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Effect of Compressive Load on Uplift Capacity of Pile Groups in Sand

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***Abstract* - An experimental cum analytical study has been carried out to quantify the effect of compressive load due to stage construction on uplift capacity of model pile groups embedded in sand. Pull out tests were conducted by placing a static compressive load of 0, 25, 50, 75, and 100% of their ultimate capacity in compression on pile groups of different configuration and length to diameter ratio embedded in sand. The experimental results indicated that the presence of compressive load on the pile group decreases the net uplift capacity of the group and the decrease depends on the magnitude of the compressive load. Based on the experimental results a semi empirical method has been suggested to predict the net uplift capacity of a group of piles in the presence of compressive loading. The predictions are found to be in good agreement with the measured values validating the developed method of analysis.**

***Keywords:* Model Test, Pile Group, Sand, Stage Loading, Uplift**

I. Introduction

The uplift resistance of a pile in sand is assumed to depend on limiting skin friction between the pile and surrounding soil (Mayerhof and Adams, 1968; Das and Seeley, 1975; Poulas and Davis, 1980 and Chattopadhyay and Pise, 1986).The skin friction resistance is significantly lower for tensile loading than for compressive loading (Nicola and Randolph, 1993; Ramasamy *et al,* 2004). Several investigations on the behavior of single piles and group of piles under uplift loads have been reported by Chattopadhyay and Pise (1986), Das (1983), Das and Seeley (1975), Ismael & Klym(1979), Meyerhof (1973), Levacher and Sieffert (1984), Rao and Venkatesh (1985), Vesic (1970), Das *et al* (1976). However, their studies do not take into account the effect of compressive load due to stage construction on uplift capacity of pile groups. Construction is a gradual process and load transferred to soil through foundation is incremental in nature. The placement of the compressive load on the pile from super structure changes the soil fabric at the pile soil interface of a pile. The effect of such changes in the fabric on stress strain response could also be important in the mobilization of shaft resistance. Due to the construction of superstructure, skin friction resistance under tensile loading varies in the presence of compressive load (Dash and Pise 2003). The full static compressive load comes on it when the superstructure is completed in all respects. Normally a factor of safety of 2.0 to 2.5 is allowed on the ultimate capacity for the design of piles either in compression or tension. Considering the average factor of safety, such a full static load at the completion of the superstructure, amounts to 40-50% of the ultimate load carrying capacity of a pile in compression. At present there is no substantial information available on the behavior of group of piles under uplift load when they are simultaneously subjected to compressive load. However, only limited literature is available on single and group of piles (Dash and Pise, 2003; Joshi, 2004).

As such, in the present study an attempt has been made to study the effect of the stage compressive load on the pull out resistance of model pile groups of different configuration by subjecting them simultaneously to different levels of compressive loads in relation to their ultimate capacity in compression. Laboratory model tests on single pile and group of piles at different length to diameter ratio (λ=L/d) have been conducted. Based on the experimental results a semi empirical procedure has been suggested for estimating the uplift capacity of group of piles at different stages of compressive loading.

II. Analysis

Till now, there is no proper analysis to estimate the effect of the presence of compressive load on the uplift capacity of pile groups. It is difficult to asses the different factors, which are responsible for the reduction of net uplift capacity in the presence of compressive loading. As already pointed out, one of the factors may be change in the fabric along the shaft due to the presence of compressive load on the pile, Oda and Koishikawa (1977) and Ochiai and Lade (1983) observed that fabric change along the shaft can result in a reduction of soil friction angle measured with particle alignment perpendicular to the major principal stress. Some of the other factors that affect the shaft resistance of piles are soil characteristics, pile surface characteristics, method of installation, type of loading etc. Thus, it may be assumed that the effect of the compressive load on the pile may alter the soil-pile friction angle.

The uplift capacity of the pile group without compressive load can be analyzed considering as two different cases depending upon the centre to centre spacing (s) of the piles as follows;

A. Case-1 ($s \geq 2\, x_G$)

For this case overlapping of failure surfaces does not take place and each pile in the group acts independently as shown in Fig. 1(a). Hence, the net uplift capacity of the pile group is equal to the number of piles in the group times the net uplift capacity of a single pile.

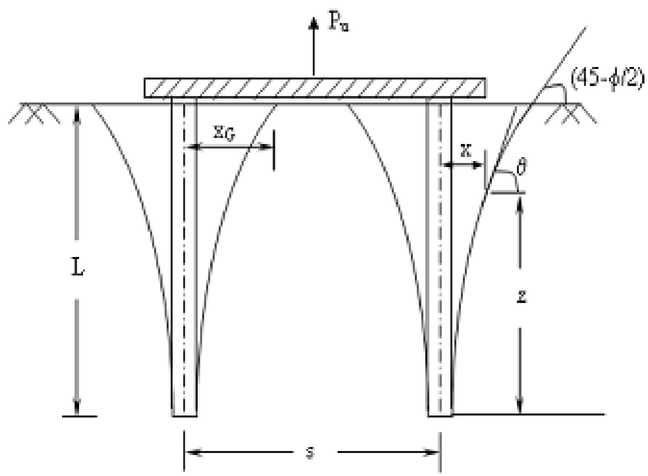


Fig. 1.(a). Pile group without overlapping of failure surfaces

[1] $P_{nu}\text{(Group)} = N \times P_{nu}$

Where N= Total number of piles in the group

[2] P_{nu}= Net uplift capacity of single pile =

$$\int_0^L \pi\gamma L d\left\{\frac{2x}{d}\left(1-\frac{z}{L}\right)\left(\frac{1}{M_1}+M\right)\right\}dz$$

