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Suction development during pullout of superpile anchors in soft saturated clay

Le développement de succion pendant la retraite d'ancres de superpile dans l'argile saturée douce

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ABSTRACT

As an alternative to long pile anchors as foundations for tension leg platforms, superpile anchors or suction caissons are being increasingly favored. Superpiles derive portions of their pullout capacity from the self-weight of the soil plug and bottom resistance at the base. An experimental investigation was conducted to study the pore water pressure changes during vertical pullout and the resulting suction development above the soil plug and beneath the base of model superpiles.

RÉSUMÉ

Comme une alternative aux ancres de tas longs comme les fondations pour les plate-formes de jambe de tension, les ancres de superpile ou les caissons de succion sont favorisées de plus en plus. Superpiles dérive des portions de leur capacité de retraite du soi-poids du bouchon de sol et la résistance inférieure à la base. Une investigation expérimentale a été dirigée pour étudier les changements de pression d'eau de pore pendant la retraite verticale et le développement de succion résultant au-dessus du bouchon de sol et en dessous de la base de superpiles modèle.

1 INTRODUCTION

Off the eastern coast of India in the Bay of Bengal, the offshore environment is characterized by a narrow continental shelf. In the deeper continental slope, commercially exploitable reserves of hydrocarbons have been confirmed under deposits of soft clay. The large water depth and low shear strength of soil will require the installation of compliant structures such as tension leg platforms (TLPs). Off the western coast at Bombay High, fixed jacket-type structures have been used extensively on account of the shallow water depths.

A TLP consists of a semi-submersible hull anchored to the seabed by steel tendons under tension. The foundations of TLPs are subjected to tensile load instead of compressive load. Once the anchoring problem is solved, TLP technology can be economically extended into progressively deeper waters. As there are technical problems associated with the driving of long piles in deep water, alternative foundation systems are being adopted.

The superpile system proposed by Albert et al. (1989) is one such anchoring system that is a combination of pile and gravity foundations. Unlike driven piles, this system consists of piles that are of large diameter (6 to 12 m) and of short length (12 m to 20 m). They are lowered on the seafloor and then allowed to penetrate through the surficial soils under their own weight. The trapped water is vented at the upper end through a suction line. It sucks the water out thus mobilizing the hydrostatic pressure to drive the pile to full penetration. The installation process is faster than that of pile anchors. Reversing the process and pumping water into the top can retrieve superpile anchors that are misplaced or unable to achieve full penetration.

On account of the closed top, the large quantity of soil within the superpile is envisaged to remain there and function as a soil plug to resist pullout loads. In fact, a pulsating tension applied to the superpile generates suction in the pore water inside the superpile top that tends to keep the soil plug, and can prevent extraction of the superpile from the foundation soil.

This paper provides results from laboratory tests on model superpile anchors embedded in soft saturated clay and subjected to vertical static and cyclic pullout loading. The pore water pressures that develop above the soil plug and beneath the base of model superpiles were investigated so as to study the development of suction.

2 BREAKOUT LOAD OF SUPERPILE ANCHORS

The components of breakout load for a superpile anchor (Fig. 1) are:

1. Self-weight of the anchor (W_{sp})
2. Weight of ballast and grout (if any)
3. Weight of the soil plug (W_s)
4. Skin friction along the external anchor wall (F_{ext})
5. Bottom resistance beneath the anchor (R_{b1}) on account of reversed bearing capacity failure, and/or development of negative pore water pressure.

In the laboratory model tests, no ballast was used on top of the model superpile and no grout was placed above the soil plug inside. There was only water between the top of the soil plug and the underside of sealed top. The overall equilibrium of the superpile and the equilibrium of the soil plug are shown in Fig. 2.

For overall equilibrium (Fig. 2a), the following equations explain the force equilibrium:

$$P_u = W_{sp} + W_s + W_w + F_{ext} + R_{b1} \tag{1}$$

where P_u = Breakout load
W_w = Weight of water above the soil plug

$$R_{b1} = Pu - Wsp - W_s - W_w - F_{ext} \tag{2}$$

For plug equilibrium (Fig. 2b), the resistance at the bottom, R_{b2}, can be computed as:

$$R_{b2} = S_t - W_s + F_{int} \tag{3}$$

where S_t = Suction above the soil plug
F_{int} = Skin friction on the internal superpile wall

