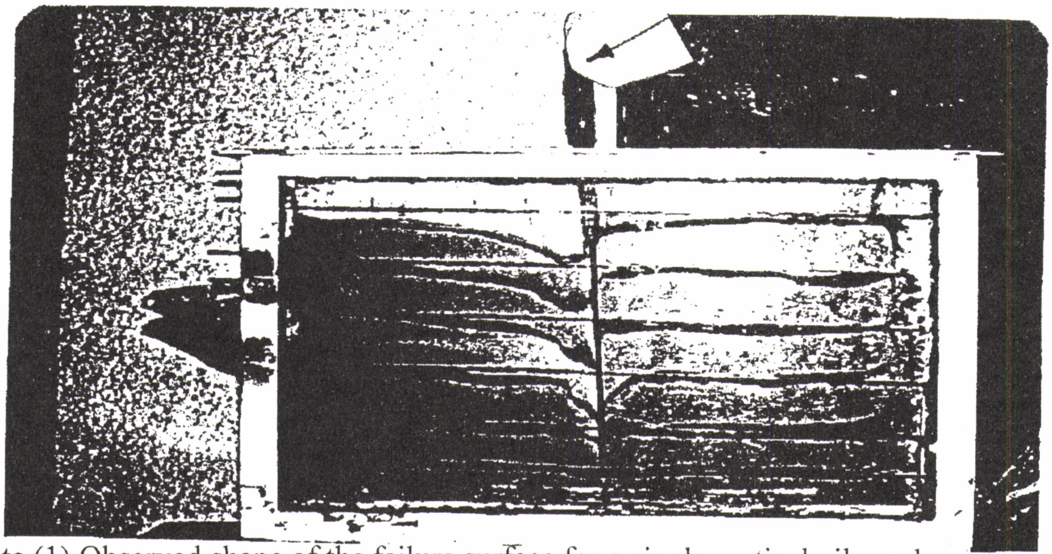


Plate (1) Observed shape of the failure surface for a single vertical pile under compressive load ($\alpha = 30^o$).

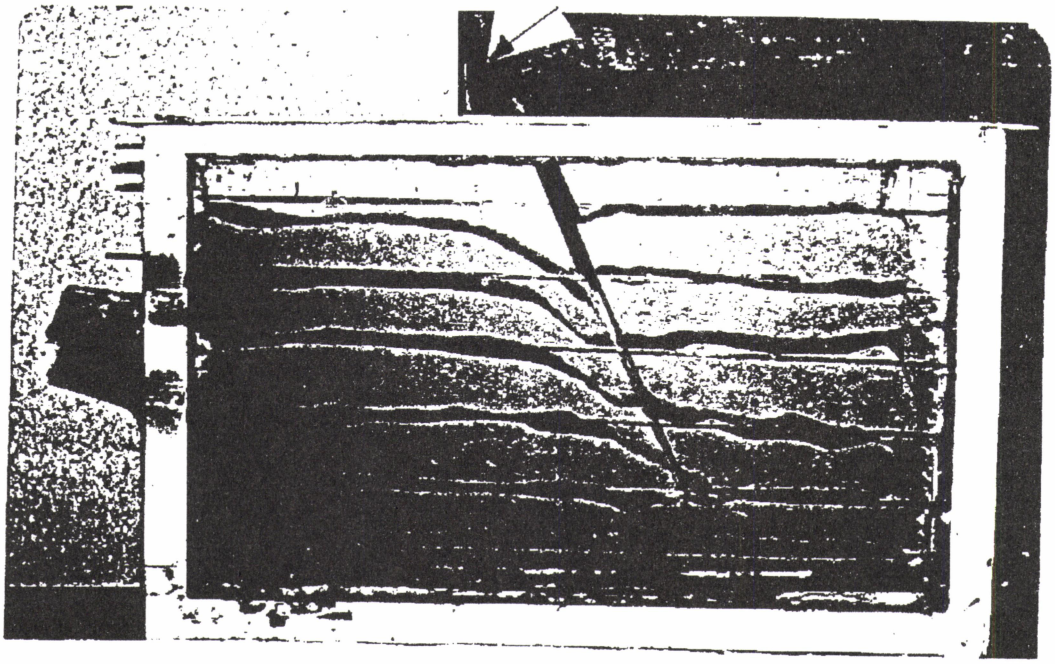


Plate (2) Observed shape of the failure surface for negative batter pile under compressive load ($\alpha = 30^o$) and ($\beta = -15^o$).

