Analysis of Suction Caissons in Soft Clay

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Abstract. The cost of establishing any offshore structure is quite expensive. One of the largest expenses in offshore infrastructure is the foundation as environment like wind, wave and soil or a combination, poses a challenge in most cases. For observation platforms, suction piles offer an unique advantage that it can be reused any number of times by just shifting the location which helps reduce the cost of preliminary infrastructure for potential identification quite feasible. Suction piles or suction buckets are hollow cylindrical steel or concrete caisson, closed at the top and open at the bottom[2]. They are installed by applying suction inside the air tight caisson therefore not difficult for setting up. Once the required data is collected, the pressure inside the caisson is reversed, to be moved to another location. These suction piles resist loads due to the mobilized frictional resistance occurring inside shaft as well as the outside while the bearing resistance comes from the annulus and top plate as it rests on the ground surface [1]. An analysis on the aspect ratio of the caisson for soft clay encountered in the gulf regions is studied in detail [4].

An optimum aspect ratio of the bucket considering various failure conditions is obtained for the gulf regions using numerical computation which can be easily adopted to other location by changing the input parameters. The ratios which are ideal for the gulf regions are also stated in the paper. The suction pile installation has also been studied using a finite element analysis tool and the failure pattern due to reversal is observed. It is observed that once the suction exceeds the required value, reverse bearing failure occurs causing the bucket to fail.

Keywords:Suction Caissons, Soft Clay, Offshore Foundation, Numerical Computation.

1   Introduction

The foundations often encountered in offshore are monopiles, suction buckets and gravity foundations. These foundations are subjected to heavy lateral loads caused by wind, wave and seismic forces. Therefore, the foundations account for a significant cost of the total construction or erection cost for offshore structures. For a wind turbine to be set up, extensive field studies and measurements are carried out with the help of coastal and offshore observation platforms. Suction buckets act as better alternative in economical and re-use point of view for observation platforms [3].

Suction buckets or suction caissons are large cylindrical structure, usually made of steel, open at the base and closed at the top. It might be used as a shallow foundation or as short stubby pile. The suction buckets as shallow foundations are generally used in sandy soils while the suction piles or anchors are used in clayey soil [1]. The suction bucket consists majorly of two installation stages: i) Penetration due to self weight and ii) Penetration due to application of suction. By reversal of suction, the bucket can be removed from the area of installation. This application of suction is what makes suction buckets a viable alternative. The suction buckets can be shifted from one location to another after required observations are made.

The Gulf regions of India offer huge potential in terms of offshore wind energy. Based on three borelogs obtained during a geotechnical investigation carried out in this region, it is observed that it has very soft clays with the shear strength values ranging between 20 to 25 kN/m^2 to a depth ranging between 8 -15 m. As per literature, the bucket is to be designed as a short pile for clayey soils. However, this paper deals with the determination of preliminary dimensions and suitable aspect ratio for the particular soil. This methodology can also be used for all soil types with the same algorithm. The same aspect ratio is then modeled using a Finite Element Package to validate the result.

Table 1 Material Properties used in the study

Parameter	Symbol	Value	Units
Self- weight of the structure	P	220	kN
Factored Self-weight of the structure	P_f	550	kN
Submerged unit weight of soil	γ'	6.5	kN/m^3
Adhesion factor	α	0.9	-
Undrained shear strength	c	20	kPa

2   Installation

The resistance offered to loads onto the suction bucket is offered by the mobilized skin friction both on the inner and outer sides of the wall and the end bearing is met by the plate closing the cylinder on the top and the area of the annulus [2]. The areas of resistance offered are represented in Fig. 1. It is to be noted that the end bearing due to top plate occurs only after full installation of the suction bucket after a contact is established. The properties used in the analytical calculation are as given in Table 1. It is also to be noted that for the simplification of the study, a constant shear strength value is adopted. There are two main stages of installation: 1) self-penetration and 2) suction assisted penetration. Apart from this, the installation has to be checked for failure that maybe caused due to reverse bearing capacity failure, buckling of the suction walls and the maximum suction that can be applied. The terminologies used in the equations are given in Table 2.
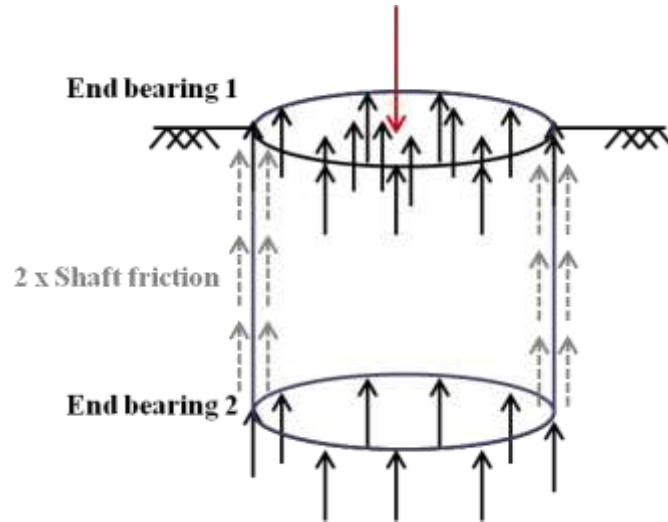
Figure 1 Resistance offered by suction pile

