Inelastic response of two-pile group under moment loading

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Abstract Shallow foundations are mostly used in transmitting loads from the superstructure to the supporting soils. In several cases, these footings are subjected to moment loading such as vertical load and bending moment due to wind and earthquake. The main objective of the present investigation is to find out the load-displacement response of group of two piles subjected to pure moment loading in sand bed without any reinforcement. The advantage of model study is that the pertinent parameters influencing the behaviour of 2-pile group embedded in sand can be controlled easily as per the requirement. In addition, the cost of carrying out model investigations is quite less and convenience is more compared to field tests. Therefore, model study is adopted in the present investigation. The relevant parameters considered for the study are (a) dimensions of the pile models (l/d ratios), (b) Relative density conditions, (c) spacing between piles (s/d ratios). Key words: load-displacement, 2-pile group, l/d ratios, relative density, s/d ratios.

1. Introduction: Many well-known towers have tilted from the original position or have collapsed by overturning. Also, silos, water tanks, chimneys have experienced some tilting and occasional overturning. The similarity between all these structures is that their centres of gravity are at high position and thus causing leaning instability even due to a slight disturbance [1-4]. A few published works on towers originally at vertical position or tilted [5, 6]. Present studies of their instability. Structure on the soft soil having low deformation modulus is more prone to instability [7, 8]. In most of the cases, the foundations are rigid and stability depends on moment-rotation relationship of the soil-foundation system. For the footings under moment loading, the four edges settle by different amounts, causing the footing to tilt. The amount of tilt and the pressure at the base depend upon the value of the length diameter ratio (l/d ratio) and spacing diameter ratio (s/d ratio) [9-12]. When this ratio is more than a limited value, the contact pressure will be tensile at the edge away from the load. However, since the soil is not a tension medium, such situation cannot develop; hence, the footing loses contact with the soil.

2. Soil data: The material used in the study was well graded sand. The sand is properly passed through 4.75 mm and retaining on 0.075 mm IS sieve. Dry sand is used as soil medium for the test as it does not include the effect of moisture. The uniformity coefficient (C_u) and coefficient of curvature (C_c) for the sand were 6.5 and 1.06, as per the IS Soil Classification System, the sand is classified as well graded sand (SW). The moisture content of the fill sand was kept at about 0%, dry condition, over the testing period. Angle of shearing resistance is found to be 37° and the specific gravity of sand is 2.6. Care was taken to achieve consistent soil densities and inclusion conditions in the soil models, procedures of construction were carefully controlled during model preparation. The relative density achieved during the tests was monitored by collecting samples in small, moisture content measurement cans of known volume placed at several locations in the test tank.

3. Pile models: In this investigation single piles and 2-pile groups are used. In single pile investigation, the model piles used were vertical steel piles of 25mm diameter and length of the piles is 375mm and 500mm (length/diameter ratios are 15 and 20). In 2-pile group models centre to centre spacing between two piles is 62.5mm, 75mm and 100mm (space/diameter ratios are 2.5, 3.0 and 4.0). Depth/diameter ratios are 12.5 and 17.5).
4. Methodology: A laboratory testing program was conducted to study the load-settlement response and soil structure interaction of 2-pile group under moment loading. A total of 20 tests were performed in which the load diameter ratios (l/d) are 15 and 20 and centre to centre spacing of pile, diameter ratios (s/d) is 2.5, 3.0 and 4.0 with constant diameter of 25mm. The $k_u$ (stiffness of pull-out pile) values of 2-pile group compared with single piles. The test soil consisted of a fine and poorly-graded sand contained in a tank of circular in shape having 111cm diameter in cross section and 55 cm deep.

The soil was compacted in 5 layers with approximate relative density of 71% and 34%. In each test, the moment load and the settlement at the four edges of the pile cap were measured. The corresponding moment and rotations of the 2-pile group were calculated based on the measured values of settlement. The $k_u$ values of 2-pile group and single pile are calculated by using initial slope of load-displacement curve. The initial subgrade modulus $k$ is estimated for single pile and 2-pile group.