Where

$$M_1 = \tan\left\{90-\left(\frac{45+\phi/2}{L}\right)z\right\}\exp\left\{(\lambda)^{1.9}\frac{(\phi_{max}-\phi)}{2\delta}\left(1-\left(\frac{z}{L}\right)^{\frac{1}{\lambda}}\right)\right\}$$

and

[3] $M = (\cos\theta + K\sin\theta)\tan\phi$

Where

$\theta = \tan^{-1}\left(\frac{dz}{dx}\right)$ and K= Lateral earth pressure coefficient assumed as (1-sinϕ)

[4] $$\frac{dz}{dx} = \tan\left\{90-\left(\frac{45+\phi/2}{L}\right)Z\right\}\exp\left\{(\lambda)^{1.9}\frac{(\phi_{max}-\phi)}{2\delta}\left(1-\left(\frac{z}{L}\right)^{\frac{1}{\lambda}}\right)\right\}$$

B. Case-2 *(s < 2 x_G)*

For this case overlapping of failure surfaces takes place as shown in Fig1(b).and the net uplift capacity of the pile group can be evaluated as,

[5] P_{nu} (Group) = $(P_{nu})_1 + (P_{nu})_2$

Where,

[6] $(P_{nu})_1$=N

$$\int_{0}^{Z_{eff}} \pi\gamma L d\left\{\frac{2x}{d}\left(1-\frac{z}{L}\right)\left(\frac{1}{M_1}+M\right)\right\}dz$$

Where z_{eff} is the distance between the pile tip to the starting point of overlapping of failure surface.

[7] $$(P_{nu})_2 = \int_{Z_{eff}}^{L} \frac{dP}{dz}dz$$

$$= \int_{Z_{eff}}^{L} 2\gamma d L\left(1-\frac{z}{L}\right)\left\{\left(K_2+\frac{4x_2}{d}\right)\frac{dx}{dZ}+\left(K_2-2+\pi\left(\frac{x_2}{d}+\frac{1}{2}\right)\right)M\right\}dz$$

Where $K_2 = (a + b)/d$ and $x_2 = x - \frac{d}{2}$

Where a and b are the outer to outer distance in the plan between the extreme piles in the group.

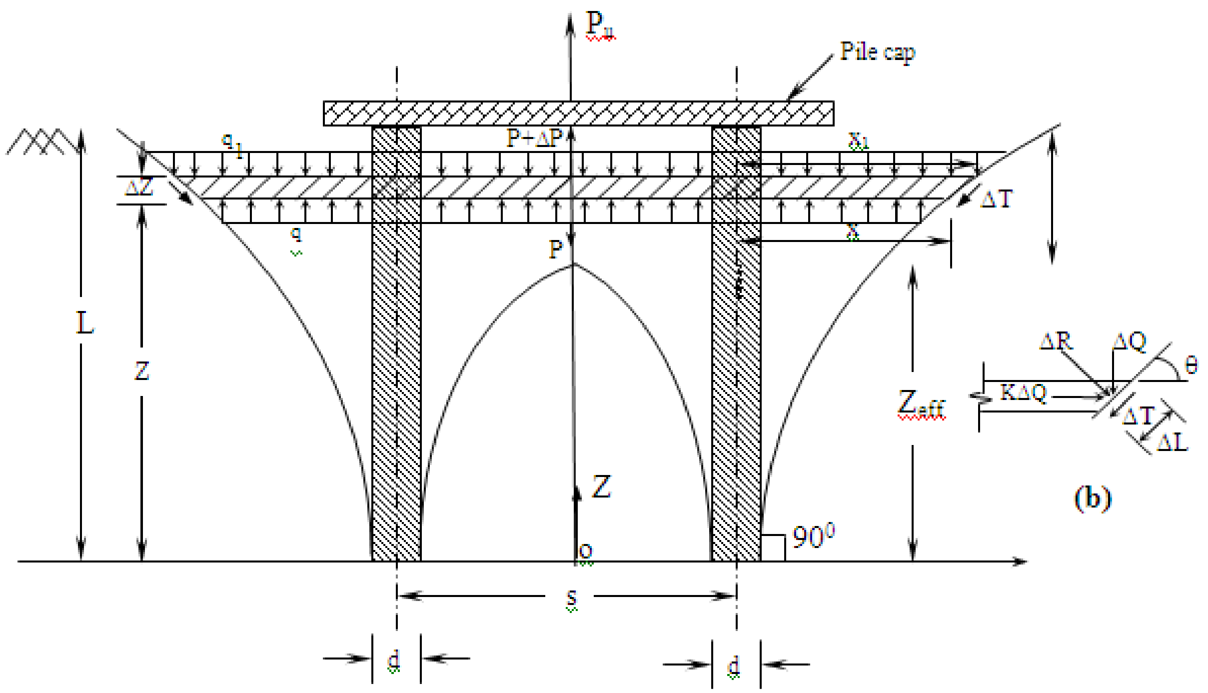
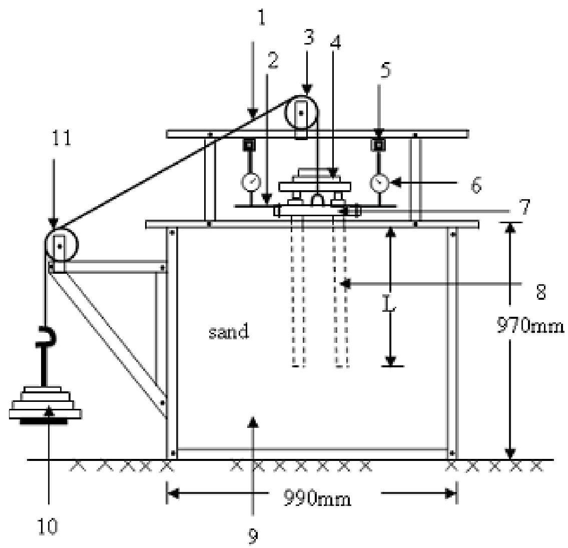


