Indian Geotechnical Journal, 41(4), 2011, 196-205

A Model Study of Micropiles subjected to Lateral Loading and Oblique Pull

Binu Sharma[1]

Key words

Micropile, model study, relative density, length to diameter ratio, failure mechanism

Abstract: Micropiles are small diameter cast in situ reinforced grouted piles. Micropiles are mainly applied for structural support and in situ reinforcement. As structural support it can be used for underpinning of distressed historical monuments, seismic retrofit mainly in congested and low headroom areas, resisting uplift dynamic loads. As in situ reinforcement it can be used for slope stabilization, for arresting structural settlement, excavation support in congested areas and as retaining structures. Its wide application makes it necessary to study the soil micropile interaction under various loading conditions. The investigation consists of two model experimental study of single micropiles of different length to diameter ratio installed in sand bed. In the first study the piles were subjected to lateral loading condition and in the second study the piles were subjected to vertical pull and oblique pull condition. Length to diameter ratio has been found to be a major variable influencing ultimate lateral and oblique resistance. The failure mechanism of the piles were found to be influenced by the relative density of the sand bed. The failure mechanism of the piles were also found to be influenced by the angle of inclination of the oblique pull.

Introduction

Strengthening of foundations of existing buildings in earthquake prone megacities and addition of new floors to existing buildings due to very high land values in big cities, usually need excavation and temporary support system below the foundation level. This creates problem due to limited head room and access in congested area. Also there is risk of collapse of the structure during the excavation process itself. Moreover, underground spaces need to be utilized for alternate modes of transport. Distressed historical monuments need to be saved. Micropiles may be used economically in such situations.

Micropiles are small diameter grouted drilled piles. The majority of micropiles are between 100 and 250mm in diameter, 20 to 30m in length and 300 to 1000kN in compressive or tensile service load, although far greater depths and much higher loads are not uncommon in the United States (Bruce et al., 1995). The grout is either placed or injected under pressure (grouting pressures about 0.8 to 1 MPa). It consists of a continuously threaded hollow reinforcing tendon as a load carrying steel member together with a grout body of furnace (Portland) cement which allows transfer of tension and compression forces mainly from the friction of the threaded tendon via the grout body into the surrounding soil. Due to high pressure grouting there is insignificant shrinkage between the pile and the soil. The penetration of the fluid part of the cement mix into the surrounding soil creates a transitory zone between the body of the micropile and the soil leading to a strong grout/ ground bond. Due to this reason ultimate load carrying capacity of micropile is higher than anticipated capacity based on conventional bearing capacity theory. Micropiles are typically used for structural support. It is usually installed for bridge and building foundations supports and seismic retrofits. Another main application of micropile is soil reinforcement eg slope stabilization / earth retention projects.

Micropiling technology first started in Italy in the early 1950's, when the search was on for innovative restoration work and reliable method of underpinning historic buildings and monuments. It was in 1952 when Lizzi, F. , the Technical Director of Italian firm Fondedile developed a new type of pile and piling system called paliradice (root piles) and reticolo- di- radice (reticulated root piles) respectively. The paliradice developed by Lizzi is recognized as the original micropiles used in those days for variety of geotechnical problems. Fondedile introduced root piles to the U. K. in 1962 and the same was introduced into the United States after two decades by Italy (Bruce, 1989).

Since the middle 1980's in particular, there has been a rapid growth in its use, mainly as foundation support elements in static and seismic applications and as in- situ reinforcement for slope and excavation stabilisation.

---

[1] Professor, Department of Civil Engineering, Assam Engineering College, University of Guwahati, Assam, Email : binuaec@yahoo.co.in

Significance of micropile in soil reinforcement and in underpinning works are reported in literature by various research workers. [Schlosser and Juran (1979), Sabini and Sapio (1981), Messad, Niyama and Rocha (1981), Lizzi (1982), Lizzi (1983), Soliman and Munkoph (1988), ONeill and Pierry (1989), Brandle (1988), Attwood (1987). Bruce (1989) presented about American developments on application of micropiles as insitu reinforcement. Yamane et al. (2000) conducted lateral and vertical load test on micropiles in order to study its seismic efficiency for retrofit purposes. Juran et.al (2001) performed a series of centrifuge test on single micropile, micropile groups and micropile networks. In India too, the use of micropiles was found effective as reported by Deshmukh and Ganpule (1990), Rao (1992).