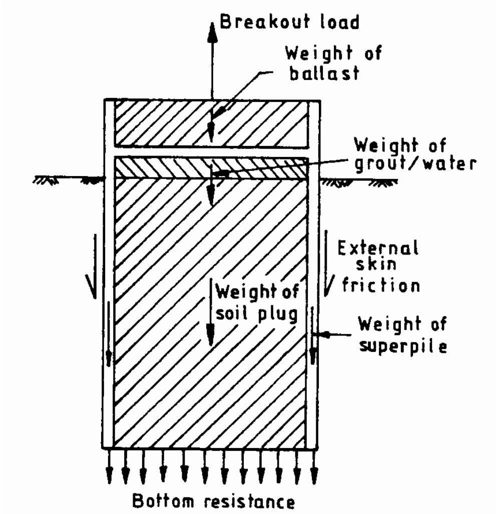

Figure 1. Components of breakout load for a superpile anchor

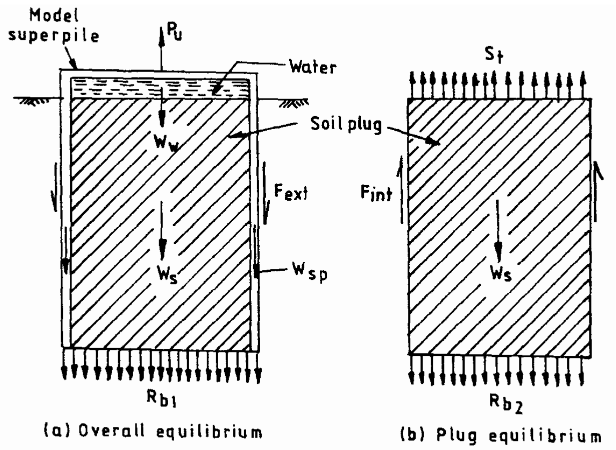

Figure 2. Equilibrium of model superpiles anchors in laboratory tests

3 LITERATURE REVIEW

Goodman et al. (1961) carried out laboratory model tests to determine the pullout resistance of an inverted cup-type anchor subjected to different vacuum pressures. They showed that vacuum anchorage in moist soils was feasible, and that clay responded better than silt and sand, and that clay responded best when the moisture content was near the plastic limit.

Brown and Nacci (1971) investigated the effectiveness of a hydrostatic anchor in sand. They observed that a soil wedge was attached to the anchor after pullout. The results indicated that the factors governing the performance of the anchor were diameter and skirt length of the anchor, soil properties and magnitude of active suction.

Wang et al. (1978) showed that the breakout force of the hydrostatic anchor was composed of external skin friction and end bearing at the tip, in addition to the weight of the anchor and the soil plug.

Finn and Byrne (1972) found through model studies that the breakout capacity of objects lying on the seabed surface with a limited penetration was primarily on account of suction beneath the object. Later, Byrne and Finn (1978) showed through model testing under high ambient pressure in a modified triaxial cell that the maximum breakout capacity for such an object could be estimated by assuming a general bearing capacity failure with the direction reversed.

Fuglsang and Steensen-Bach (1991) studied the pullout behavior of suction piles in clays under static loading through laboratory investigations. They observed that the pore water pressure at the top of the soil plug decreased with displacement and reached a minimum value.

Iskander et al. (2002) have reported a laboratory study on suction caissons in sand and clay. The test results indicated that the use of suction pressure for installation of caissons is a viable alternative to conventional methods. Suction was also shown to resist some axial tensile loads.

4 EXPERIMENTAL INVESTIGATION

Circular steel tanks of 55 cm internal diameter and 45 cm height were used as model test tanks. The soil used was a riverbed clay having liquid limit of 45% and plastic limit of 28%. The undrained strength of the soil, S_u, varied from 0.025 to 0.060 kg/cm^2 indicating that the soil was very soft.

Model superpiles made of perspex, having an internal diameter of 11 cm, wall thickness of 5 mm and lengths of 16.5 cm and 8.3 cm were used. A model superpile had two outlets at the top. At one outlet, a pressure transducer could be attached for pore water pressure measurement. The other outlet was used as an air vent during installation of the model superpile by vertical pushing and then closed thereafter.

A motorized gearbox was used for applying static pullout loads. For applying cyclic loads, a pneumatic loading system was used. A square wave pattern tension cyclic loading was applied between pre-specified maximum and minimum pullout load limits at a pre-set time period of 12 seconds.

Pore water pressure was measured at two locations - above the soil plug in the model superpile and beneath the base of the model superpile. For measuring pore water pressure above the soil plug, a pressure transducer was mounted on to the top of the model superpile ensuring that the diaphragm of the transducer was in contact with water above the soil plug. For measuring pore water pressure at the bottom, a system comprising a piezometer tip, an incompressible tube and a pressure transducer was used. The stationary piezometer tip of coarse porous stone was located at the centre of the soil mass at the tip level of the model superpile in its initial position.