5. Results and Discussions:

5.1. Calculation of Pile Stiffness Ratio for single piles

The load-displacement variation of single pile under compression and pull out is shown in Fig.1 for l/d=15, $R_d$=71% and $d$=25mm. The pile stiffness $k$ is calculated by considering the initial slope of the load-displacement plot. The stiffness for compression pile is $k_c$ and for Pull out pile is $k_u$. The stiffness for the pile under compression, $k_c$ is about 166.7 N/mm and for the pile under pullout, $k_u$ is about 400.08 N/mm. Hence the response of pile under compression is different from pullout. The ratio of pile stiffness under pullout to compression is defined as $m=k_u/k_c=2.4$

The load-displacement variation of single pile under compression and pull out is shown in Fig.2 for higher l/d=20, $R_d$=71%; $d$=25mm. The pile stiffness for the pile under compression, $k_c$ is about 450.00 N/mm and for the pile under pullout, $k_u$ is about 1478.858 N/mm. The ratio of pile stiffness under pullout to compression is 3.28. For the constant diameter of pile of 25mm and relative density of 71%. As the l/d ratio increases from 15 to 20, the ratio of pile stiffness increases from 2.4 to 3.28.

The load-displacement variation of single pile under compression and pull out is shown in Fig.3 for l/d=15, $R_d$=34%; $d$=25mm. The stiffness for the pile under compression, $k_c$ is about 120.00 N/mm and for the pile under pullout, $k_u$ is about 271.59 N/mm. The ratio of pile stiffness is 2.3 which is less than the corresponding ratio for relative density of 71%. The pile stiffness increases with increase in relative density for the constant value of l/d=15. As the relative density is lower i.e, 34% $k_u$ is
less than the corresponding value for obtained higher relative density of 71%. The difference is about 32%.

The load-displacement variation of single pile under compression and pull out is shown in Fig.4 for l/d=20, Rd=34%; d=25mm. The stiffness for the pile under compression, $k_c$ is about 200.00 N/mm and for the pile under pullout, $k_u$ is about 563.00N/mm. The ratio of pile stiffness is 2.81. The ratio of pile stiffness is slightly more than the earlier case as shown in Fig.3. For a constant relative density of 34%, as l/d ratio increases from 15 to 20, the pile stiffness also increases from 2.25 to 2.81.

Table 1 shows the variation of pile response of in terms of $k_u$ and $k_c$ for two different values of l/d ratios of 15 and 20 and for relative densities of 34% and 71%. The effect of increase in relative density is reflected in corresponding k values for both compression pile and pullout pile.

### 5.2. Response of 2-pile groups

The moment a clockwise direction applied on the 2-pile group. The pile which is in the direction of moment undergoes compression which the other one experience pull out. The load-displacement variation of 2-pile group under compression and pull out is shown in Fig.5 for l/d=15, Rd=34%, s/d=2.5 and d =25mm. The pile stiffness k is calculated by considering the initial slope of the load-displacement variation. The pile stiffness for compression pile is $k_c$ and for Pull out pile is $k_u$. The pile stiffness for the pile under compression, $k_c$ is about 562.95 N/mm and for the pile under pullout, $k_u$ is about 2533.28 N/mm.

The ratio of pile stiffness under pullout to compression is about 4.5 which is greater than the...
corresponding ratio for single pile.

The load-displacement variation of 2-pile group under compression and pullout is shown in Fig.6 for \(l/d=15\), \(R_d=34\%\), \(s/d=3.0\) and \(d=25\)mm. The pile stiffness for the pile under compression, \(k_c\) is about 1080.75 N/mm and for the pile under pullout, \(k_u\) is about 3241.71 N/mm. Similar response as described in Fig.5 is observed but with higher values of \(k_u\) and \(k_c\). The pile stiffness ratio, \(m\) decreases from 4.5 to 3.0 due to increase in \(s/d\) from 2.5 to 3.0 for the same \(R_d\) of 34\% and \(l/d\) of 15. The increase in spacing beyond decreases the pile stiffness ratio, \(m\).