Table 2 Symbolic notations with units

Parameter	Symbol	Units
Depth of penetration/ Height of bucket	h	m
Depth of penetration due to self-weight	h_s	m
Depth of suction assisted penetration	h_{req}	
	$h-h_s$	m
Depth of water above seabed	h_w	m
Inner diameter of bucket	D_i	m
Outer diameter of bucket	D_0	m
Average diameter of bucket	D	M
Thickness of bucket	t	m
Selected Aspect ratio(h/D)	β	-
Self- weight of the structure during installation	P	kN
Factored Self-weight of the installed structure	P_f	kN
Atmospheric Pressure	p_a	kPa
Unit weight of water	γ_w	kN/m^3
Submerged unit weight of soil	γ'	kN/m^3
Adhesion factor	α	-
Undrained shear strength	c	kPa
Suction	s	kPa

The bearing capacity after installation is the sum of end bearing at the annulus given by $\pi DtcN_c$, end bearing of top plate given by $\pi D_i^2 cN_c/4$, skin friction on the inner and outer surfaces of the vertical walls given by $\pi\alpha hc(D_0-D_i)$ to compensate the self weight of the entire structure.

3　　Capacity Calculation

As the aim is to determine the least aspect ratio of a suction bucket to successfully work for the gulf regions, the h/D ratios are varied from 0.1 to 5[5] and checked to see if the bucket sustains all the failure mechanisms. The aspect ratios that need to be determined are the height of the bucket (h), average diameter of the bucket (D) and the thickness (t) of the bucket. Three simultaneous equations, namely Eqn. 1 Eqn. 2 and Eqn. 3, are utilized to determine these three unknowns.

Based on the final bearing capacity of the suction bucket explained above:

$$\frac{\pi D_i^2 c\, N_c}{4} + \pi Dt\ c\ N_c + \pi\alpha hc(D_o + D_i) - P_f = 0 \tag{1}$$

Based on the selected h/D ratio:

$$h - \beta D = 0 \ ; \tag{2}$$

Based on the minimum thickness required to prevent buckling of the caisson, as per API standards:

$$\frac{D}{100} + \frac{6.35}{1000} - t = 0 \ ; \tag{3}$$

By simultaneously solving all the three equations, the required aspect ratios are derived for a particular h/D ratio. With the obtained aspect ratio, the next step is to find the plug height or the height of self-penetration, h_s.

3.1　　Self- Penetration

The self-penetration is achieved due to the weight of the superstructure and the self-weight of the bucket due to the action of gravity against the bearing capacity of the footing on the soil. This self-penetration creates a soil plug inside the annulus which prevents the soil from flowing into the bucket during the application of suction, effectively preventing 'reverse bearing capacity' failure. The height achieved due to self-penetration is computed by equating the frictional and end resistance offered by the soil to the bucket and the weight acting against it. Substituting the P_f with P and h by h_s and rearranging Eqn. 1 gives the height of self-penetration achieved as in Eqn. 4.

$$h_s = \frac{P - (\pi Dt\ cN_c)}{\pi\alpha c\ (D_o + D_i)} \tag{4}$$

The remaining height yet to be penetrated, h_{req}, is the difference between the total height of the bucket and the depth of self-penetration achieved, h_s.