Fig. 1.(b). Pile group with overlapping of failure surfaces

As mentioned earlier to predict the net uplift capacity of pile groups with the presence of stage compressive load it is assumed that the soil-pile friction angle (δ) changes with the presence of compressive loading. The change in d value depends on several factors such as stage loading, pile group configuration and length to diameter ratio of the pile group. To check the validity of the above developed method of analysis a series of tests have been conducted on model pile groups and details are as follows;

III. Testing Program and Procedure

Tests on model pile groups were conducted in a steel tank (size 990mmx 975mm x 970mm). The tank was sufficiently large to take care of the effect of the edges of the tank on the test results as the zone of influence of the piles and loading there on is reported to be in the range of 3-8 pile diameters (Kishida, 1963). A schematic diagram of the complete experimental set-up with the loading system and pile in place and ready for test is shown in Fig. 2.



Legends

1. Wire rope
2. Aluminum strip
3. Pulley 1
4. Compressive load
5. Magnetic base plate
6. Dial gauge
7. Pile cap
8. Piles
9. Model tank
10. Uplift load
11 .Pulley 2

Fig. 2. Schematic diagram of experimental set-up

Model piles were prepared from mild steel rod of 20mm x 20mm cross section. The length of embedment of pile, L in sand bed was 400mm, 600mm and 800mm resulting L/d as 20, 30 and 40 respectively. Pile caps were prepared for 2x1, 3x1, 2x2, 3x2 and 3x3 pile groups (at 3d, 4d and 6d spacing) using 12mm thick mild steel plate. Tension tests were conducted by preloading the pile groups to a static compressive load of 25%, 50%, 75%, and 100% of their ultimate capacity in compression.

The model pile groups were embedded in homogeneous dry sand bed composed of uniformly graded Ennore sand having uniformity coefficient 1.71 and specific gravity 2.65. The maximum and minimum dry unit weights of the sand were found to be 16.2 and 14.74 kN/m^3 respectively. Sand was poured uniformly in the tank by using rail fall technique to prepare loose, medium dense and dense bed. The details of the soil properties of different densities are presented in Table I.

Table I Details of Soil Properties

Soil properties	Loose bed	Medium dense bed	Dense bed
Relative density (D_r)	34.4%	54.3%	69%
Unit weight (γ_d), kN/m^3	15.4	15.8	16.1
Angle of internal friction (ϕ)	34^0	38^0	41^0
Pile-soil friction angle (δ)	22^0	26^0	28^0

TABLE I DETAILS OF SOIL PROPERTIES

L/d	Pile group	Spacing (s/d)	Measured P_{nu} (N)					Predicted P_{nu} (N)					%error				
			Stage compressive loading (%)					Stage compressive loading (%)					Stage compressive loading (%)				
			0%	25%	50%	75%	100%	0%	25%	50%	75%	100%	0%	25%	50%	75%	100%
20	2x1 Joshi (2004)	3	174	160	139	129	89	151.4	150.9	140.6	130.5	120.5	13.3	5.5	-0.7	-0.7	-34.5
		4	194	174	159	94	74	154.5	152	139.5	127.3	115.2	20.4	12.6	12.3	-35.4	-55.7
		6	211	186	151	96	81	157.5	151	135.2	118.8	104.6	25.4	18.8	10.5	-23.8	-29.1
	3x1	3	266	210	190	168	145	216.4	207.5	190	172	154.7	18.6	1.2	0.0	-2.4	-6.7
		4	278	216	195	180	152	224.3	211.6	189.6	167.6	146.3	19.3	2.0	2.8	6.9	3.7
		6	289	224	204	185	164	234.4	213.8	183.6	155.1	127.9	18.9	4.6	10.0	16.2	22.0
	2x2 Joshi (2004)	3	305	241	190.5	110	100	281.3	257.6	238.8	216.9	197.6	7.9	-7.1	-25.4	-54.4	-64.7
		4	314	244	213.8	194	154	293.6	265.9	241.4	215.2	188.8	6.4	-9.1	-12.9	-11.0	-22.8
		6	356	316	275.7	256	226	315.3	275.0	239.6	203.2	169.5	11.4	12.9	13.1	20.5	24.9
	3x2	3	409	329	290	254	-	401.3	365.9	327.0	296.2	-	1.9	-11.3	-12.8	-16.6	-
		4	440	373	329	280	-	422.6	380.4	330.7	287.2	-	4.0	-1.9	-0.5	-2.6	-
		6	470	384	339	292	-	463.5	393.0	328.8	265.6	-	1.4	-2.3	3.0	9.0	-
30	2x1	3	300	280	240	195	155	285.8	276.5	257.8	239.3	221.8	4.7	1.3	-7.4	-22.7	-43.1
		4	324	309	264	199	166	291.8	278	255.6	233.6	213	9.9	10.0	3.2	-17.4	-28.1
		6	335	311	271	210	185	296	277.7	248.3	220.8	195.5	11.6	10.9	8.5	-5.1	-5.7
	3x1	3	408	383	328	261	218	216.4	207.5	190	172	154.7	-1.0	0.9	-6.0	-21.5	-31.7
		4	440	410	350	271	226	224.3	211.6	189.6	167.6	146.3	3.0	6.0	1.1	-14.0	-21.1
		6	464	434	364	294	255	234.4	213.8	183.6	155.1	127.9	4.6	10.1	7.3	1.6	3.7
			0%	25%	50%	75%	100%	0%	25%	50%	75%	100%	0%	25%	50%	75%	100%
30	2x2	3	504	484	419	335	269	510.8	474.6	438.8	401.6	369.5	-1.3	1.9	-4.7	-19.9	-37.4
		4	550	528	453	353	283	536.3	486.2	438.2	394.9	355.1	2.5	7.9	3.3	-11.9	-25.5
		6	581	556	466	370	310	568.2	499.2	439.1	377.6	323.9	2.2	10.2	5.8	-2.1	-4.5
	3x2	3	660	640	536	411	-	725.7	664.6	608.9	545.9	-	-10.0	-3.8	-13.6	-32.8	-
		4	681	661	553	430	-	771.3	683.5	611.1	539.9	-	-13.3	-3.4	-10.5	-25.6	-
		6	717	698	596	500	-	828.4	718.9	600.8	502.3	-	-15.5	-3.0	-0.8	-0.5	-
	3x3	3	755	730	586	-	-	1038.9	937.4	845.8	-	-	-37.6	-28.4	-44.3	-	-
		4	864	830	614	-	-	1114.9	965.5	844.8	-	-	-29.0	-16.3	-37.6	-	-
		6	1001	940	747	-	-	1210.5	1021.8	830.3	-	-	-20.9	-8.7	-11.2	-	-
40	2x1	3	560	553	492	382	270	441.5	423	395	368.7	344.2	21.2	23.5	19.7	3.5	-27.5
		4	582	572	501	385	285	448.5	424	391	359.7	331.4	22.9	25.9	22.0	6.6	-16.3
		6	619	601	511	398	310	458.2	425.2	380.8	341.6	307.4	26.0	29.3	25.5	14.2	0.8
	3x1	3	678	638	548	483	390	631.3	583	537.7	493.9	452.6	6.9	8.6	1.9	-2.3	-16.1
		4	730	670	565	505	415	650	590	534.5	481.3	432.6	7.1	11.9	5.4	4.7	-4.2
		6	812	685	578	515	470	677.4	596	521.4	454.2	393.8	16.6	13.0	9.8	11.8	16.2
	2x2	3	834	808	744	625	-	785.5	729.6	682.0	627.9	-	5.8	9.7	8.3	-0.5	-
		4	878	848	753	645	-	815.7	744.4	685.0	617.6	-	7.1	12.2	9.0	4.2	-
		6	961	890	762	675	-	865.5	763.8	680.0	592.3	-	9.9	14.2	10.8	12.3	-
	3x2	3	1113	1068	950	-	-	1119.5	1025.8	947.8	-	-	-0.6	4.0	0.2	-	-
		4	1228	1138	990	-	-	1172.8	1050.0	950.2	-	-	4.5	7.7	4.0	-	-
		6	1293	1184	1060	-	-	1258.8	1082.0	745.0	-	-	2.6	8.6	29.7	-	-