The load-displacement variation of 2-pile group under compression and pullout is shown in Fig.7 for \(l/d=15\), \(R_d=34\%\) and \(s/d=4.0\). The pile stiffness for the pile under compression, \(k_c\) is about 525.84 N/mm and for the pile under pullout, \(k_u\) is about 1472.50 N/mm. The response the 2-pile group under higher \(s/d\) ratio of 4.0 is shown in Fig.7 for the same relative density of 34\% and \(l/d\) of 15. The increase in \(s/d\) to 4, causes decrease in \(k_u\) and in \(k_c\). Hence the stiffness ratio, \(m\) decreased to 2.8 with respect the 2-pile group with \(s/d\) of 3.0.

The load-displacement variation of 2-pile group under compression and pullout is shown in Fig.8 for \(l/d=20\), \(R_d=34\%\), \(s/d=2.5\) and \(d=25\)mm. The pile stiffness for the pile under compression, \(k_c\) is about 3744.00 N/mm and for the pile under pullout, \(k_u\) is about 9852.63 N/mm. The ratio of pile stiffness is about 2.63.

The load-displacement variation of 2-pile group under compression and pullout is shown in Fig.9 for \(l/d=20\), \(R_d=34\%\), \(s/d=3.0\) and \(d=25\)mm. The pile stiffness for the pile under compression, \(k_c\) is about 7040.00 N/mm and for the pile under pullout, \(k_u\) is about 11733.00 N/mm. The ratio of pile stiffness is about 1.70 which is slightly less than previous case as shown in Fig.8. For constant relative densities of 34\% and \(l/d\) ratio of 20, as \(s/d\) increases from 2.5 to 3.0, the ratio of pile stiffness decreases from 2.6 to 1.70.
The load-displacement variation of 2-pile group under compression and pull out is shown in Fig. 10 for \( l/d=20 \), \( R_d=34\% \), \( s/d=4.0 \) and \( d =25\)mm. Similar response as depicted in Fig. 5 is observed. But with lower values of \( k_c \) and \( k_u \). The pile stiffness for the pile under compression, \( k_c \) is about 2376.3 N/mm and for the pile under pullout, \( k_u \) is about 3326.9 N/mm. The ratio of pile stiffness is about 1.40 which is less than the previous two case as shown in Fig. 8 and Fig. 9. For a constant relative density of 34\% and \( l/d \) ratio of 20, as \( s/d \) increases from 2.5 to 4.0, the ratio of pile stiffness decreases from 2.6 to 1.40.

The load-displacement variation of 2-pile group under compression and pull out is shown in Fig. 11 for \( l/d=15 \), \( R_d=71\% \), \( s/d=2.5 \) and \( d =25\)mm. The pile stiffness for the pile under compression, \( k_c \) is about 3000.00 N/mm and for the pile under pullout, \( k_u \) is about 9875.7 N/mm. The ratio of pile stiffness is about 3.3 which is greater than the corresponding ratio for single pile, for a constant \( l/d \) ratio of 15 and \( s/d \) ratio of 2.5, as relative densities increases from 34\% to 71\%, the pile stiffness ratio increase from 2.8 to 3.3.

The load-displacement variation of 2-pile group under compression and pull out is shown in Fig. 12 for \( l/d=15 \), \( R_d=71\% \), \( s/d=3.0 \) and \( d =25\)mm. The pile stiffness for the pile under compression, \( k_c \) is about 5448.89 N/mm and for the pile under pullout, \( k_u \) is about 11442.67 N/mm. The ratio of pile stiffness is about 2.1 which are less than the previous case of 2-pile group of \( s/d \) is 2.5.