The interaction between soil and groups of micropiles is different for vertical loads, horizontal loads and inclined loads. Consequently a super position of these loads and bending moments causes complicated statical conditions. To study the interaction between soil and micropiles, researcher's like Lizzi (1985) carried out tests on reduced scale model micropiles placed in artificially prepared homogeneous soil. Experimental results on single and group micropiles under oblique pull and upto the failure load are not reported in literature. Therefore there is a need to study the behaviour of micropiles subjected to pulling loads for proper understanding of the soil pile loading interaction. Again it has been found that systematic investigations on the qualitative and quantitative influence of parameters such as embedment length to diameter ratio, spacing, soil friction angle on ultimate horizontal resistance are practically scanty. Research work is necessary to understand the behaviour of single and group micropiles subjected to horizontal loads.

The present work consists of two model experimental studies. The first study was on single micropiles having length to diameter ratio of 8, 12, 15, 18, 21, 24, 27, 30, 35 and 55 installed in sand beds of three different relative densities of 30%, 50% and 80%. The micropiles were subjected to lateral loading conditions. Influence of embedment length to diameter ratio (L/D), influence of relative density on the ultimate lateral load, mode of failure of the piles and influence of relative density on the mode of failure of the piles were investigated. The second investigation was undertaken on single micropiles having length to diameter ratio of 40, 60 and 80 installed in a sand bed of relative density 50%. The micropiles were subjected to oblique loading conditions. Influence of embedment length to diameter ratio (L/D), influence of angle of inclination of the load with the vertical on the ultimate oblique resistance and modes of failure of the piles were investigated.

Properties of Sand

Locally available dry sand was used in the model tank for the experimental model study. Dry sand was used in order to obtain a reproducible density in the foundation medium. For the first model investigation which consists of micropiles being subjected to horizontal loading conditions, the uniformity coefficient, coefficient of curvature and specific gravity of the sand ranged from 2.97, 1.003 and 2.61 respectively. The effective grain size was 0.17 and maximum and minimum void ratio were 0.91 and 0.59 respectively. The angle of internal friction at relative densities 30%, 50% and 80% are 33^0, 38^0, and 43^0 respectively.

For the second investigation which consists of micropiles being subjected to oblique loading conditions, the effective grain size, uniformity coefficient and coefficient of curvature were 0.2mm, 2.4 and 1.13 respectively. The specific gravity of the sand was 2.66 and the maximum void ratio and minimum void ratio came out to be 0.87 and 0.63 respectively. Density and angle of internal friction (ϕ) at relative density 50% was 1.5 gm/cc and 37^0 respectively. To obtain uniform relative density throughout the tank, rainfall technique was used to fill up the tank.

Installation of the Micropiles

The micropiles were cast in sand of 50% relative density through an aluminium casing pipe of external diameter 12 mm and internal diameter 10 mm. At the lower end of the pipe a 60^0 conical wooden shoe was attached. A 1.5mm diameter mild steel rod was placed inside the pipe as reinforcing element. The aluminium casing pipe along with the steel rod and the wooden shoe were pushed inside the sand manually, keeping the pipe exactly vertical. The pipe was then grouted with cement slurry having a water cement ratio of 0.5.

Since pressure grouting in the model tank was not possible the piles were grouted under a constant slurry head of 100cm. The pipe was initially filled up upto 100 cm by cement slurry, then gradually lifted up by 2cm and additional cement slurry equivalent to 2cm height was poured from the top. This was done in order to maintain a constant slurry head of 100cm. This process was repeated till the whole pile was grouted. To make the piles free standing, a 50mm long aluminium pipe was attached to the top of the grouted pile, keeping the mild steel rod at the centre and again cast with cement slurry. The piles were tested after an interval of 4 to 5 days of grouting.

Micropiles Subjected to Lateral Loading Conditions

Measurement of load and deflection

Load deflection test was done according to IS 2911 (Pt-4) 1985 code of practice for load test on pile except the gradual application of load was upto failure. Load applied to the pile cap by a mechanical jack, was measured by means of a proving ring and displacement measured by a dial gauge attached to the pile cap.

Loading arrangement

The loading arrangement is shown from the view of the experimental assembly in Figure 1.