For finding the total ultimate pile group capacity in compression, the pile group is loaded with incremental compressive load until it fails. Two magnetic base dial gauges having sensitivity of 0.01 mm were used to measure the displacement of the pile group placed equidistant from the centre of the pile cap and their average value as observed under load application is taken as the final displacement. The load-displacement curves were plotted for different pile groups. From these sets of curves the ultimate capacity in compression is determined using double tangent method. Corresponding pile group is first loaded with the required stage of compressive load, and then it is subjected to incremental uplift loads till failure take place.

IV. Test Results and Discussion

Most of the tests were conducted in medium dense soil to study the effect of the stage compressive loading on the pull out capacity of model pile groups. Few tests were also conducted in loose and dense soil to asses the role of soil density on pull out capacity of pile groups with stage loading. Unless and until mentioned the tests results discussed below belongs to medium dense soil.

The load verses displacement curves were plotted for all the pile groups at different pile spacing and L/d ratio. Fig.3 shows typical load displacement response of a 2×2 pile group at 3d pile spacing under uplift load with and with out compressive load. The load-displacement curves show similar behavior under different values of compressive loading. By using the double tangent method the gross ultimate uplift load was found. The net ultimate load on a pile was reworked by subtracting the corresponding compressive load along with self weight of pile and cap. The pile head displacement required to mobilize the peak uplift resistance corresponding to the various levels of stage loading as estimated from the above figures reveal that these values generally corresponds to about 3 % to 7% of pile diameter.

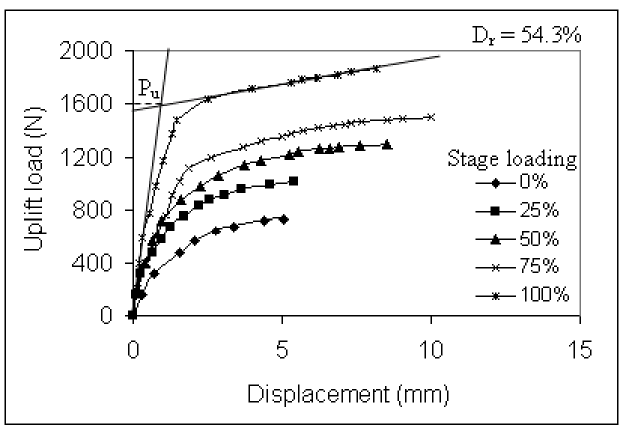


Fig. 3 Uplift load V_s Displacement curve (L/d=30, 2 x 2 pile group, 3d spacing)

Variation of net uplift capacity of 2 x 1 and 2 x 2 pile groups with percentage of stage loading and pile spacing are presented in Figs. 4 (a) and 4(b). It is observed from these figures that there is a definite trend of decrease in the net uplift capacity with the increase of stage compressive loading and the least value of the net ultimate capacity would manifest at 100% stage compressive loading. The rate of decrease in the value of the net uplift capacity increases up to a limiting value of the percentage of stage compressive loading beyond which it decreases significantly. These figures also demonstrate that the net uplift capacity is significantly affected by the pile spacing and as the spacing is increased from 3d to 6d for a 2 x 2 pile group (Fig. 4b) the increase in the net uplift capacity in the absence of any axial compressive load is 77N while the same when there is cent percent stage loading is 40N. Similar trend is observed for other pile groups.

