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Behaviour of Plate Anchors in Soft Cohesive Soils under Cyclic Loading

by

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Introduction

FOR the recovery of ocean resources in water depths exceeding 250m, compliant structures such as guyed towers and tension leg platforms are more economical than fixed offshore structures. These structures are held in position by foundations anchored to the sea-bed. The pullout loading transmitted by these structures to their foundation comprises of a static as well as a cyclic component.

Plate anchors are one type of anchor foundations which may be used for resisting pullout loads transmitted by these structures to the foundation. The behaviour of plate anchors under static loading has been studied extensively by Vesic (1971), Bemben *et. al.* (1973).

Davie and Sutherland (1977), Das (1978) and others. However their behaviour under cyclic load has not been a subject of detailed study. Bemben *et al.*, (1973) Davie and Sutherland (1977), Das (1978) and others. However their behaviour under cyclic load has not been a subject of detailed study. Bemben *et al.*, (1973) and Bemben and Kupferman (1975) have presented some results on the behaviour of fluke anchors under cyclic loading. Their data is limited and pertains to λ shaped fluke anchors only. This paper describes results of a study undertaken to find out the influence of cyclic loading on the pullout behaviour of plate anchors embedded in soft cohesive soil. The study is confined to vertical pullout loading only.

Cyclic Loads on Anchors

Tension leg platforms (TLP) are floating compliant structures fixed in position by vertical moorings (tension legs). The Hutton TLP in the world's

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first TLP installed in 150m water depth in 1983. After the successful installation of the Hutton TLP, numerous other TLP's have been proposed for deep water sites. The nature and magnitude of pullout forces to be resisted by anchors foundations of these TLP's are summarised in Table-1.

The pullout loads transmitted to the anchor foundation comprise of static pretension and cyclic loads on account of environmental effects of waves, wind, current, tides and other factors. For a 20 year design life the anchor foundation may be subjected to more than 10^8 load cycles. From Table-1 it is evident that cyclic loads induced by environmental conditions form a significant part of the maximum pullout load. It is, therefore, important to identify the influence of cyclic loading on the pullout behaviour of anchors.

Scope

Model circular plate anchors were embedded in test tanks filled with soft cohesive soil and were subjected to vertical pullout under static loads and cyclic loads to identify:

(*a*) the influence of number of cycles on movement of plate anchors,

(*b*) the influence of cyclic stress level on the movement of plate anchors, and

(*c*) the influence of cyclic loading on subsequent static pullout behaviour.

Experimental Set-up

Circular plate anchors, 5cm in diameter were embedded in soft clay to a depth of 30 cm in model test tanks having a diameter of 30cm and height of 50cm. The embedment depth to diameter ratio was kept at 6 to simulate deep anchor behaviour.

Cyclic loading is applied to model anchors using a pneumatic system. An air cylinder (Fig. 1) is used for this purpose. A constant base pressure is fed to chamber 1 whereas the pressure in chamber 2 is varied between a maximum and a minimum level corresponding to the cyclic pullout load to be applied to the plate anchor. This is achieved by means of two solenoid valves and a timer which change the pressure in chamber 2 as per the time period corresponding to wave loading. The complete set up of the air pressure application systems is shown in Figs 2 and 3. The resulting wave form is essentially a square wave (Fig. 4).

Three air pressure regulators control the air pressures required for application of cyclic loads (Fig. 2). Pressure regulator C1 is connected to chamber 1 of the air cylinder to apply the base pressure. The other two pressure regulators (C2 & C3) are connected through solenoid valves to chamber 2.