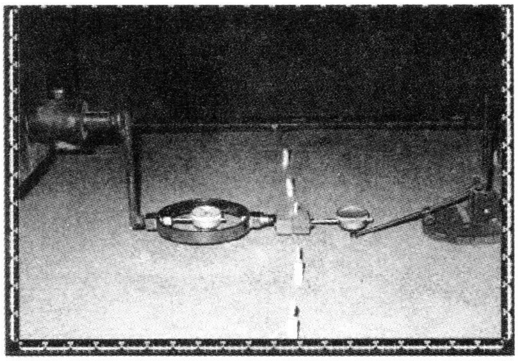

Fig.1 Lateral loading arrangement

A mechanical jack was adopted for applying lateral load. The mechanical jack was mounted to a horizontal cross beam with bolts and nuts along which it is free to slide when required. One end of an extension rod of length 17cm was fixed to the tip of the lever arm of the mechanical jack and the other end to a proving ring. The other end of the proving ring was pivoted to the pile cap, fixed at the top of the pile, by ball and socket arrangement. The pile cap was made of wood having size (6.4cm x 6.2cm x 2.8cm). The cap consists of two halves with semi circular groove to accommodate the pile head. The two halves were screwed tightly to the pile top.

Test Results

Single micropiles were cast for length/diameter (L/D) ratios of 8, 12, 15, 18, 21, 24, 27, 30, 35 and 55. Morever for each L/D ratio three micropiles were cast at three different relative densities of 30%, 50% and 80%. In total 30 numbers of micropiles were tested. Ultimate resistance of pile under lateral load has been taken as the point on the lateral load versus lateral displacement curve at which the curve maintains a continuous displacement increase with no further increase in lateral load.

Figure 2 shows the variation of ultimate lateral load with length/ diameter ratio of the micropiles at the three different relative densities. It is observed from the figure, that at relative density 30%, the ultimate load increases at a high rate upto L/D 15.

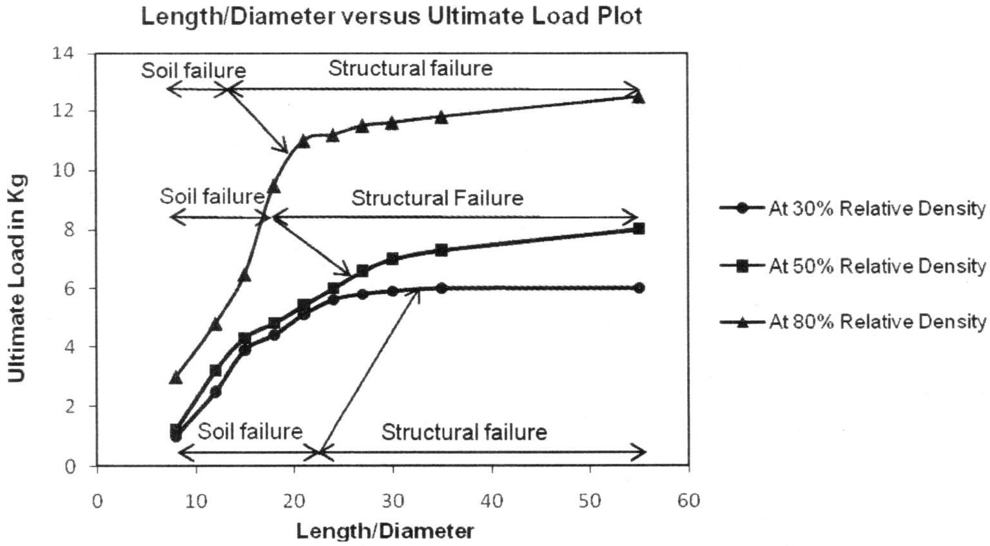

Fig. 2 Length/diameter ratio versus Ultimate load plot at 30%, 50% and 80% relative density.

There after upto L/D 30, the rate of increase slows down and after L/D ratio 35 it becomes constant. At relative density of 50%, the ultimate lateral load increases at a high rate upto L/D 15, the rate slows down upto L/D 30, thereafter the rate comes out to be insignificant. At relative density of 80% the rate of increase is high upto L/D of 24, thereafter the increase comes out to be insignificant.

The ultimate lateral load of the micropiles is plotted against relative density for the same L/D ratios. in Figure 3. This figure clearly shows the effect of Φ or relative density on the ultimate lateral resistance. More the Φ value, more is the ultimate lateral resistance but the relationship is not linear. It is observed that the effect of Φ is less upto relative density 50% and the effect of Φ is more from relative density 50% to 80%.