Effect of Load Inclination Angle (α)

A – Vertical Pile:

Fig. (9) shows clearly that the highest ultimate compressive load of a vertical pile occurs at (α) equals to (30^o) with the vertical and the ultimate compressive load then decreases with increasing load inclination. The result is similar to the result obtained by Petrasovit and Awad (1968).

Fig. (10) shows clearly that at a load inclination equals (30^o) with vertical, the ultimate compressive load is about (11 %) greater than the ultimate vertical compressive load ($\alpha = 0^o$).

At horizontal load inclination (α = 90°), the ultimate compressive load is about (46 %) smaller than the ultimate vertical compressive load.

The results of tests at various load inclinations are plotted in the form of a polar ultimate compressive load diagram as shown in **Fig. (19).** It is observed that the bearing capacity varies in the form of an ellipse.

B- Batter Piles:

Experimental results of loading tests on batter piles under various load inclinations are shown in **Figs. (11) to (15). Figs. (11) and (12)** indicate that for the batter angles tested (except for the batter angle β of 0° and 15°), the highest ultimate compressive load occurs when the load is vertical and decreses with increasing the load inclination angle α with the vertical. For batter angle β of (15°), the trend is similar to that for vertical piles.

These results are similar to those obtained by Meyerhof and Ranjan (1972a) for the same batter angles with a difference in (0 and 15°) batter angles. This difference is due to the eccentricity of the inclined load applied in this work (e = 3 cm above the sand surface), while the load applied by Meyerhof and Ranjan (1972b) was on the sand surface (e = 0). **Fig. (13)** shows clearly that the ultimate compressive load for a (15°) positive batter pile under a load inclination (α) equals to (30°), is greater by about (22%) than the ultimate vertical compressive load. The difference is (15 %) smaller for the negative batter pile at the same batter angle and load inclination. For a (30°) positive and negative batter piles, the ultimate compressive loads at an inclination angle α equals to (30°) are smaller by about (25 %) and (31 %) than the ultimate vertical compressive load as shown in **Fig. (14).**

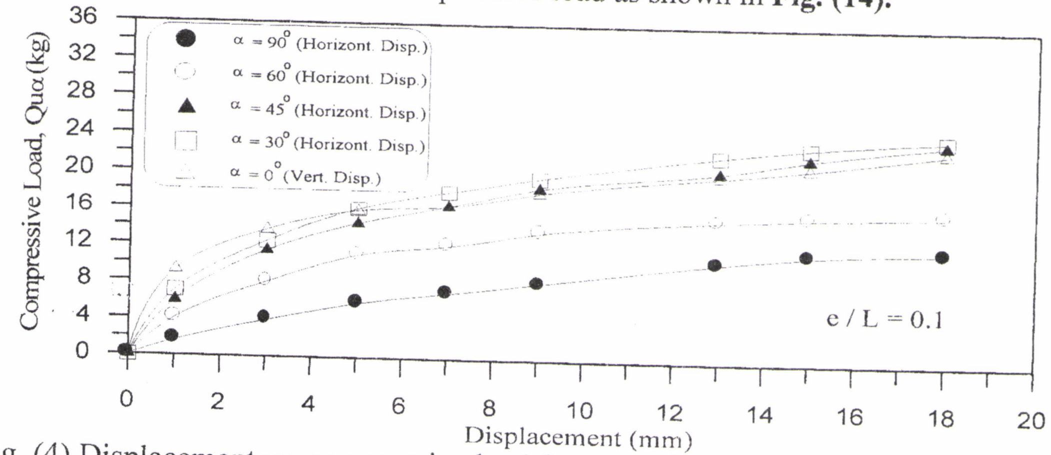


Fig. (4) Displacement vs. compressive load for vertical pile with different load inclinations (L/b = 20).