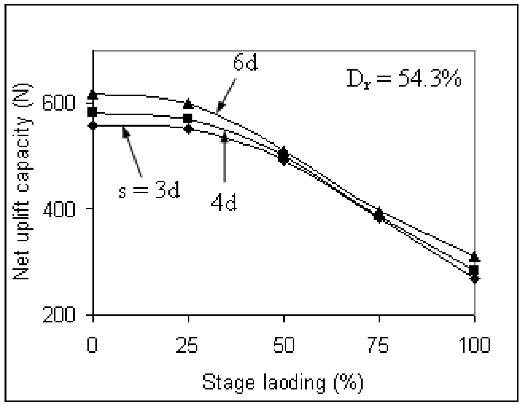


Fig. 4(a). Variation of net uplift capacity with stage loading (L/d = 40, 2 x 1 pile group)

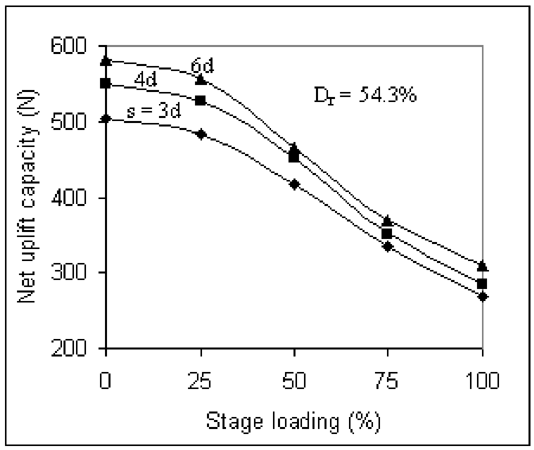


Fig. 4(b). Variation of net uplift capacity with stage loading (L/d = 30, 2 x 2 pile group)

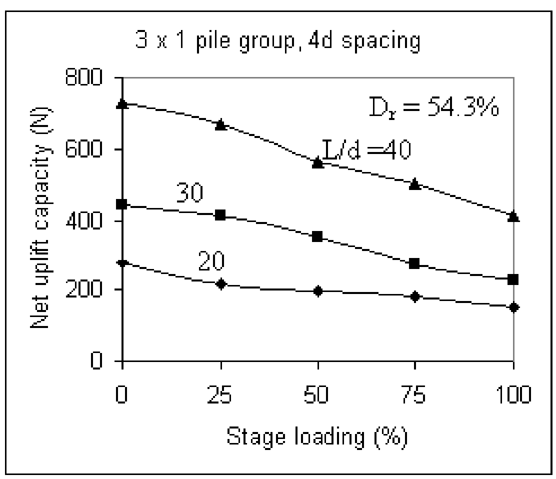


Fig. 5 Effect of stage loading and L/d ratio on net uplift capacity

Variation of net uplift capacity of pile groups with stage of compressive loading for 3x1 pile group at 4d spacing for different L/d ratio is shown in Fig. 5. At any given percentage of stage loading acting on the pile group the net uplift capacity of a pile group is observed to increase with the increase in the L/d ratio. Further, as the L/d ratio increases the rate of decrease in net uplift capacity with stage loading increases.

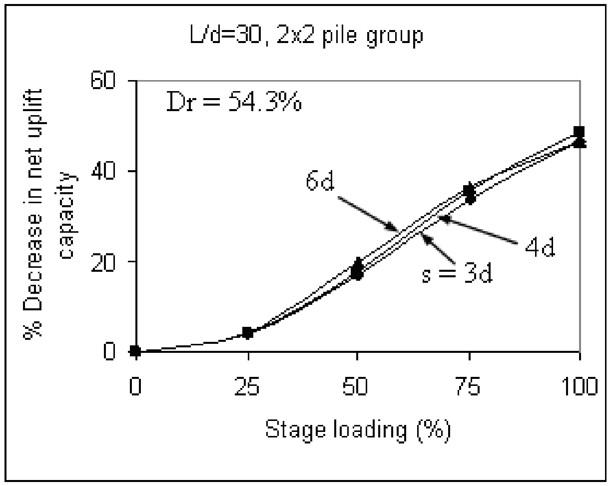


Fig. 6 Effect of stage loading and spacing on percentage decrease in net uplift capacity

To focus the significant influence of stage loading on the net uplift capacity the percentage decrease in the net uplift capacity of a 2 x 2 pile group with L/d equal to 30 is shown in Fig. 6. As the compressive load increases from 0% to 100% the reduction in net uplift capacity is of the order of 46.6%, 48.5% and 49% for 3d, 4d, and 6d pile spacing respectively. Up to 25% compressive load the effect of the compressive load on the net uplift capacity is not appreciable beyond which the percentage reduction of the net uplift capacity increases significantly almost at a constant rate irrespective of the spacing.

Net uplift capacity per pile in a group is obtained by dividing the net uplift capacity of a particular pile group by the corresponding number of piles in that group. For a 2x2 pile group with L/d equal to 30 the variation of net uplift capacity per pile in a group with stage compressive loading for different pile spacing is shown in Fig.7. On the same figure the results of tests conducted on a single pile with percentage of stage loading varying from 0 to 100% are presented for comparison. It is observed that irrespective of pile spacing and stage loading the net uplift capacity per pile in a group is always less than the net uplift capacity of single pile.

Group efficiency (η) is defined as follows as the ratio of the uplift capacity of the pile group at a given stage compressive load to the number of piles (N) in the group times the net uplift capacity of a single pile at that stage compressive load.