Mode of failure of the micropiles

Broms (1964) in his study of lateral load of piles in cohesionless soil, considered two types of failure of piles. One is failure of soil and the other is fracture of piles by formation of plastic hinges or structural failure. The first type is observed by a short pile. A short pile on application of lateral load rotates and passive resistance is developed near the ground surface at the opposite face. Failure occurs at the toe when passive resistance at the head and toe is exceeded. The second type is observed in case of a long pile, where cumulative passive resistance developed at the lower part of the pile is quite high due to which the pile cannot rotate and failure occurs at the point of maximum bending moment.

At relative density of 30% piles having L/D ratios 8, 12, 15, 18 and 21 failed by soil failure and piles having L/D ratios of 24, 27, 30, 35 and 55 failed by structural failure.

At relative density of 50% piles having L/D ratios 8, 12, 15 and 18 failed by soil failure and piles having L/D ratios of 21, 24, 27, 30, 35 and 55 failed by structural failure. At relative density of 80% piles having L/D ratios 8 and 12 failed by soil failure and the rest of the piles failed by structural failure. Therefore it can be concluded that at relative density of 30%, piles having L/D ratio upto around 21 behaved as short piles where as the rest behaved as long piles. Similarly at relative density of 50% and 80%, piles having L/D ratio upto around 18 and 12 behaved as short piles and the rest behaved as long piles.

Structural failure occurred by formation of cracks at the pile body. The position of cracks were observed to be 0.2 to 0.4 times the pile depth. This agrees with Poulos and Davis's(1980) observation for conventional long piles that long piles fail at the point of maximum bending moment.which is within 0.1 to 0.4 times the length of piles. This is experimentally shown in Figure 4 for relative density of 80%.

The dominant factor in the interaction between soil and the micropile is stiffness of the pile, which determines whether mechanism of failure is one of rotation, translation or failure by bending. As relative density increases, passive resistance developed at the lower part of the pile also increases. This increases the stiffness of the pile soil system. Therefore the mechanism

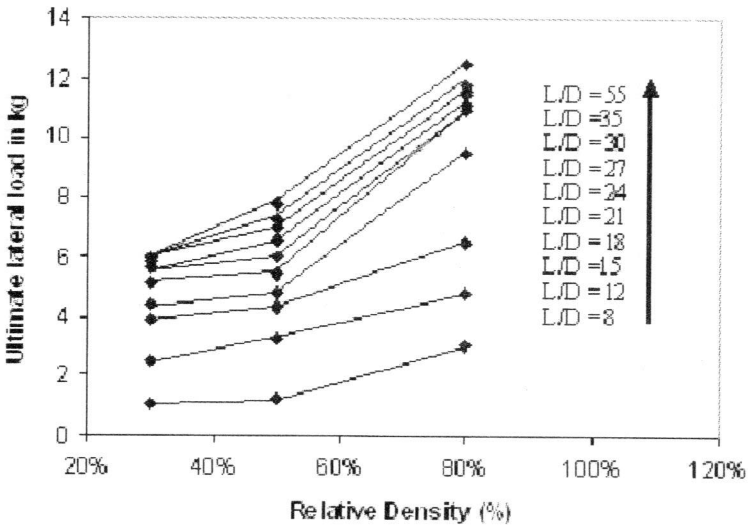

Fig.3 Ultimate load versus relative density at different L/D ratio

of failure of a pile will be a function of relative density of the soil. In the present investigation it was observed that transition from short pile to long pile occurred at L/D ratio between 21 to 24 at relative density of 30% where as at relative density of 50% and 80%, it occurred at L/D between 18 and 21 and between 12 and 15 respectively. Hence it is seen that relative density is a governing factor in the mode of failure of a single free head micropile subjected to lateral loading condition.

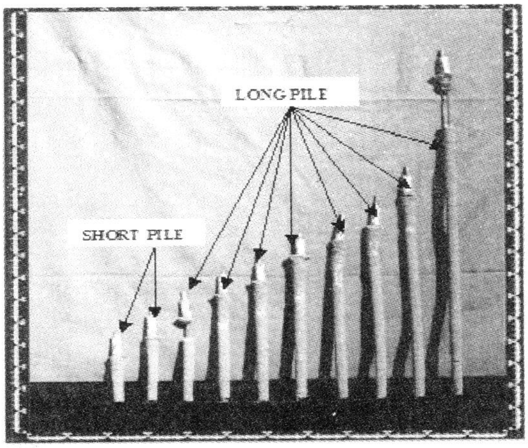

Fig. 4 Mode of failure of laterally loaded model micropiles (Relative density 80%)