The load-displacement variation of 2-pile group under compression and pull out is shown in Fig. 13 for \( l/d=15 \), \( R_d=71\% \), \( s/d=4.0 \) and \( d =25\)mm. The pile stiffness for the pile under compression, \( k_c \) is about 1466.7 N/mm and for the pile under pullout, \( k_u \) is about 2640.00 N/mm. The ratio of pile stiffness is about 1.80. It is less than the ratio of pile stiffness as shown in Fig. 11 for \( s/d \) of 3.0 for the same relative density of 71\%. 

![Fig.10 load vs displacement plot of 2-pile group under moment loading, for \( l/d=20 \), \( s/d=4 \), \( R_d=34\% \)](image)

![Fig.11 load vs displacement plot of 2-pile group under moment loading, for \( l/d=15 \), \( s/d=2.5 \), \( R_d=71\% \)](image)

![Fig.12 load vs displacement plot of 2-pile group under moment loading, for \( l/d=15 \), \( s/d=3 \), \( R_d=71\% \)](image)

![Fig.13 load vs displacement plot of 2-pile group under moment loading, for \( l/d=15 \), \( s/d=4 \), \( R_d=71\% \)](image)
The load-displacement variation of 2-pile group under compression and pull out is shown in Fig.14 for l/d=20, R_d=71%, s/d=2.5 and d=25mm. The pile stiffness for the pile under compression, k_c is about 3957.00 N/mm and for the pile under pullout, k_u is about 10792.00 N/mm. The ratio of pile stiffness is 2.70, for a constant relative density of 71% and s/d ratio of 2.5, as l/d increases from 15 to 20, the ratio of pile stiffness is decreases from 7.20 to 2.70.

The load-displacement variation of 2-pile group under compression and pull out is shown in Fig.15 for l/d=20, R_d=71%, s/d=3.0 and d=25mm. The pile stiffness for the pile under compression, k_c is about 6923.48 N/mm and for the pile under pullout, k_u is about 12534.26 N/mm. The ratio of pile stiffness is 1.5, for a constant s/d ratio of 3.0 and relative densities of 71%, as l/d ratio increases from 15 to 20, the ratio of pile stiffness are almost the same which is 1.50.

The load-displacement variation of 2-pile group under compression and pull out is shown in Fig.16 for l/d=20, R_d=71%, s/d=4.0 and d=25mm. The pile stiffness for the pile under compression, k_c is about 2640.00 N/mm and for the pile under pullout, k_u is about 3428.00 N/mm. The ratio of pile stiffness is 1.30, for a constant s/d ratio of 4.0 and relative densities of 71%, as l/d ratio increases from 15 to 20.

Table 2. The pile stiffness, k for 2-pile group under moment loading (l/d=15,20 and relative density of 34% and 71%) for three different space to diameter ratios (s/d).

| S.NO | R_d, % | l/d | s/d | k_u | k_c | m=k_u/k_c |
|------|--------|-----|-----|-----|-----|-----------|
| 1    | 34     | 15  | 2.5 | 2533.3 | 562.95 | 4.5       |
| 2    | 34     | 15  | 3   | 3241.7 | 1080.5 | 3.0       |
| 3    | 34     | 15  | 4   | 1472.5 | 525.89 | 2.8       |
| 4    | 34     | 20  | 2.5 | 9852.6 | 3744.0 | 2.6       |
| 5    | 34     | 20  | 3   | 11733 | 7040.0 | 1.7       |
• Effect of relative density
For the constant l/d and s/d, the $k_u$ and $k_c$ values increase with increase in relative density from 32% to 71% as listed in Table 2.

• Effect of l/d
For the constant s/d and relative density, the $k_u$ and $k_c$ values increase with increase in l/d.

• Effect of s/d
For low density, increases in s/d causes increase in $k_u$ and $k_c$ up to a value of s/d of 3, beyond which a reduction is observed for both densities of 34% and 71%.