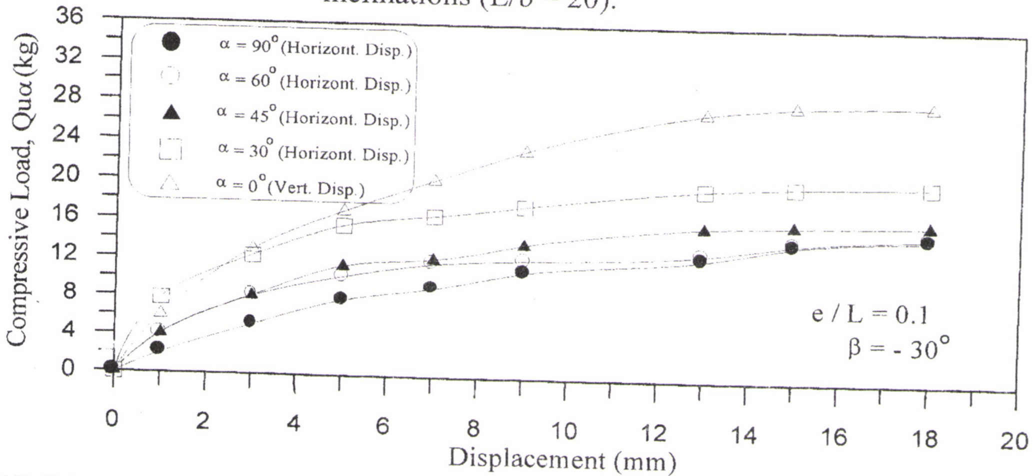


Fig. (5) Displacement vs. compressive load for negative batter pile with different load inclinations (L/b = 20), (β = -30°).

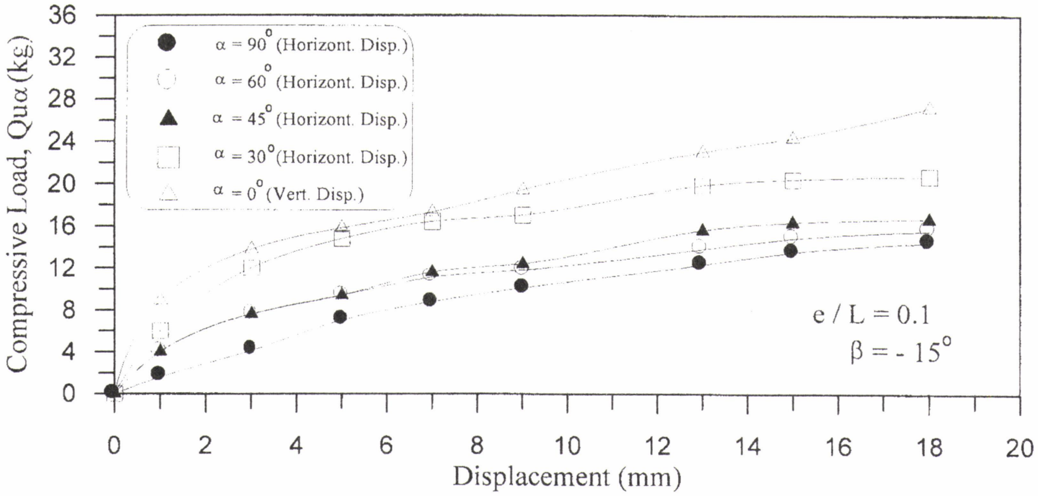


Fig. (6) Displacement vs. compressive load for negative batter pile with different load inclinations (L/b = 20), (β = -15°).