Micropiles Subjected to Oblique Loading Conditions

Loading arrangement

The loading arrangement for oblique loading is shown from the schematic view of the experimental assembly in Figure 5. Loads are applied on pile top through a double pulley (frictionless) arrangement. Non extensible flexible steel wire was attached to the 'S' hook at the top of the pile cap. Wire was taken through the adjustable pulley (which is fitted with nut and bolt to the top solid steel channel) near the pile head and then over a second pulley to the loading pan where weights were put for loading in stages. Loads were applied at 0^0, 30^0, 60^0 and 90^0 inclinations with the vertical. Vertical dial gauge readings and lateral dial gauge readings were recorded corresponding to axial pulling loads, oblique pulling loads and lateral pulling loads respectively.

Test Results

Single micropiles were cast for length/diameter ratios of 40, 60 and 80. Moreover for each length/diameter ratio, four piles were installed for four different loading conditions viz. 0^0 (vertical pull), 30^0 (oblique pull), 60^0 (oblique pull) and 90^0 (lateral pull). In total 36 numbers of micropiles were tested (3 trials for each length/diameter for 4 different loading conditions). Average of three ultimate pull out load gave the final ultimate load for that specific pile.

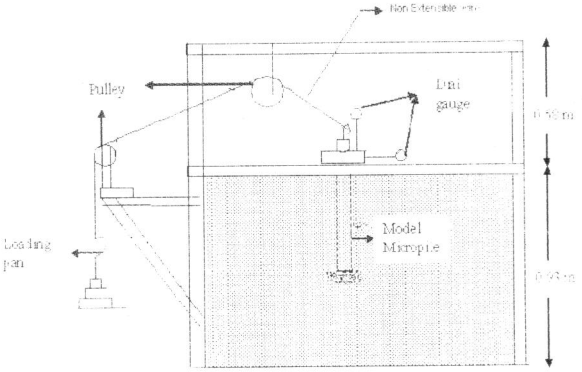

Fig.5 Loading arrangement for oblique pull

The ultimate load of pile under vertical pull (0^0) is taken as the load at which the pile moves out of the soil. In such a situation, the vertical pull versus vertical displacements curve becomes parallel to the vertical displacement axis.

The ultimate load of pile under oblique pull for $\theta = 30^0$ and 60^0 conditions have been estimated from oblique pull versus displacement diagram. It is taken as the point at which the curve exhibits a continuous increase in displacement with no further increase in pull. Ultimate resistance of pile under lateral pull (90^0) has been taken as the point on the lateral pull versus lateral displacement curve at which the curve maintains a continuous displacement increase with no further increase in lateral pull.

Table 1 shows the ultimate load of the single micropiles of different length/diameter ratio under different loading condition. Figures 6 - 9 show the load deflection curves of the piles at length/diameter ratio 80 and at the 4 different loading conditions which are typical of all the load defection curves. From Table 1 it is observed that in all the four loading conditions, the ultimate pull out load increases with increase in L/D ratio. It is also observed that in case of vertical pull out and oblique (30^0) pull out the ultimate pile load increases at a high rate from L/D ratio 40 to 80. Whereas in oblique (60^0) pull out, the ultimate pile load increases with a low rate and for lateral pull the ultimate load increases very insignificantly with increase in L/D ratio of piles.

Table 1 Ultimate load of the single micropiles under different loading conditions

Load applied at an angle	L / D ratio	Ultimate pile load (kg)			Average pile load (kg)
		1st	2nd	3rd	
0°(vertical)	40	21.075	21.075	22.48	21.54
	60	42.765	45.616	48.467	44.67
	80	76.977	79.828	82.679	79.828
30°	40	18.265	19.67	19.67	19.2
	60	31.361	35.658	38.181	35.07
	80	59.625	62.722	65.573	62.64
60°	40	6.076	8.68	11.284	8.68
	60	9.126	10.14	11.284	10.18
	80	11.154	13.182	13.182	12.506
90°(lateral)	40	6.303	6.876	7.449	6.876
	60	6.876	6.876	7.449	7.067
	80	7.449	7.449	8.595	7.831

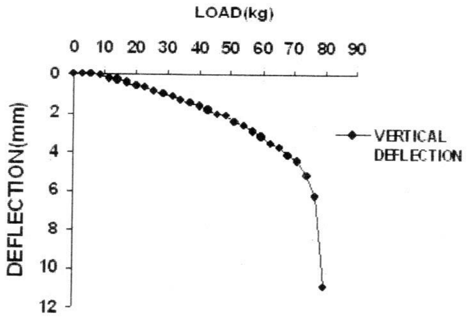

Fig.6 Load deflection curve at L/D = 80 and at 0° inclination.