The influence of strain-controlled pullout rate and maximum cyclic stress level were studied for two ratios of superpile length to diameter (L/D) at two water contents (w.c.) of the soil.

5 RESULTS

5.1 *Pullout behavior under static loading*

The displacement-controlled pullout tests were conducted fast enough so as to allow no drainage within the superpile. Pullout rates of 0.16 to 16 mm/min were selected as being reasonable. A typical plot of the static pullout behavior of model superpiles is shown in Fig. 3. The soil plug was retained inside the superpile even after complete pullout indicating no shear failure had taken place on the inside wall. The breakout loads at a displacement equal to 60% of the superpile diameter are tabulated in Table 1. The predominant component was the bottom resistance, R_{b1}. The low values of self-weight and external wall skin friction were on account of the perspex material, and the weight of the soil plug was dependent on the dimensions of the superpile.

When a tensile load is applied to a superpile, suction pressure is developed beneath the sealed top, providing resistance against pullout. Under undrained pullout, a general shear failure occurs at the base in the reversed direction. Prolonged tensile loading will result in the dissipation of this suction pressure leading to superpile withdrawal without the soil plug. Under such long-term tensile loading conditions, shearing will take place along both the interior and the exterior of the superpile wall.

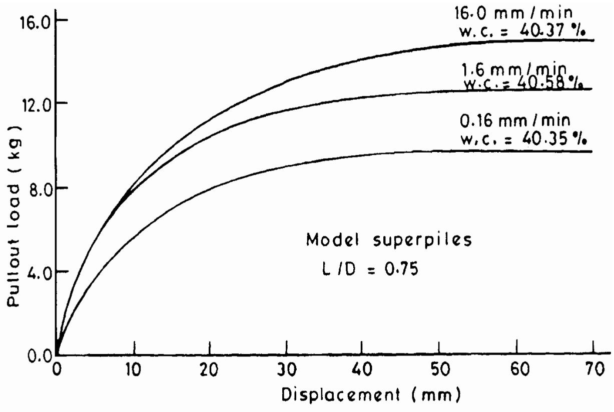

Figure 3. Behavior of model superpiles during static pullout

Table 1: Components of breakout load for model superpiles

L/D	w.c. (%)	Pullout rate (mm/min)	Breakout load (kg)	Components of breakout load (kg) W_{sp}	W_s	W_w	F_{ext}	R_{b1}
1.5	34.18	0.16	21.80	0.80	2.70	0.11	1.35	16.84
	33.95	1.6	25.30	0.80	2.70	0.11	1.40	20.29
	34.07	16.0	30.60	0.80	2.70	0.11	1.65	25.34
0.75	34.12	0.16	20.40	0.54	1.30	0.11	++	18.45
	34.18	1.6	24.80	0.54	1.30	0.11	"	22.85
	33.94	16.0	29.50	0.54	1.30	0.11	"	27.55
0.75	40.35	0.16	9.60	0.54	1.20	0.11	++	7.75
	40.58	1.6	12.60	0.54	1.20	0.11	"	10.75
	40.37	16.0	14.90	0.54	1.20	0.11	"	13.05

++ Negligible as the model superpile is about to come out totally from the soil mass.

5.2 *Suction above the soil plug during static loading*

During pullout, negative pore water pressures were developed within the superpile and the loading rate had a significant influence on the pullout capacity. A typical plot of change in pore water pressure above the soil plug is shown in Figure 4. The chosen pullout rates and the low clay soil permeability allowed no pore water pressure dissipation. The pore water pressure continued to decrease indicating that suction remained developed during the entire pullout process. This suction held the soil plug inside the model superpile as well as counteracted the resistance at the bottom. The suction developed at the top corresponding to an upward displacement equal to 60% of the superpile diameter are tabulated in col. 4 of Table 2.