3.2 Suction Assisted Penetration

The suction acts on the top plate of the caisson, upwards. The suction load is therefore computed by the multiplication of the suction pressure and the area of the top plate. This suction works on creating a differential pressure on the inside and the outside of the caisson. However, a huge difference in the stress inside and outside of the caisson creates a flow of soil instead of the installation of suction bucket. To maintain equilibrium of forces in the caisson, the equilibrium equation can be rearranged to find suction, as described in Eqn. 5

$$s = \frac{(2\pi h_{req}\alpha c D) + (\gamma' h_{req} + c N_c)\pi D t - P}{\frac{\pi D_0^2}{4}} \qquad (5)$$

The suction acts on the top plate of the caisson and the end and skin friction to be overcome by the suction is equated to obtain equation 5. The suction obtained for the equation, is the required pressure to be applied to install the caisson flush on to the seabed level. This pressure is however theoretical and is limited to the cavitation pressure of water, pump capacity and the pressure differential that can be created between the inside and the outside of the caisson, which depends on the water depth at the area of installation.

3.3 Reverse bearing capacity failure

In case of failure of plugs, a plastic zone is created in the plug region. This plastic zone stops further penetration of the caisson during application of suction. The soil flows inwards during application of suction, effectively preventing the installation. The minimum height required for the reverse bearing failure not to occur as given by Houlsby[] is computed from Eqn. 6.

$$P + \frac{c N_c \pi D_i^2}{4} - h_f \alpha c \pi D_0 \left(1 + \frac{D_i^2}{(0.01h^2 + 0.2D_0 h_f)}\right) - \left(\gamma' h_f + c N_c\right)\pi D t = 0 \qquad (6)$$

This value should always be less than the h_s for the effective plug formation. This phenomenon is further studied with the use of a numerical package, to understand the plastic zone formation and the movement of soil inside the bucket foundation.

4   Optimization

Optimization is to be done to determine the maximum economical section and suction for a given weight and soil conditions in the Gulf regions. A computational tool, Matlab R2019a was utilized solve the equations and carry out the iterations. The input are as shown in Table 1. For h/D ratios ranging from 0.1 to 5 and the corresponding h_s, h_f and suction pressure required is computed and is as given in the Fig. 3. The entire output of the program is seen in table 3.

It is observed that as the h/D ratio is increased, the h of the bucket increases, which in turn increases the self-weight of the bucket, thus increasing the height due to self-penetration. It is also seen that as h/D increases, the suction to be applied also increases. For some cases of h/D as seen up to the case of 0.9, the suction obtained is negative. With regard to this study, it simply means that no suction is necessary for installation. It is seen to that the height of penetration is always kept high as compared to the height of failure for successful installation.

Table 3 Variation of study parameters with respect to h/D

h/D	h (m)	t (mm)	h_f (m)	h_s (m)	S (kPa)	h/D	h (m)	t (mm)	h_f (m)	h_s (m)	S (kPa)
0.1	0.21	28	0.92	1.25	-43.5101	2.6	3.66	21	1.26	2.19	116.1052
0.2	0.41	27	0.93	1.3	-37.287	2.7	3.75	21	1.27	2.22	121.7855
0.3	0.6	27	0.95	1.35	-30.4433	2.8	3.85	21	1.28	2.25	128.3912
0.4	0.78	26	0.96	1.4	-24.7143	2.9	3.95	20	1.3	2.27	134.6206
0.5	0.96	26	0.98	1.45	-17.9194	3	4.04	20	1.31	2.3	140.7282
0.6	1.13	26	0.99	1.49	-11.4055	3.1	4.14	20	1.32	2.33	147.5371
0.7	1.29	25	1	1.54	-5.12265	3.2	4.23	20	1.33	2.35	153.8268
0.8	1.45	25	1.02	1.58	1.267024	3.3	4.32	20	1.35	2.38	160.1877