TABLE I

Forces in Vertical Moorings of Tension Leg Platforms

Type	Water depth (m)	No. of anchor columns	No. of tendons per col.	Static Pretension (t) Total	Static Pretension (t) per col.	Maximum tension per col(t)	Minimum tension per col. (t)	Maximum wave induced cyclic tension amplitude (t)	Remarks	Source
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
Square (Hutton)	150	4	4	13000	3200	9600*	Almost zero	3000	*On the basis basis of 2400 t per tendon	Bradshaw *et. al* (1985), Tetlow and Leece (1982)
Square TLP	300	4	4	11950	2990	7540	—	1000	—	Larsen *et al.* (1984)
	600	4	4	17000	4250	9070	—	1000	—	
	900	4	4	23550	5890	10820	—	—		
Square TLP	400	4	—	7200	1800	—	—	1200	Wave effects only	Kobayashi *et al* (1985)
Concrete TLP	500-1000	5	4	14500	2900	—	—	—	—	Sparks *et al* (1985)
Square TLP	600	4	6	15000	3700	7200	—	3000	Values based Time History Records	Sabasliadi *et al* (1983)
Square TLP	450	—	—	1400	3500	—	—	1500	Wave effects only	DeBook *et al.* (1983)
Rectangular TLP	Deep	4	4	12000	3000	4400	1900	2400	Wave effects only	Dunsire and Owen (1984)
Hexagonal TLP	Deep	6	6	14400	3400	3600	1900	1700	—	Dunsire and Owen (1984)