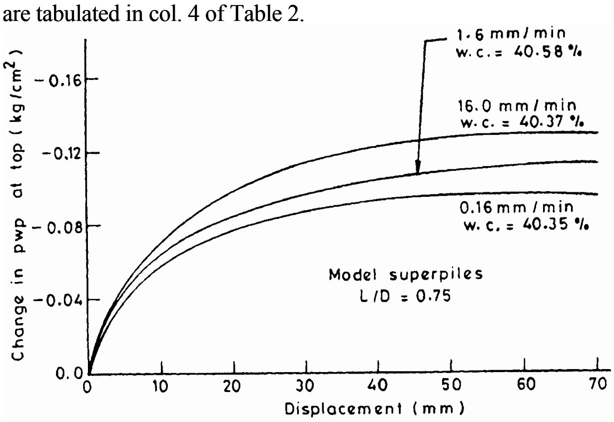

Figure 4. Variation of pore water pressures above soil plug in model superpiles during static pullout

5.3 *Suction beneath the base during static loading*

In all the tests, the piezometer tip was stationary as the model superpile was subjected to static pullout. The pore water pressure at the bottom decreased with displacement thereby confirming the development of resistance as the model superpile moved up. A typical plot of change in pore water pressure beneath the base of model superpiles is shown in Figure 5. The suction pressure reached a maximum at a relatively low displacement of the superpile, and then diminished gradually as water filtered in from the surrounding soil. The peak negative pore water pressures at the piezometer tip location are presented in col. 5 of Table 2.

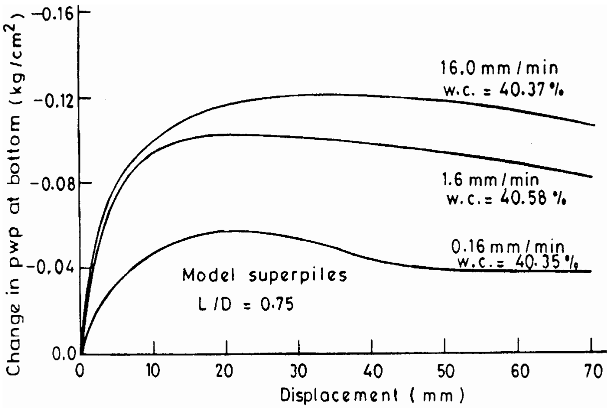

Figure 5. Variation of pore water pressures beneath the base of model superpiles

Table 2: Suction developed above the soil plug and beneath the base of model superpiles

L/D (1)	w.c. (%) (2)	Pullout rate (mm/min) (3)	Suction at the top (kg) (4)	Peak suction pressure at the bottom (kg/cm^2) (5)
1.5	34.18	0.16	-11.21	-0.136
	33.95	1.6	-16.35	-0.194
	34.07	16.0	-20.34	-0.218
0.75	34.12	0.16	-14.73	-0.120
	34.18	1.6	-19.20	-0.204
	33.94	16.0	-23.47	-0.230
0.75	40.35	0.16	-9.03	-0.058
	40.58	1.6	-10.74	-0.102
	40.37	16.0	-12.16	-0.122

5.4 *Bottom breakout factors under static loading*

The resistance at the bottom were expressed as bottom breakout factors (N_b) and are tabulated in Table 3:

(i) From overall equilibrium: $N_{b1} = R_{b1} / (A_b \times S_u)$ (4)

(ii) From plug equilibrium: $N_{b2} = R_{b2} / (A_b \times S_u)$ (5)

(iii) From the measured peak suction pressure at the bottom:

N_{b3} = Measured peak suction pressure / S_u (6)

where

A_b = Base area of the model superpile

S_u = Undrained shear strength at a depth equal to half the model superpile diameter below the tip in its initial position.

The factors were found to be strongly dependent on the pullout rate. They lied in the range of 1.75 to 3.24 for the pullout rate of 0.16 mm/min and in the range of 3.47 to 4.96 for the pullout rate of 16 mm/min.

Table 3: Bottom breakout factors

Pullout rate (mm/min)	L/D	w.c. (%)	S_u (kg/cm^2)	From overall equilibrium (N_{b1})	From plug equilibrium (N_{b2})	From peak bottom suction (N_{b3})
0.16	1.5	34.18	0.059	2.99	1.75	2.30
	0.75	34.12	0.060	3.24	2.36	2.00
	0.75	40.35	0.028	2.95	2.99	2.10
1.6	1.5	33.95	0.060	3.55	2.60	3.23
	0.75	34.18	0.057	4.23	3.32	3.59
	0.75	40.58	0.028	4.00	3.55	3.60
16.0	1.5	34.07	0.056	4.72	3.47	3.81
	0.75	33.94	0.058	4.96	3.99	3.93
	0.75	40.37	0.029	4.74	4.41	4.21

5.5 *Pullout behavior under cyclic loading*

The model superpiles were tested under vertical cyclic tension to determine their resistance to simulated environmental loads and to correlate its cyclic capacity with the static breakout load. The static bias load or the minimum cyclic stress level was kept equal to the self-weight of the superpile. The superimposed cyclic loads were increasingly varied in different tests so that the final max. cyclic stress levels nearly equaled the breakout loads presented in Table 1 with the bottom resistance component as high as 66%.