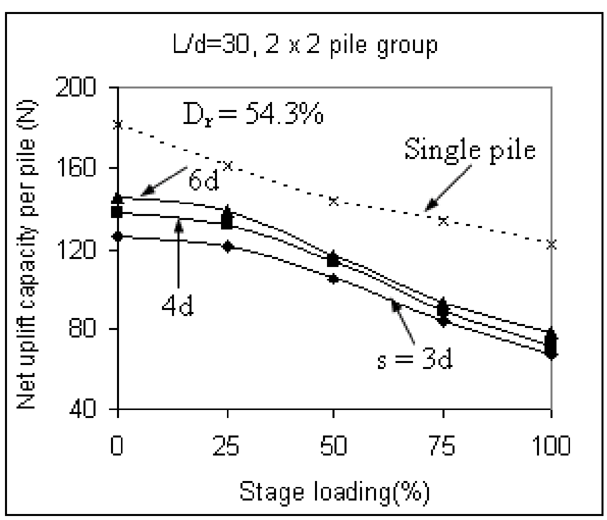


Fig. 7 Effect of stage loading and pile spacing on net uplift capacity per pile

$$[8] \quad \eta = \frac{\text{Net uplift capacity of pile group}}{N \times \text{Net uplift capacity of single pile}} \times 100$$

In Fig. 8 the percentage variation of the pile group efficiency with the percentage stage loading is shown for a 2 x 2 pile group at different spacing with an L/d ratio of 30. It can be observed from the above figure that for a given pile group and spacing, efficiency in uplift first increases from 0% to 25% compressive load and there after it decreases continuously. Thus, maximum efficiency is observed at 25% compressive load and minimum efficiency is observed at 100% compressive load. From Fig. 9 it is observed that for a particular pile group configuration higher spacing is attributed with higher efficiency (maximum for 6d and minimum for 3d spacing) for all the stages of compressive loading. Similar observations were made for other test conditions. Fig. 10 shows the variation of group efficiency for different pile group configuration with spacing for an L/d ratio of 30 at 50% stage compressive loading. For a particular spacing, a 2 x 1 pile group has more efficiency as compared to other pile groups. The reduction in group

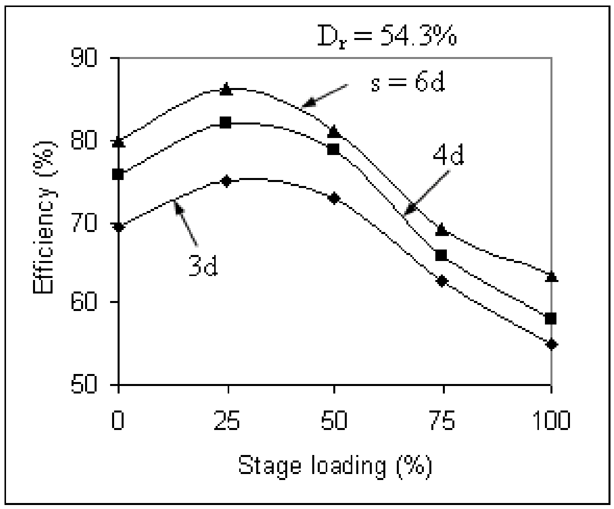


Fig. 8 Effect of stage loading and spacing on group efficiency (L/d = 30, 2 x 2 pile group)

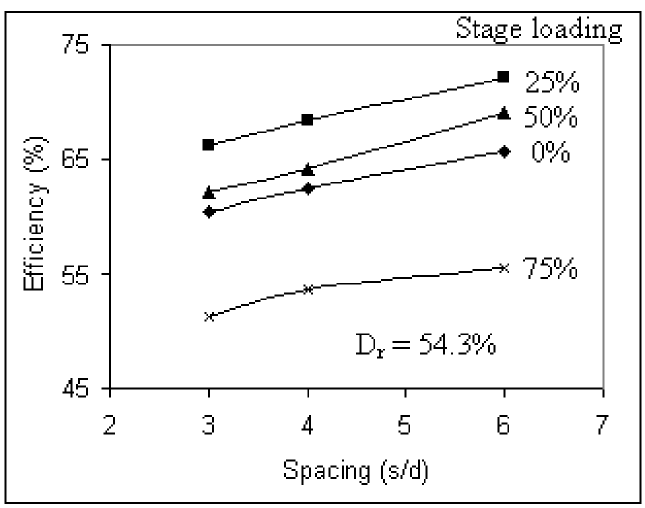


Fig. 9 Effect of spacing and stage loading on group efficiency (L/d = 30, 3 x 2 pile group)

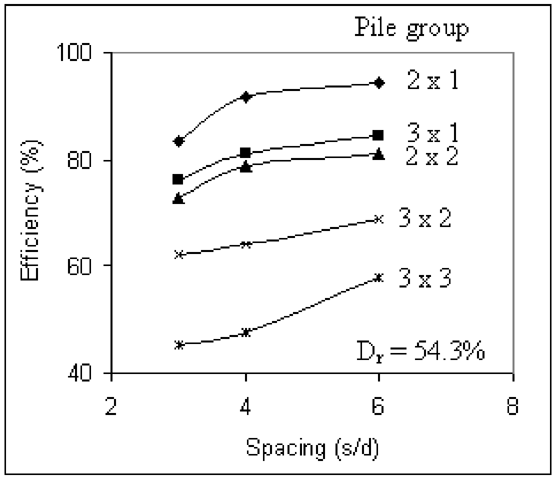


Fig. 10 Effect of spacing and pile group configuration on efficiency (L/d = 30, 50% Stage compressive loading)

efficiency at 50% stage compressive load is in the order of 10.7%, 14.2%, 302% and 48.3% from 2x1 groups to 3x1, 2x2, 3x2 and 3x3 respectively. However, irrespective of stage compressive load the group efficiency decreases as the number of piles in a group increases.