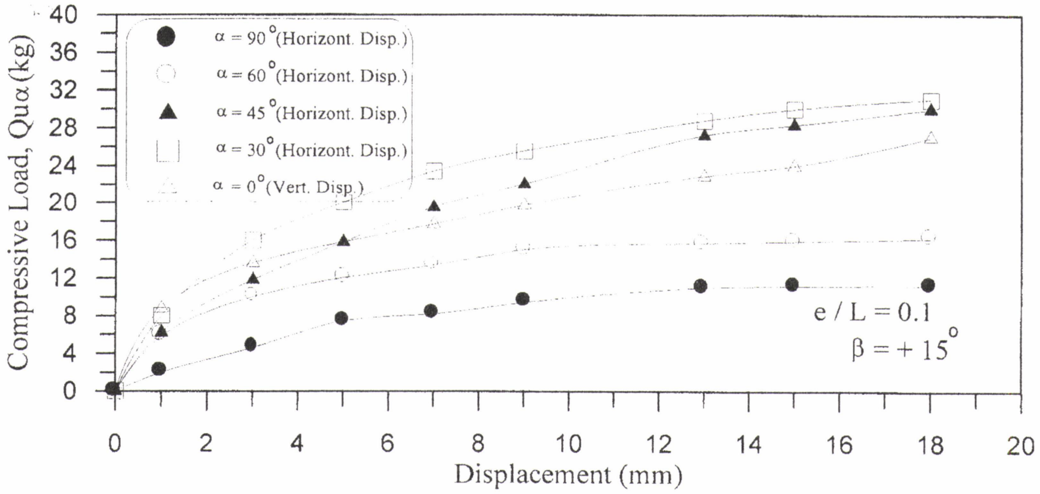


Fig. (7) Displacement vs. compressive load for negative batter pile with different load inclinations (L/b = 20), (β = +15°).

Effect of Pile Inclination Angle (β)

Fig. (15) shows clearly that for smaller inclinations of load with the vertical, a positive batter pile has a higher ultimate compressive load than the corresponding negative batter pile. However, this trend changes at larger inclinations and at α equals to (60°). The negative batter pile takes more load to fail than the corresponding positive batter pile. The results recorded in **Fig. (15)** are similar to those obtained by Meyerhof and Ranjan (1972).

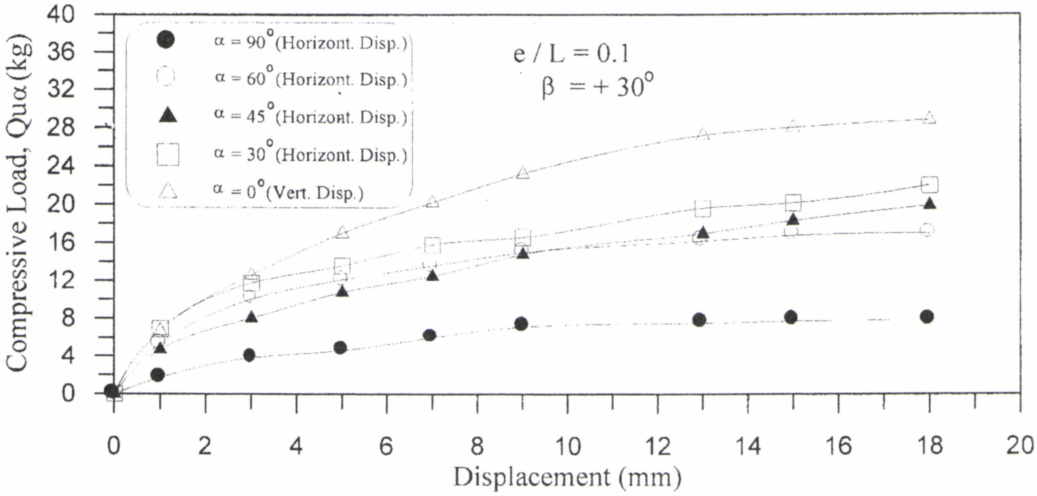


Fig. (8) Displacement vs. compressive load for negative batter pile with different load inclinations (L/b = 20), (β = +30°).

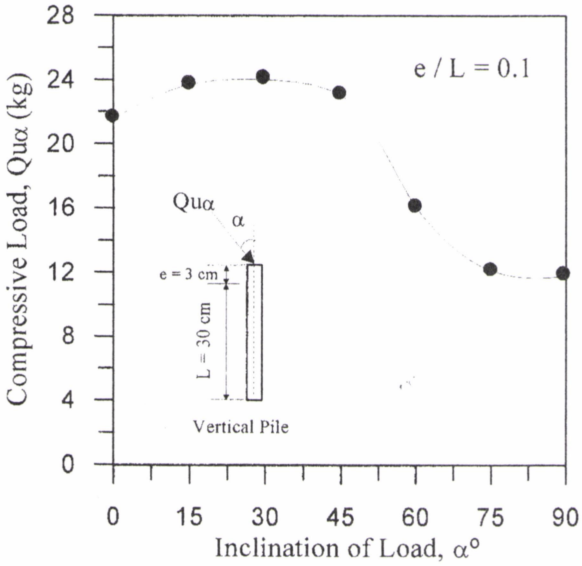


Fig. (9) - Inclination of load vs. inclined compressive load for vertical piles (L/b = 20).