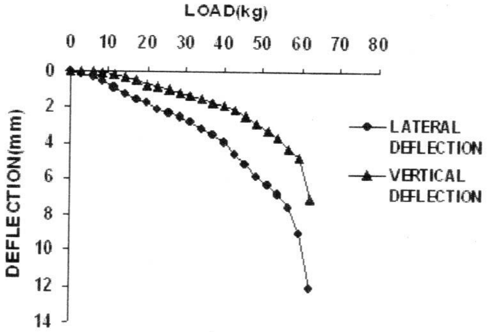

Fig.7 Load deflection curve at L/D = 80 and at 30° inclination.

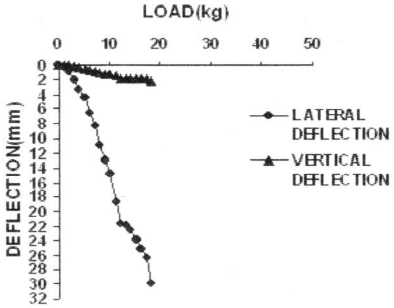

Fig.8 Load deflection curve at L/D = 80 and at 60^0 inclination

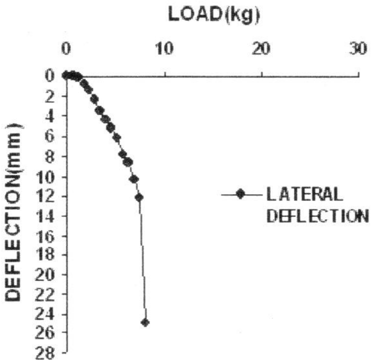

Fig 9 Load deflection curve at L/D = 80 and at 90^0 inclination

From the above discussion it is observed that in case of vertical pull out and oblique (30^0) pull the ultimate load is dependent on the length of the pile and it increases at a high rate with increase in its length. But in case of oblique (60^0) pull and lateral pull, the effect of length on the ultimate pile load is very less and hence increases very insignificantly with further increase in L/D ratio of piles. This implies that if the length of a pile is greater than a particular length especially in case of laterally loaded piles, the increase in length for oblique (60^0) pull and laterally pull, free head micropile looses its significance. This is in agreement with the findings for the laterally loaded piles at the three different relative densities. This also agrees with Polous and Davis (1980) approach for conventional pile that the behaviour of pile will not be affected if the length of pile is greater than a particular length. This is shown clearly in Figure 10. Figure 10 also shows the variation of ultimate pile load with load inclination. For a particular L/D ratio of pile, the ultimate pile load for vertical (0^0) pull out test comes out to be maximum i.e. for L/D =40 the ultimate load increases in the following pattern-

$$P_{(0^0)} > P_{(30^0)} > P_{(60^0)} > P_{(90^0)}$$

The same is the case for other L/D ratio of micropiles.

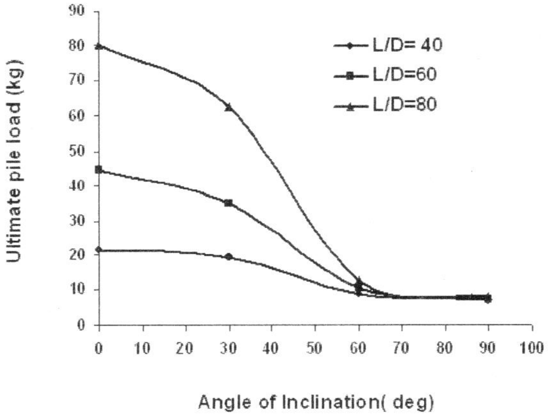

Fig. 10 Variation of pile load with angle of inclination

Failure Modes

According to Poulos and Devis (1980), in case of piles subjected to inclined loading, the ultimate load capacity is a function of both the lateral resistance and the vertical load capacity of the pile. When the applied load deviates only slightly from the axial direction, failure will occur essentially by axial slip. Lateral failure will occur when the inclination of the applied load is large, that is, as the load becomes perpendicular to the pile axis. The above two failure will occur as follows:-

Axial failure will occur when the ultimate lateral capacity exceeds the horizontal component of the ultimate inclined load. Lateral failure will occur when the ultimate lateral capacity is less than the horizontal component of the ultimate inclined load.