The variation of group efficiency for different spacing with an L/d ratio of a 3x2 pile group at 50% stage compressive load is presented in Fig.11. It is observed that here also for a given spacing the group efficiency decreases as the L/d ratio increases. The reduction in efficiency is observed to be 9% and 29% from an L/d ratio of 20 to 30 and 20 to 40 respectively. Similar trend has been observed at other stages of loading.

To study the effect of soil density on net uplift capacity of pile groups, limited model tests were conducted on 2 x 2 pile group with an L/d ratio of 30 at 4d spacing in a loose, medium dense and dense soil bed. The results are presented in Fig.12 and it is observed that at 0% compressive loading the net uplift capacity increases from loose to dense medium. However, with the presence of compressive load on the pile group the net uplift capacity in dense soil is less as compared in medium dense soil. At 100% stage loading

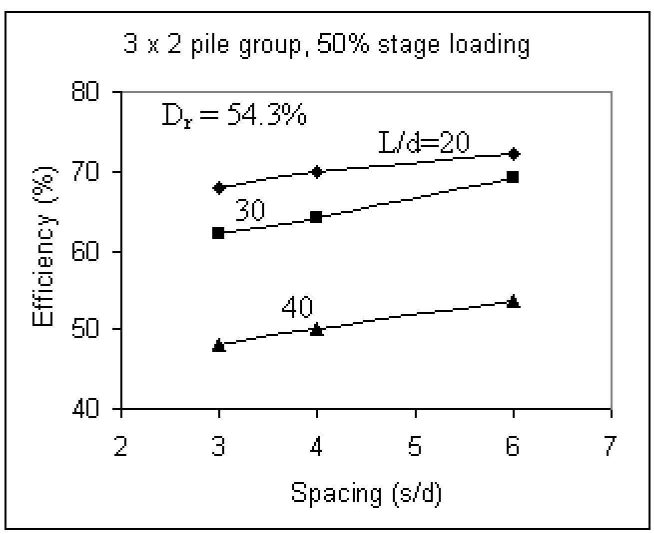


Fig. 11 Effect of spacing and L/d ratio on efficiency

the net ultimate uplift capacity is almost same for both medium dense and dense soil. The percentage reduction in net uplift capacity with stage loading is observed more for dense soil and less for loose soil. It is interesting to note that as the percentage of stage loading increased beyond a value of about 20% stage compressive loading the net uplift capacity of a pile group in dense bed is lower than the same placed in medium dense sand bed. It may be due to the fact that the presence of compressive loading on the pile head in dense sand bed may loosen the soil around the pile.

As discussed earlier, in the present analysis it is assumed that the placement of compressive load on the pile group alters soil-pile friction angle (δ). So, based on the above model test results at different stages of compressive loading and pile groups the modified soil-pile friction angle has been back calculated using the proposed model. From the back calculated values it is observed that the reduction in d value depends upon the percentage of stage compressive load and pile group configuration and the following empirical relation is suggested to reflect the phenomenon.

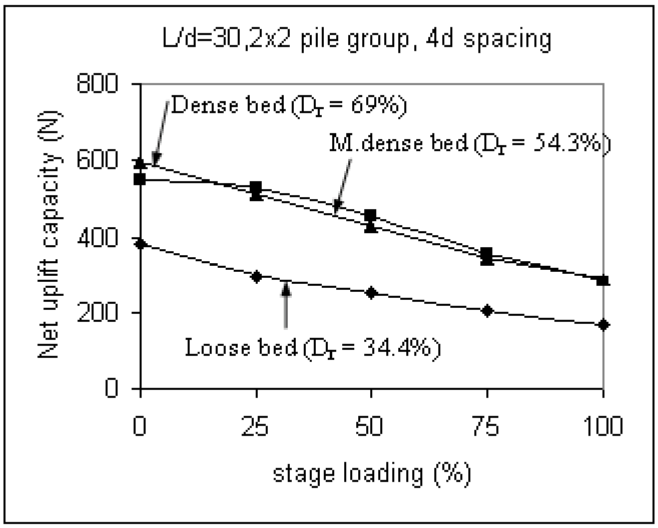


Fig. 12 Effect of soil density on net uplift capacity

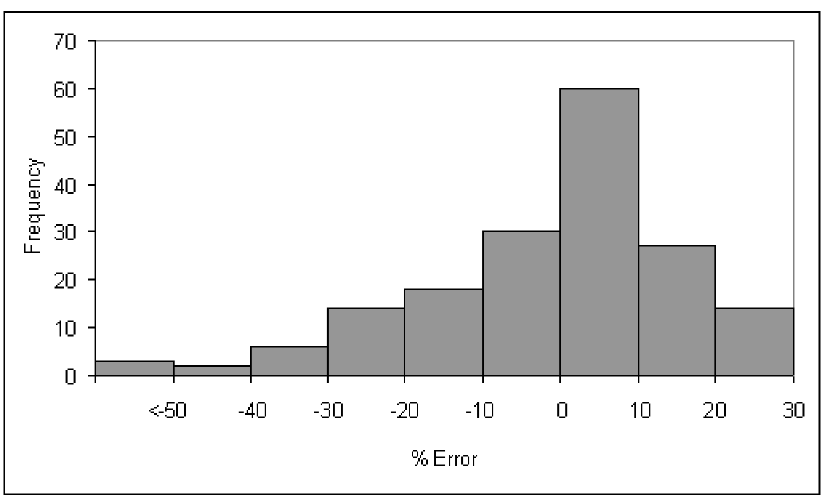


Fig. 13 Frequency distribution diagram

[9] $\delta = \delta_0\left[1 - 0.05 s_1 (m+n)\sqrt{s/d}\right]$

Where,

δ_0 = Initial soil-pile friction angle

s/d = pile spacing

m = number of rows in a group

n = number of columns in a group

s_1 = stage loading (in fraction)