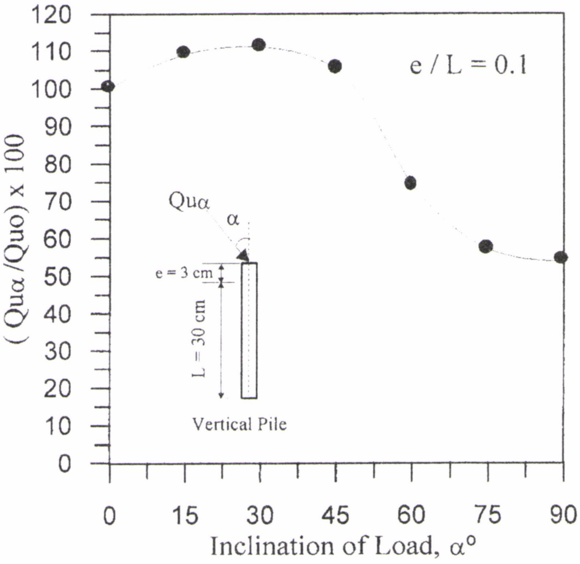


Fig. (10) - Inclination of load vs. ratio of inclined ultimate load to vertical ultimate load for vertical piles (L/b = 20).

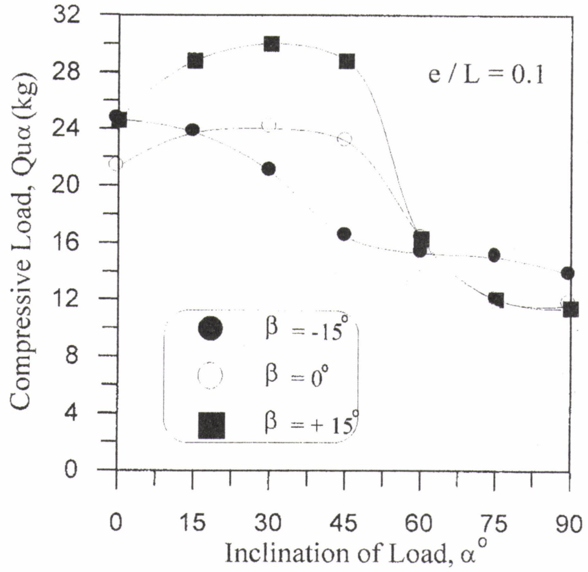


Fig. (11) - Inclination of load vs. inclined compression load for vertical and batter piles (L/b = 20), (β=±15°).

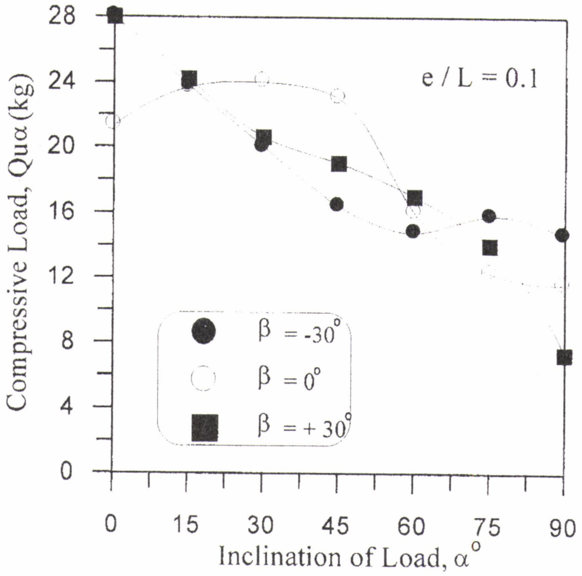


Fig. (12) - Inclination of load vs. inclined compressive load for vertical and batter piles (L/b = 20), (β= ± 30°).