5.3. Effect of l/d ratio

The effect of l/d ratio on load-displacement variation of two pile group for s/d of 2.5 and for low relative density, $R_d$ of 34% is shown in Fig. 17. Moment induces compression in one pile and uplift in other. The corresponding displacements are plotted against load on the pile. The pile stiffness, $k$ is the initial slope of load-displacement plot. The initial slope of load-displacement is steeper for the pile under pullout than the compression pile for any l/d. i.e. The pile stiffness, $k_u$ is more than $k_c$ for all l/d.

For a constant applied load on the pile group, the displacement of the pile under pullout is more than the compression pile. For an applied load of 200N, the displacement of the compression pile is 0.2mm whereas for pullout is 1.2 mm for l/d=20. Similarly for l/d=15, the displacements are 0.5mm and 2.4 mm for compression pile and pullout pile respectively. Increase in l/d ratio reduces displacement by about 60% for compression pile and 50% for pullout.

| 6 | 34 | 20 | 4 | 3326.9 | 2376.3 | 1.4 |
|---|----|----|---|--------|--------|----|
| 7 | 71 | 15 | 2.5| 9875   | 3000.0 | 3.3 |
| 8 | 71 | 15 | 3 | 11442  | 5448.8 | 2.1 |
| 9 | 71 | 15 | 4 | 2640.2 | 1466.0 | 1.8 |
| 10| 71 | 20 | 2.5| 10792  | 3957.0 | 2.7 |
| 11| 71 | 20 | 3 | 12534  | 6923.4 | 1.8 |
| 12| 71 | 20 | 4 | 3428   | 2640.0 | 1.3 |

Fig.17 load- displacement variation of 2 pile group for s/d=2.5, $R_d$=34% and d=25mm - effect of l/d.
Fig.18 load-displacement variation of 2 pile group for s/d=2.5, R_d=71% and d=25mm - effect of l/d.

The effect of l/d ratio on load-displacement variation of two pile group for s/d of 2.5 and for higher relative density, R_d of 71% is shown in Fig.18. The similar response as described in Fig.17 is observed but with lower values of displacements for both compression pile and pullout pile. The increase in density reduces the displacement of two pile group as expected.

The pile stiffness, (k_c or k_u) which is initial slope of load-displacement plot is steeper for the pile under pullout than the compression pile for the constant l/d, i.e. The pile stiffness, k_u is more than k_c for all l/d.

For a constant applied load on the pile group, the displacement of the pile under pullout is more than the compression pile. For an applied load of 400N, the displacement of the compression pile is 0.05mm whereas for pullout is 0.25 mm for l/d of 20. Similarly for l/d=15, the displacements are 0.7mm and 2.6 mm for compression pile and pullout pile respectively. Increase in l/d ratio reduces the displacement by about 93% and 90 % for compression pile and pullout pile respectively. The reduction in displacements is more by 33% and 40% for compression pile and pullout pile respectively with respect to the response of the same 2-pile group embedded in sand of low relative density of 34%.

The effect of l/d ratio on load-displacement variation of two pile group for increased spacing to diameter ratio (s/d) of 3.0 and R_d of 34% is shown in Fig 19. As the spacing is increased from 2.5 to 3.0, the pile group displacements are reduced from 1mm to 0.25mm for compression pile and from 4.0mm to 0.6mm for the pullout pile for l/d=20. Similarly for l/d=15, the displacements are 1.1mm and 5.0mm for compression pile and pullout pile respectively. Increase in l/d ratio reduces the displacement by about 73% and 86 % for compression pile and pullout pile respectively.