For a give pile group configuration and percentage of stage loading, net uplift capacity has been estimated using the corresponding δ value as determined with the help of the Eq. 9. The predicted and measured values of net uplift capacity of pile groups are presented in Table II showing a very good agreement between both. The error is even less than 15% in case of 68% of the data (119 out of 174). A bar chart is given in Fig.13 showing the frequency distribution diagram of the number of test data and the percentage error. From this figure it is observed that majority of the data is having error in between 0 to ± 20% and in case of only11 data points out of 174 the error is more than 30% on unsafe side.

V. Conclusions

From the foregoing study the following conclusions are drawn.

1. The stage compressive loading is a significant parameter influencing the net uplift capacity of a pile group. The net uplift capacity degreases with the increase in the stage compressive loading and the maximum decrease occurs at 100% stage compressive loading.
2. For a given pile group configuration, the group efficiency is observed to be high at 25% of stage loading and least efficiency is at 100% stage loading.
3. It is observed that for a given spacing and stage loading the group efficiency decreases with an increase in the L/d ratio. For all the stages of compressive loading higher spacing is attributed with higher efficiency (maximum for 6d and minimum for 3d spacing).
4. The proposed semi empirical method to predict the net uplift capacity of a group of piles with the presence of compressive loading has excellent potential because 93% of the predicted values have error less than 30% in comparison to the experimentally observed values.

REFERENCES

[1] B.C. Chattopadhyay, and p.j. Pise, P.J. "Uplift Capacity of Piles in Sand". *Journal of Geotech. Eng.,* 112(9), pp. 888-904, 1986.

[2] B.M.Das, "A Procedure for Estimation of Uplift Capacity of Rough Piles". *Soils and Foundations,* 23 (3), pp.122-126,1983

[3] B.M.Das, and G.R.Seeley, "Uplift Capacity of Buried Model Piles in Sand". *Journal of the Geotech. Engrg. Div*., ASCE, 101(10), pp. 1091-1094,1975

[4] B.M.Das, G.R Seeley, and E.J.Smith, "Uplift Capacity of Group Piles in Sand".. *Journal of the Geotech*. Engrg. Div., ASCE, 102(3), pp. 282-286, 1976.

[5] B.K.Dash. and P.J. Pise, "Effect of Compressive Load on Uplift Capacity of Model Piles". Journal of Geotech And Geoenv.Engng.,ASCE, 129(11), pp.987-992, 2003

[6] N.F.Ismael, and T.W. Klym, "Uplift and Bearing Capacity of Short Piers in Sand". *Journal of the Geotech. Engrg*. Div., ASCE, 105(5), pp. 579-594, 1979.

[7] H.Kishida, "Stress distribution by model piles in sand". *Soils and Foundations,* 4(1), pp.1-23,1963

[8] D.R. Levacher, and J.G Sieffert, "Test on model tension piles". *Journal of the Geotech. Engrg. Div*., ASCE, 110(12), pp.1735-1748, 1984

[9] G.G. Meyerhof, "Uplift Resistance of Inclined Anchors and Piles". *Proc. 8th Int. Conf. on Soil Mech. and Found. Engrg*., Moscow, Vol.2, pp.167-172,1973.

[10] G.G.Meyerhof, and J.I. Adams, "The Ultimate Uplift Capacity of Foundations". *Can. Geotech. Jour.,* 5(4), pp.225-244,1968

[11] A.D. Nicola, and M.F.Randolph, "Tensile and Compressive Shaft Capacity of Piles in Sand". *Journal Geotech. Engrg., ASCE,* 119 (12), pp.1952-1973,1993

[12] H.Ochiai, and P.V.Lade, "Three dimensional behavior of sand with anisotropic fabric". *Journal of Geotech.Eng.,* ASCE, 109(10), pp.1313-1328, 1983

[13] M.Oda and I. Koishikawa, "Anisotropic fabric of sand". *Proc., 9th International Conf. on Soil mechanics and Foundation Engg.,* Vol.1, 235-238, 1977

[14] H.G. Poulos, and E.H. Davis, "Pile foundation analysis and design". *1st Ed., Wiley,* New York, 1980.

[15] K.S. Rao and K.H.Venkatesh, "Uplift Behavior of Short Piles in Uniform Sand". *Soils and Foundations*, 25(4), pp.1-7, 1985.

[16] G. Ramasamy, B.Dey, and E. Indrawn, "Studies on Skin Friction in Piles under Tensile and Compressive Load". *Indian Geotechnical Journal,* 34(2), pp. 276-289, 2004

[17] A.S.Vesic, "Tests on Instrumented Piles, Ogeechee River Site". *Journal of the Soil Mech. and Found. Engrg*. Div., ASCE, 96(2), pp.561-584, 1970.

List of symbols

a & b plan dimensions of the pile group

D_r relative density

d pile diameter

K lateral earth pressure coefficient

L embedded length of pile

m number of rows in a group

n number of columns in a group

N number of piles in a group

P_{nu} net ultimate uplift capacity of pile

s pile spacing

s_l stage loading (in fraction)

x lateral extent of failure surface

x_G lateral extent of failure surface at ground surafce

ϕ angle of internal friction of the soil

δ_0 initial soil-pile friction angle

δ soil-pile friction angle

γ unit weight of the soil

λ length to diameter ratio (L/d)

θ angle of failure surface with respect to vertical

η efficiency