Study on single micropiles subjected to lateral loading condition showed that in case of relative density

50%, transition from short pile to long pile occurred at L/D ratio of 18 to 21. Hence all the piles tested in the study are long piles of L/D ratio of 40, 60 and 80. Table 2 shows the horizontal component and the vertical component of the ultimate inclined load. The lateral component of the ultimate inclined load comes out to be more than the ultimate lateral capacity (90^0 inclination) of the piles. Hence for the long piles axial failure is noted for $\theta = 0^0$ and lateral failure for $\theta \geq 30^0$. Again the piles being long piles, all the piles in this study subjected to oblique and lateral pull failed by structural failure. Figure 11 shows a typical structural failure in a single pile. Cracks occurred at a depth of 5% to 20% of the total length of the pile from the top. The piles subjected to axial pull failed by axial failure.

The ultimate resistance of piles subjected to oblique pulling loads can be represented by polar diagrams. In a polar diagram the variation of a function with direction (θ in this case) can be represented. For this work the ratio P_θ/P_U is taken where P_θ is the ultimate resistance of the single micropiles subjected to oblique pull and P_U is the axial uplift capacity of the piles.

The dimensionless ratio Pθ/PU is then plotted against θ which is measured clockwise from a reference line passing through the origin.

Fig. 11 Structural failure in a single pile

Table 2 Lateral and vertical components of the ultimate oblique loads

Inclinations	L/D ratio	Average ultimate pile load (kg)	Lateral component (kg)	Vertical component (kg)
30°	40	19.2	9.6	16.63
	60	35.07	17.535	30.37
	80	62.64	31.32	54.25
60°	40	8.68	7.52	4.34
	60	10.18	8.82	5.09
	80	12.506	10.83	6.253
90°	40	6.876	6.876	0
	60	7.067	7.067	0
	80	7.831	7.831	0

Figure 12 shows the variation of ultimate oblique resistance of the micropiles as represented through the polar diagram. For the long single micropiles of the different L/D ratio 40,60 and 80, the resistance to oblique pull is highest at $\theta = 0^0$ and this resistance to oblique pull decreases with an increase in θ. This decrease is gradual upto 30^0 inclination. Beyond 30^0 the ultimate oblique load decreases at a fast rate till it reaches a minimum value at 90^0 inclination.

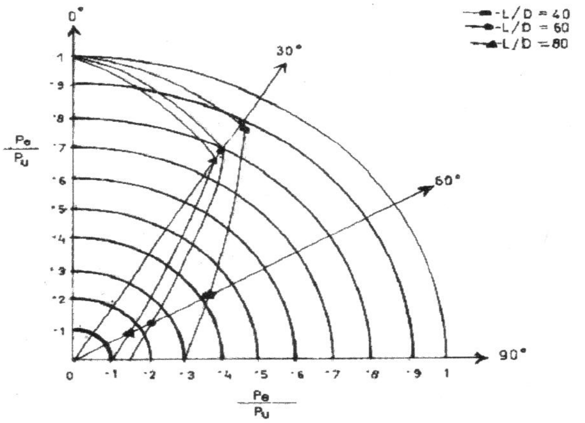

Fig. 12 Experimental values of P_θ/P_U represented through polar diagram

Conclusions

In case of free head single micropiles subjected to lateral loading condition it is observed that the ultimate lateral resistance increases with the L/D ratio of a pile but the increase is not linear. Beyond a certain L/D ratio the increase in length of a pile looses it's significance. Again it is observed that ultimate lateral resistance of piles with same L/D ratio increases with increase in relative densities. Two types of pile behaviour and failure mechanism were observed. Piles that fail by soil failure were taken as short piles and piles that failed by structural failure were taken as long piles. However the failure mechanism was observed to be influenced by relative density of the sand bed. Transition from short pile to long pile occurred at L/D ratio between 21 to 24 at relative density of 30% where as at relative density of 50% and 80%, it occurred at L/D ratio between 18 and 21 and between 12 and 15 respectively. As relative density increased, number of piles showing structural failure also increased.

On micropiles subjected to oblique pull it is observed that in case of vertical pull (0°) and oblique pull (30°) the ultimate load is a function of L/D ratio of the piles. In case of oblique pull (60°) the ultimate load increases very insignificantly with L/D ratio.In case of lateral pull (90°) the ultimate load becomes almost constant even with the increase in L/D ratio of piles. Two modes of failure were observed. Piles subjected to vertical pull failed due to axial or soil failure whereas piles subjected to oblique pull and lateral pull failed structurally at the point of maximum bending moment.