|											
0.9	1.6	25	1.03	1.62	7.769173	3.4	4.41	20	1.36	2.41	166.6249
1	1.75	24	1.04	1.66	14.05291	3.5	4.49	20	1.37	2.43	172.4388
1.1	1.89	24	1.06	1.7	20.34815	3.6	4.58	20	1.39	2.46	179.0571
1.2	2.03	24	1.07	1.74	26.8036	3.7	4.66	19	1.4	2.48	184.709
1.3	2.17	24	1.08	1.77	33.82176	3.8	4.75	19	1.41	2.51	191.4915
1.4	2.3	23	1.1	1.81	39.64401	3.9	4.83	19	1.43	2.53	197.6067
1.5	2.42	23	1.11	1.84	45.80001	4	4.91	19	1.44	2.55	203.7951
1.6	2.55	23	1.12	1.88	52.30547	4.1	4.99	19	1.45	2.58	210.0539
1.7	2.67	23	1.14	1.91	58.7246	4.2	5.07	19	1.46	2.6	216.3922
1.8	2.79	22	1.15	1.95	64.88228	4.3	5.15	19	1.48	2.62	222.8074
1.9	2.91	22	1.16	1.98	71.55599	4.4	5.23	19	1.49	2.65	229.2965
2	3.02	22	1.18	2.01	77.73983	4.5	5.31	19	1.5	2.67	235.8689
2.1	3.13	22	1.19	2.04	84.04242	4.6	5.38	19	1.52	2.69	241.7233
2.2	3.24	22	1.2	2.07	90.46671	4.7	5.46	18	1.53	2.71	248.2117
2.3	3.35	21	1.22	2.1	96.64339	4.8	5.53	18	1.54	2.74	254.214
2.4	3.45	21	1.23	2.13	102.8924	4.9	5.61	18	1.55	2.76	261.1111
2.5	3.55	21	1.24	2.16	109.0168	5	5.68	18	1.57	2.78	266.8439
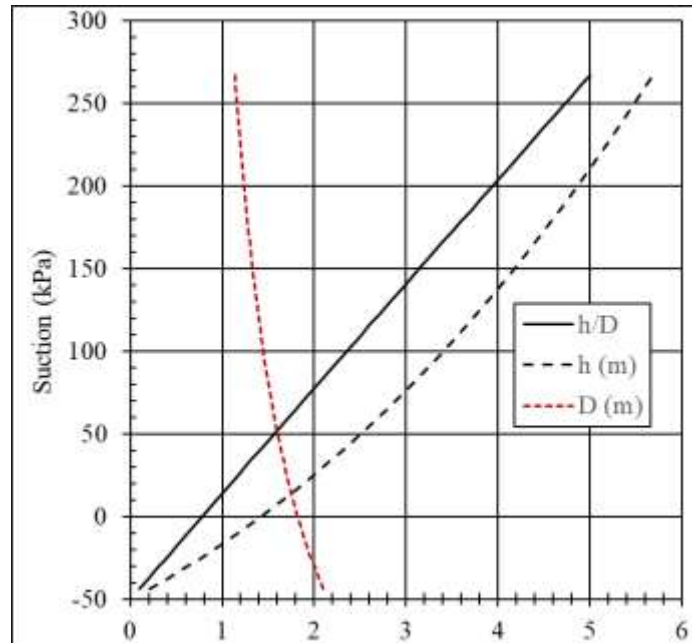
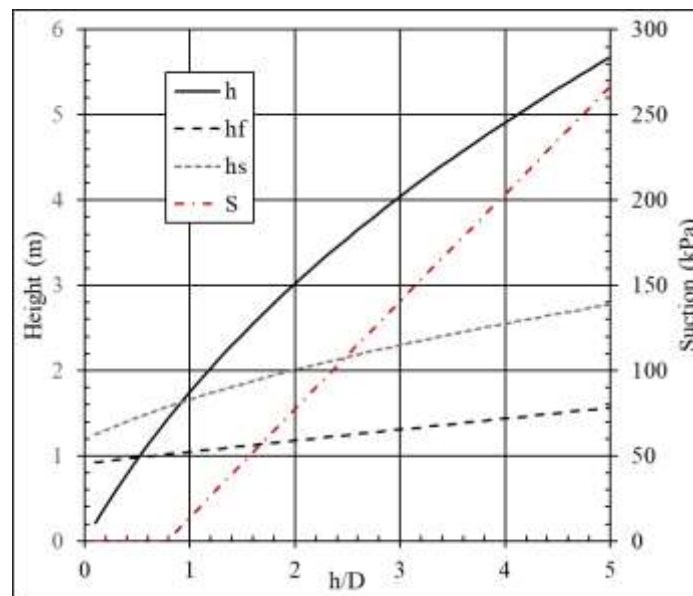**Figure 2 Variation of suction on lateral dimensions of the caisson**

Figure 3 Design chart for optimization

5   Numerical Analysis

A numerical model using a finite element package called PLAXIS 3D was utilized to study 'reverse bearing capacity failure' inside the caisson. The reverse bearing capacity of the suction plays a crucial role in the determination of the aspect ratio of the bucket. A study is to be carried out by increasing the suction value applied to the caisson and the reaction in studied. A suction bucket of 2m nominal diameter, 3m height is chosen for the study. Based on the formulation, it is observed that the bucket self-penetrates only to a depth of 7cm on its own and the remaining height requires a suction of about 210 kPa.