Fig.19 load-displacement variation of 2 pile group for s/d=3, R_d=34% and d=25mm - effect of l/d.
The effect of l/d ratio on load-displacement variation of two pile group for s/d of 3.0 and for higher relative density, R_d of 71% is shown in Fig 20. The similar response as described in fig.19 is observed with lower values of displacements for both compression pile and pullout pile. For the effect of increased relative density is not much significant on the pile of l/d=20. Which has displacements almost same as earliest case of R_d=34%. But for the pile having l/d ratio of 15, the displacements are reduced from 1.25mm to 0.6mm for compression pile.

For a constant applied load on the pile group, the displacement of the pile under pullout is more than the compression pile. For an applied load of 400N, the displacement of the compression pile is 0.2mm whereas for pullout is 0.5mm for l/d of 20. Similarly for l/d=15, the displacements are 0.6mm and 2.5mm for compression pile and pullout pile respectively. The effect of increased relative density is not much significant on the pile of l/d=20. Which has displacements almost same as earlier case of relative density 34%. But for the pile having l/d ratio of 15, the displacements are reduced from 1.25mm to 0.6mm for compressive pile.

The effect of l/d ratio on load-displacement variation of two pile group for s/d of 4.0 and for lower relative density, R_d of 34% is shown in Fig21. The similar response as described in fig.20 is observed with higher values of displacements for both compression pile and pullout pile. The for the constant l/d and R_d increase in s/d ratio increases the displacement of two pile group as expected.

For a constant applied load on the pile group, the displacement of the pile under pullout is more than the compression pile. For lower relative density, R_d of 34%, the s/d is increased from 3.0 to 4.0. The displacements of both compression and pullout pile having l/d=20, are observed as 0.5mm and 1.2 mm respectively for constant load of 400N. Hence increasing in spacing increases the displacements for the constant relative density and l/d ratio. The spacing to diameter ratio of 3 is optimum for the 2-pile group of l/d=20.
Fig. 22 load-displacement variation of 2 pile group for s/d=4, R_d=71% and d=25mm - effect of l/d.

The effect of l/d ratio on load-displacement variation of 2-pile group for higher s/d ratio of 4.0 and R_d of 71% is depicted in Fig. 22 for the constant relative density, R_d of 71%, the displacement of both compression and pullout pile are 0.25mm and 0.8mm respectively for an applied load of 400N. The compression pile displacement is same as that for s/d of 3.0 whereas the pullout piles it is increased from 0.5mm to 0.8mm.

Hence the increase in spacing beyond 3.0 has no effect on higher load levels compression pile for the constant relative density, R_d.

5.4. Effect of s/d ratio

Fig. 23. load-displacement variation of 2 pile group Effect of s/d for R_d=34%, l/d=15 and d=25mm.

The effect of s/d ratio on load-displacement variation of two pile group for l/d of 15 and for low relative density, R_d of 34% is shown in Fig. 23. The displacement of the pile is compared for the increase in s/d ratio, from 2.5 to 4.0 for the constant relative density of 34%. As discussed in previous sections, the increasing in spacing beyond 3 causes increase in displacements of both the piles at higher load levels.

For a constant applied load on the pile group, the displacement of the pile under pullout is more than the compression pile. For an applied load of 200N, the displacement of the compression pile is 0.4 mm whereas for pullout is 1.2 mm for s/d=2.5. Similarly for s/d=4.0, the displacements are 0.6 mm and 3.2 mm for compression pile and pullout pile respectively. Increase in l/d ratio reduces the displacement by about 33% and 63% for compression pile and pullout pile respectively.

6. Conclusions

1) The inelastic response of two pile group under moment loading is evaluated in terms of load vs displacement. The response of pile under compression is different from that one which is in pullout due to moment loading.

2) The increase in relative density of the sand causes increase in stiffness of both the piles for any space to diameter ratio (s/d) and length to diameter ratio (l/d).

3) The pile stiffness is decreases with the increase in space to diameter ratio (s/d ratio).
4) The increase in space to diameter ratio (s/d) decreases the pile stiffness for any length to diameter ratio (l/d) for both higher relative density of 71% and lower relative density of 34%.

7. References

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