When the maximum cyclic stress level did not exceed the sum of the dead weights and the external wall skin friction, the magnitude of displacement at the end of 1000 cycles was small. Maximum cyclic stress levels greater than the above resulted in increased superpile displacement but no failure was observed. At a stress level comprising 66% of the bottom resistance, the superpiles moved up rapidly leading to failure. The number of load cycles that a superpile could resist before experiencing a significant displacement decreased with the increase of the maximum cyclic stress level.

Table 4: Changes in pore water pressures above the soil plug and beneath the base of model superpiles after 1000 cycles (max. cyclic stress level/ min. cyclic stress level)

S. No.	L/D	w.c. (%)	Max. cyclic stress level*	Pwp change at the top (kg/cm^2)	Pwp change at the base (kg/cm^2)
1	1.5	34.04	W	-0.008/-0.006	-0.023/-0.020
2	"	34.14	W + 0.5 F_{ext}	-0.011/-0.008	-0.032/-0.023
3	"	33.96	W + F_{ext}	-0.021/-0.015	-0.041/-0.028
4	"	34.19	W + F_{ext} + 0.25 R_{b1}	-0.044/-0.031	-0.045/-0.043
5	"	34.03	W + F_{ext} + 0.33 R_{b1}	-0.053/-0.034	-0.061/-0.061
6	"	33.98	W + F_{ext} + 0.50 R_{b1}	-0.070/-0.037	-0.080/-0.080
7	"	34.15	W + F_{ext} + 0.66 R_{b1}	Model superpile came out after 665 cycles	-----
8	0.75	33.95	W	-0.007/-0.004	-0.014/-0.011
9	"	34.08	W + 0.5 F_{ext}	-0.010/-0.006	-0.023/-0.014
10	"	34.04	W + F_{ext}	-0.017/-0.010	-0.032/-0.022
11	"	33.91	W + F_{ext} + 0.25 R_{b1}	-0.050/-0.023	-0.039/-0.037
12	"	34.11	W + F_{ext} + 0.33 R_{b1}	-0.068/-0.025	-0.053/-0.052
13	"	34.05	W + F_{ext} + 0.50 R_{b1}	-0.082/-0.027	-0.075/-0.075
14	"	34.10	W + F_{ext} + 0.66 R_{b1}	Model superpile came out after 574 cycles	-----

* W is the sum of the dead weights of model superpile, soil plug and water above the soil plug.

5.6 *Suction development during cyclic loading*

During cyclic loading, the measured pore water pressures above the soil plug and beneath the base of model superpiles were observed to be cyclic in nature. The changes in pore water pressures after 1000 cycles have been tabulated in Table 4. Above the soil plug, maximum suction was attained in the initial few cycles and it remained constant throughout the test. A higher stress level produced a greater suction magnitude.

Beneath the base, the pore water pressures also attained peak negative values in the initial few cycles but subsequently, they diminished with increasing number of cycles. This confirmed the development of passive suction at the level of the stationary piezometer tip as the superpile moved up.

6 SUMMARY AND CONCLUSIONS

When a tensile load is applied to a superpile anchor, suction pressure is developed beneath the sealed top thus providing resistance against pullout. Under rapid loading, a general shear failure occurs, and the pullout capacity is derived from the dead weight of the soil-foundation system, shearing along the exterior wall surface, and reversed bearing capacity at the superpile tip.

A soil plug is retained within the superpile during static pullout, and its weight substitutes for the shearing resistance along the interior wall surface. Accordingly, the weight of the plug can be counted upon to resist a fast pullout load typical of environmental effects.

The suction water pressures will dissipate under prolonged tensile loading and may result in superpile withdrawal without the plug. Under such long-term loading, the resistance is dependable only on the dead weight of the foundation and shearing along the interior and exterior of the superpile wall. Both the soil plug weight and the bottom resistance cannot be relied upon for the static long-term capacity of the foundation though their contributions can be very significant depending on the magnitude of the suction pressures developed above the soil plug and beneath the superpile base.

For maximum cyclic loads greater than the dead weights and external skin friction, the resulting displacements, when coupled with an increase in the number of applied load cycles, will cause eventual superpile pullout. The bottom resistance, though of a short-term nature, gives added uplift capacity and will prevent sudden failure.

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