Table 4 Physical parameters of the model

Parameter	Value	Units
Depth of penetration/ Height of bucket	3	m
Inner diameter of bucket	1.97	m
Outer diameter of bucket	2.03	m
Average diameter of bucket	2	M
Thickness of bucket	26	mm
Selected Aspect ratio(h/D)	1.5	-
Suction Pressure	Varies	kPa

The model consists of 39993 elements with element size varying from 0.0656 to 2.012 m and mesh refinement study was carried out. The boundary limits are considered so the results are not influenced by the boundary conditions. A suction bucket of dimensions as shown in Table 4 is considered in this study. The material properties of the model are provided in Table 5. The suction values are varied from 100, 150, 200, 250 and 300 kPa.

Table 5 Parameters used in PLAXIS model

| Description	Value	Units
Type of Analysis	Mohr- Coulomb	
Type of Drainage	Drained	
Saturated Unit Weight of Soil	17	kPa
Unsaturated Unit Weight of Soil	16	kPa
Young's Modulus, E	15000	kPa
Poisson ratio	0.2	-
Cohesion, c	20	kPa
Angle of internal friction	0	deg

The vertical displacements, mobilized shear stress and the deviatoric strains are studied to understand the effect of reverse bearing capacity as seen in fig. 5 a, b and c. From the graphs in figure 5, we can see the effect of suction on the reverse bearing capacity failure. We can see from the figures that until the suction pressure was 250 kPa, there was only nominal change in the displacements. However, as the pressure reaches 300 kPa, we can see an increase in displacement by 750%. For the mobilized shear stress, we can see that the maximum value flatlines after the suction increases more than 250 kPa. Any increase in suction pressure will not contribute to any further resistance of the caisson with the soil, leading to reverse bearing capacity of the soil. The strain value also increases rapidly once the pressure increases over 250kPa, signifying a failure of the soil.
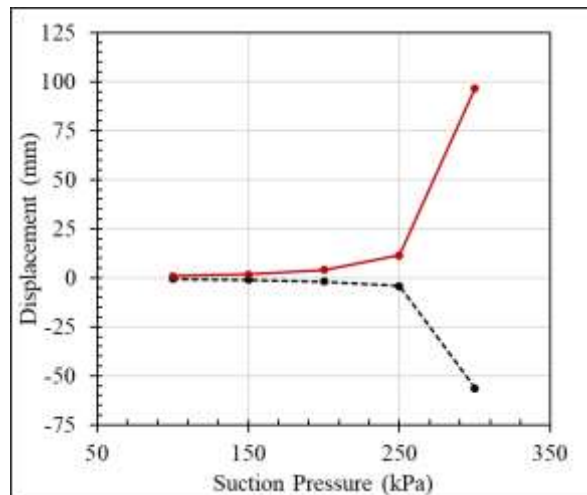
(a)
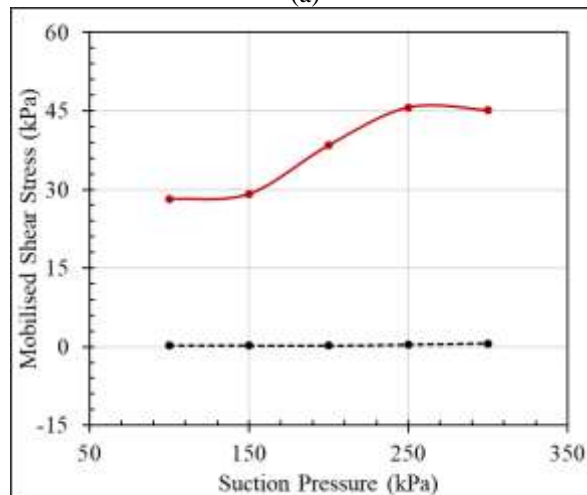
(b)
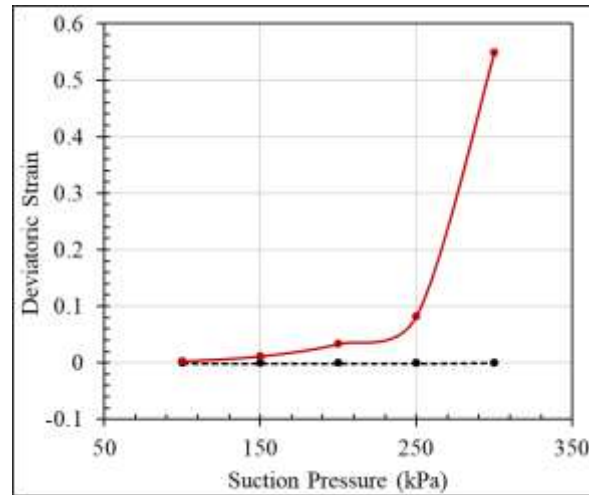
(c)