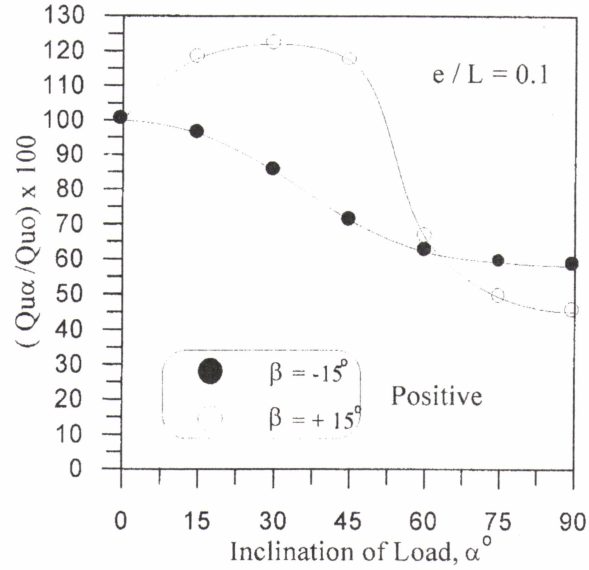


Fig. (13) - Inclination of load vs. ratio of inclined ultimate load to vertical ultimate load for batter piles (L/b = 20), (β= ± 15°).

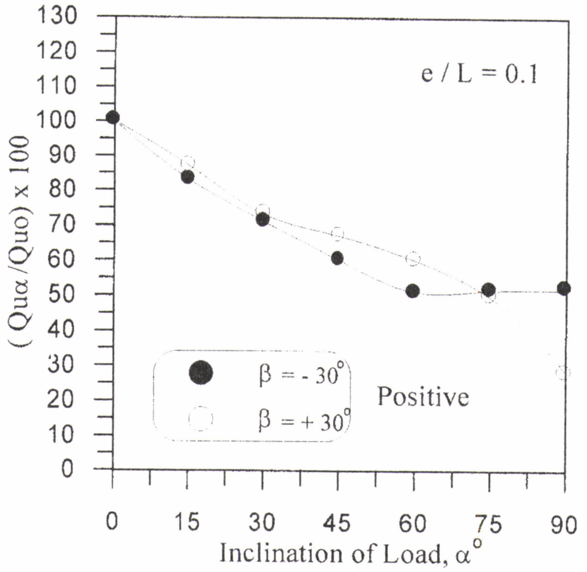


Fig. (14) - Inclination of load vs. ratio of inclined ultimate load to vertical ultimate load for batter piles (L/b = 20), (β= ± 30°).

Fig. (16) shows clearly that the highest ultimate vertical compressive load of batter piles occurs at (30°) in a batter pile of angle β. The ultimate vertical compressive loads are greater by about (32 %), (18 %) and (26 %) than the ultimate vertical compressive loads for batter angles of (0°, 15° and 45°), respectively.