References

Attwood, S. (1987): 'Pali Radice their uses in stabilization of existing retaining walls and creating insitu retaining structures.' *Ground Engineering*, 20(7) pp. 23-27.

Brandle,H. (1988) : ' The interaction between oil and groups of small diameter bored piles,' *Proceedings of the 1st International Geotechnical seminar on deep foundation on bored and auger piles* / GHNET/7-10 June, 1998, pp.3-16.

Broms.B. (1964) : ' Lateral resistance of piles in cohesionless soil' *Journal of the Soil Mechanics and Foundation Engineering Division, ASCE,* 90, pp. 123-156.

Bruce, D. A., (1988): 'Developments in Geotechnical Construction Processes for Urban Engineering,' *Civ. Eng. Practice*, Vol. 3, No. 1, Spring, pp.49-97.

Bruce, D.A. (1988 , 1989): 'Aspects of Minipiling Practice in the United States,' *Ground Engineering,* Vol.21, No.8, pp.20-33 and 22(1), pp. 35-39.

Bruce, D.A. (1995): 'Small-diameter cast-in-place elements for load-bearing and in situ earth reinforcement,' *In Ground control and Improvement by Xanthakos,* P. P., Abramson, L. W., and Bruce. D. A., John Wiley and Sons, New York, Chapter 6. pp.406-492.

Bruce, D. A., 1989: 'American Developments in the use of small diameter inserts as piles and in situ reinforcement,' *Proceedings on Int. Conf. on Piling and Deep Foundations,* May 15-18, London, pp 11-22.

Deshmukh, A.M. and Ganpule, V.T. (1990) : ' Design and Construction of mini grouted piles in Bombay region,' *Pile talk international*, July , Jakarta, Indonesia, pp.17-22.

Juran,I., Benslimane,A., and Hanna,S.(2001): 'Engineering analysis of dynamic behavior of micropile system,' *Transportation Research Record*, 1772 (01-2936), pp. 91-106.

Lizzi, F., (1982): 'The Pali radice (Root Piles),' *Symposium on soil and Rock Improvement technique including geotextiles reinforced earth and modern piling methods,* ATI, Bangkok, pp. D-1-1-D -1-21.

Lizzi,F (1983): 'The Reticolo Di Pali Radice (Reticulated Root pile) for the improvement of soil resistance, physical aspects and design approaches,'-*VIII ECSMFE*, Helsinki, pp. 521-524

Lizzi,F (1985) : *Pali Radice and Reticulated Pali Radice.* Ed. By Thornburn,S. and Hutshinson,J.F., Surrey University Press. pp. 84-141.

Messad, F., Niyama.S.and Rocha.R. (1981: 'Vertical load test on instrumented root Piles,' *Proceeding of XICSMFE*, Stockholm, 2, pp. 796-800.

O'Neil,M.W. and Pierry,R.F. (1989): 'Behaviour of minigrouted piles used in foundation underpinning in Beaumont Clay, Houston, Texas, U.S.A,' *Proceeding of the International Conference on piling and deep foundation,* London, May, pp. 101-109.

Polous H.G. & Davis.E.H. (1980): *Pile Foundation Analysis & Design,* John Willey & Sons, Newyork, USA.

Rao,B.G. (1992) : 'Behaviour, Prediction and Performance of structures on improved ground and search for new technologies,' 15th IGS Lecture, *Indian Geotechnical Conference (IGC-92),* Calcutta.

Sabini,G. and Sapio,G. (1981) : ' Behaviour of small diameter piles under axial load,' *X ICSMFE*, 2, Stockholm, pp. 823-828..

Schlosser,F. and Juran,I. (1979) : ' Design parameters of artificially improved soils,' *ECSMFE,* Brighton. 5, pp. 197-225.

Soliman,N. and Munkofh,G. (1988) : ' Foundation on drilled and grouted minipiles. A case history,' *Proceeding* 1st *International Geotechnical seminar on deep foundations on Bored and Auger piles,* GHENT/7-9 June, pp. 363-369.

Yamane, T., Nakata, Y. and Otani, Y. (2000): 'Efficiency of micropiles for seismic retrofit of foundation system,' *12th World Conference on Earthquake Engineering,* Auckland, New Zealand, pp. 1-8.