Figure 4 Variation in study parameters for different suction with a) displacement b) mobilised shear stress and c) deviatoric strain. The red solid indicates maximum value in all graphs

From Fig. 6 it is seen that the plastic zone is created inside and just below the area of installation of the caisson. This is due to the plug not being able to withstand the suction pressure applied. This causes the soil to move upwards into the caisson rather than the caisson move towards the bed level. It can also be seen from Fig. 7 a) that the pressure dissipation is attributed highly due to shear dissipation rather than bearing as seen from Fig. 6 b[6]. Further models have to be studied to understand the complex behavior of suction buckets through numerical modeling. Study also needs to be carried out in understanding the undrained behavior.
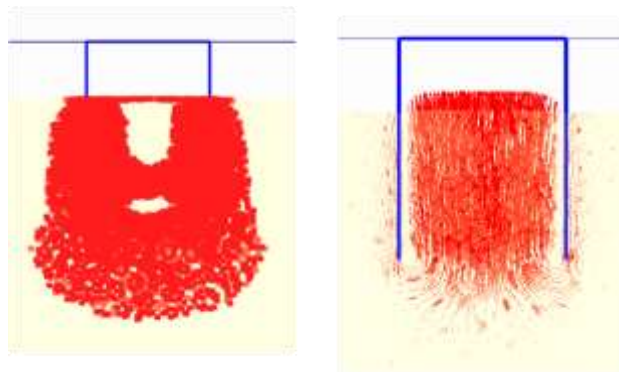

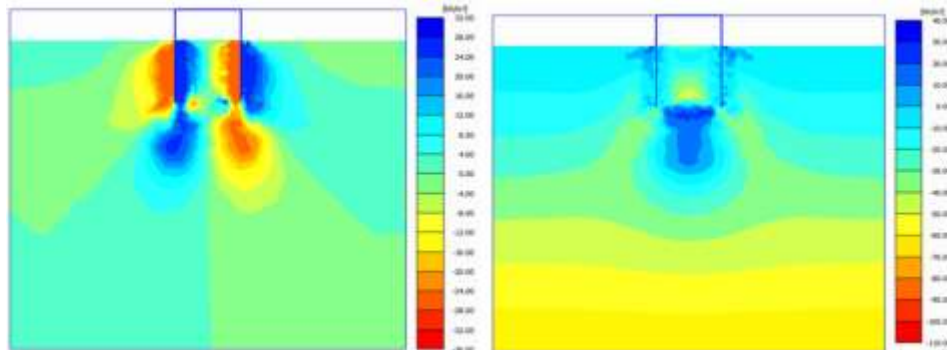**Figure 6 a) Plastic Zone b) Upward Movement of soil**

Figure 7 a) shear dissipation b) end bearing pressure

6   Conclusion

The optimal suction pile configuration has been studied for the Gulf coast of India. It has been found that for an observation platform for a soft clayey soil, increase in diameter increases the suction required to a large extent, however, increasing the height of the bucket, proves more effective. Heave inside the caisson due to application of suction has to also be studied. It is also observed that in case of reverse bearing capacity failure, as simulated in PLAXIS 3D, a plastic zone is formed which effectively stops the penetration of the bucket into the soil. A check has been applied to assure that this failure is avoided for the h/D ratios studied. The stability of these foundations to static lateral and dynamic loading has to be further studied. The increase in strength of the soil due to the formation of plug has to also be studied in detail. A numerical model has been carried out to understand the bearing capacity failure based on the displacement, shear stress and the deviatoric strain values. Further study on the complex load transfer mechanism and the behavior in undrained condition has to be studied. The lateral capacity of the bucket also plays a major role on the dimension, which has not been carried out in the study.

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