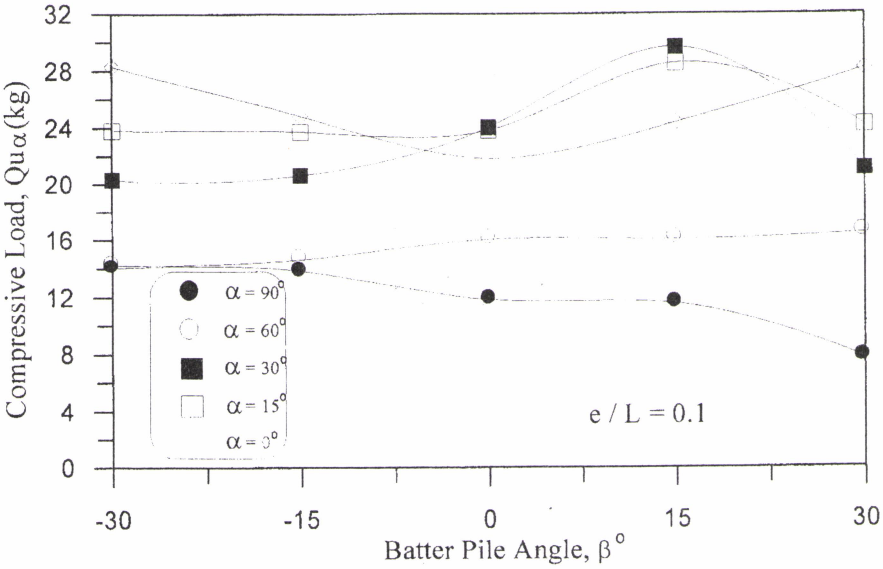


Fig. (15) Batter pile angle vs. inclined ultimate load for batter piles (L/b = 20).

Fig. (17) shows that the negative batter pile has greater ultimate horizontal compressive load than that for the vertical and the positive batter pile. A (30^{o}) negative batter pile has higher ultimate horizontal compressive loads by about (2 %), (23 %) and (60 %) more than that of $(-15^{o}, 0^{o}, 15^{o}$ and $30^{o})$ batter piles, respectively.

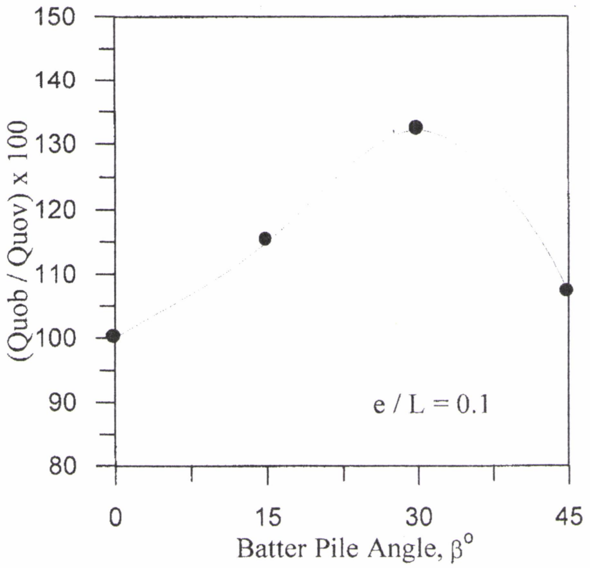


Fig. (16) - Batter pile angle vs. ratio of ultimate vertical load of batter pile to ultimate vertical load of vertical pile (L/b = 20).

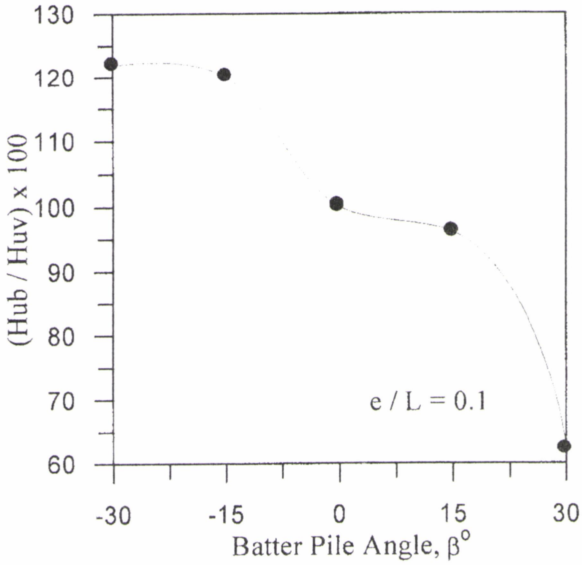


Fig. (17) - Batter pile angle vs. ratio of ultimate horizontal loasd on batter pile to ultimate horizontal load of vertical pile (L/b = 20).

Fig. (18) shows that a (15^{o}) axially loaded batter pile has a greater ultimate load than that of an axially loaded vertical pile.

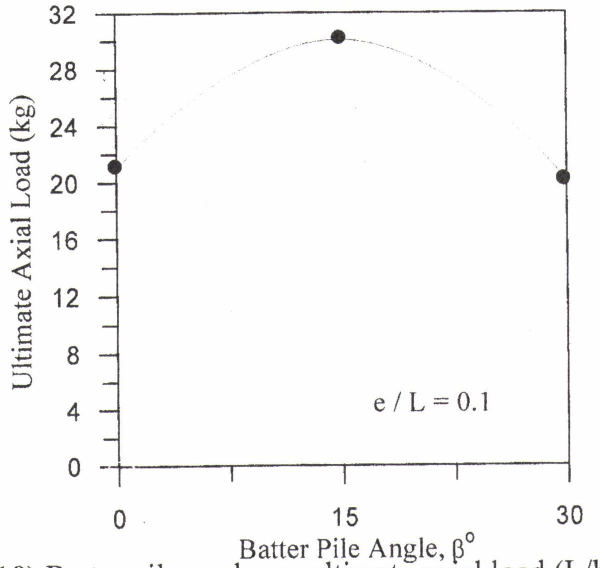


Fig. (18) Batter pile angle vs. ultimate axial load (L/b = 20).

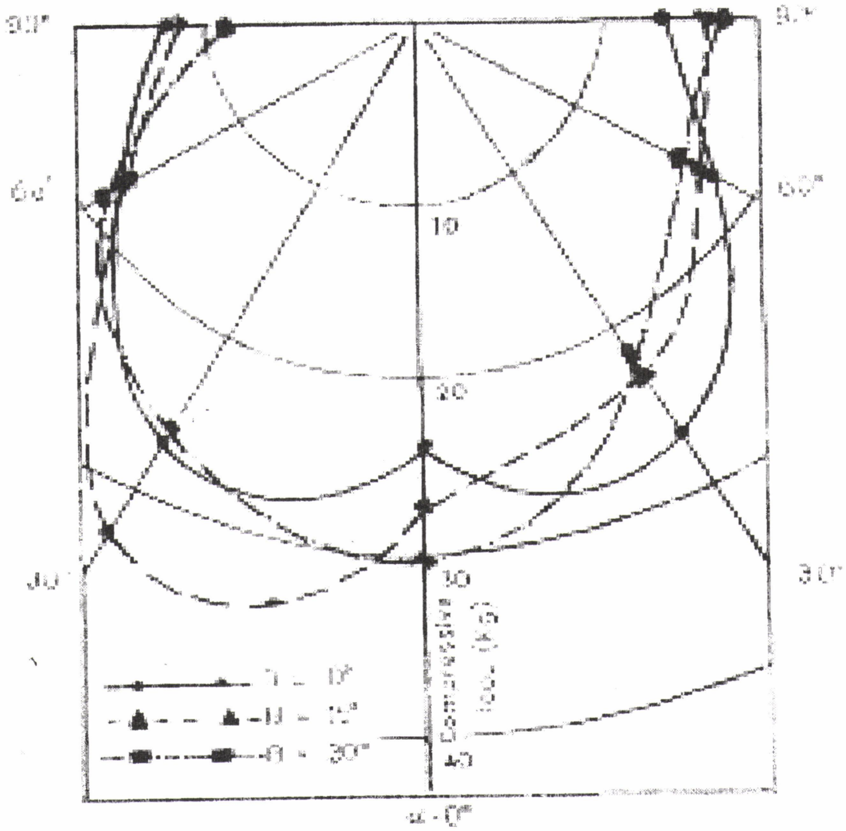


Fig. (19) Polar bearing capacity diagram for negative and positive batter piles (L/b = 20) and (e/L = 0.1).

CONCLUSIONS

The following conclusions can be made:

1 – The highest ultimate compressive load for vertical single piles occurs at (30°) load inclination.

2 – For small positive batter angles (β = 15°), the highest ultimate compressive load occurs at (30°) load inclination. Increasing the batter angle β to (30°), the highest ultimate compressive load occurs under vertical load.

3 - For negative batter piles, the highest ultimate compressive load occurs under vertical load and decreases with increasing the load inclination.

4 – The bearing capacity for vertical piles varies in the form of an ellipse.

5 – The greatest axial compressive load occurs at (β = 15°).

6 – At small inclinations with the vertical (α), a positive batter pile has a greater ultimate compressive load than that of a negative batter pile. The trend changes at larger inclinations (α > 60°).

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