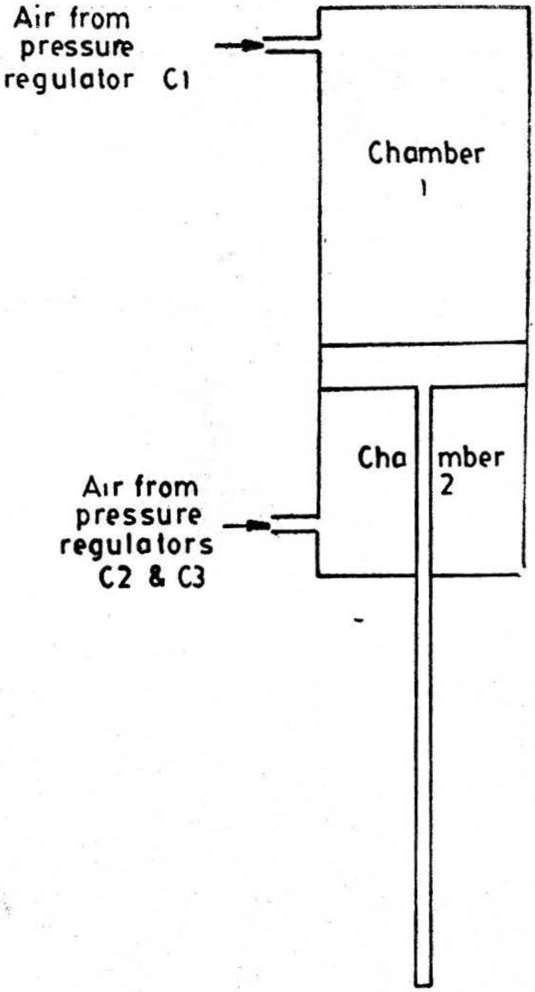

FIGURE 1 Air Cylinder for Cyclic load Application

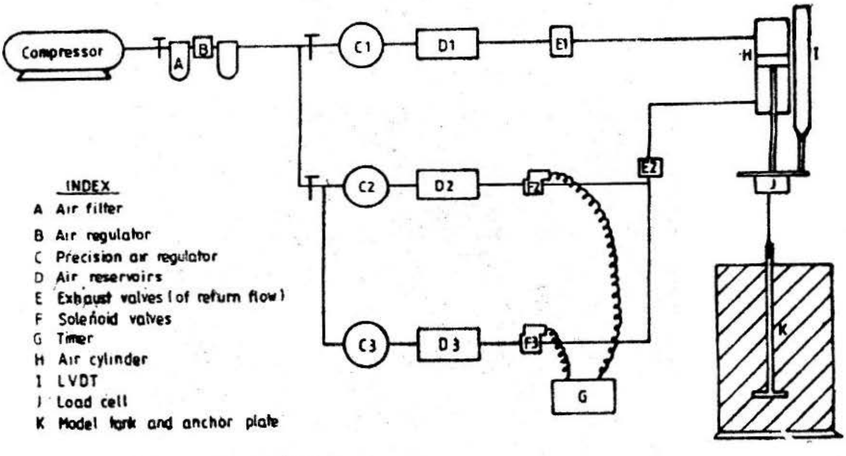

FIGURE 2 System for Applying Pneumatic Cyclic load

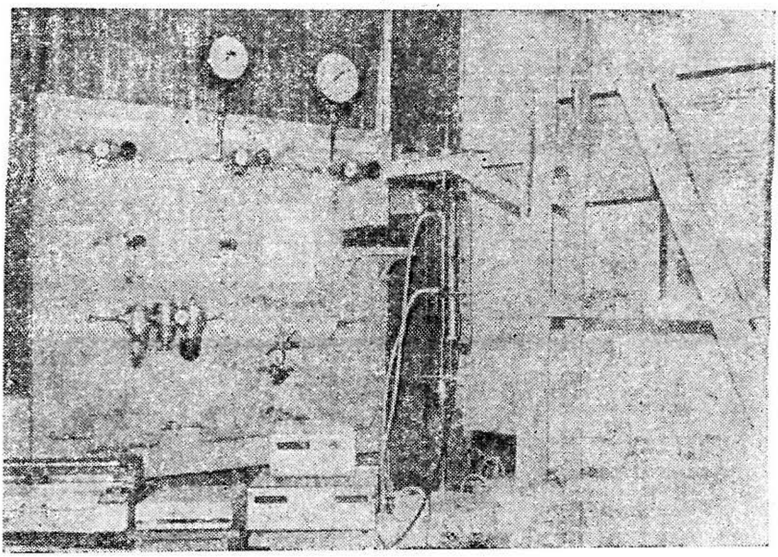

FIGURE 3(a) Cyclic Pull out Test in Progress

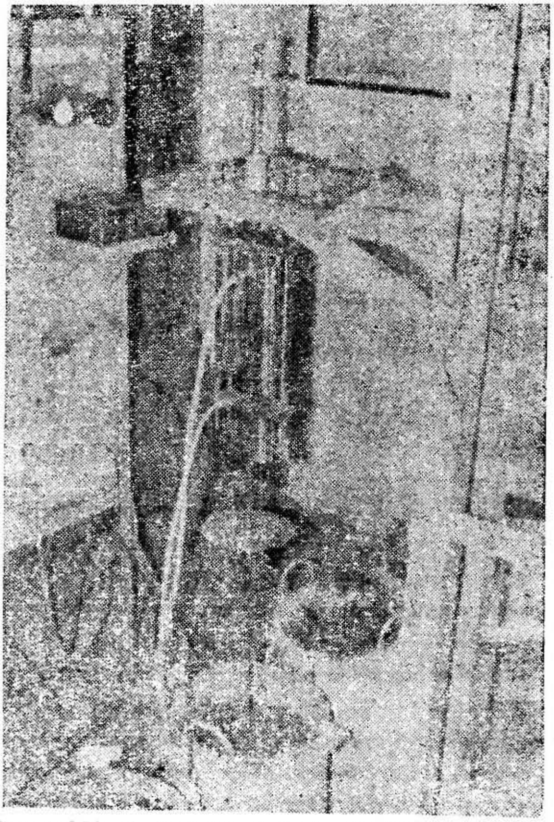

FIGURE 3(b) Air Cylinder used for Applying Cyclic loads

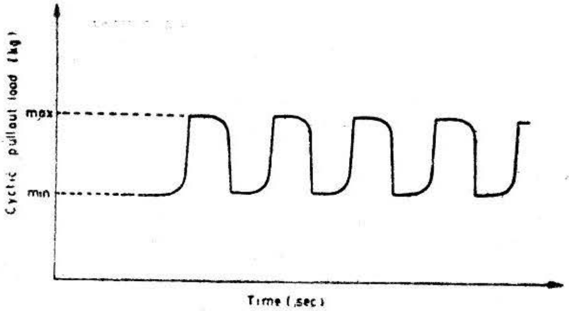

FIGURE 4 Square Wave Cyclic loading Applied to Model Anchors

The pullout cyclic loads are controlled by these regulators. The solenoid valves F2 and F3 are operated through a timer (G) which ensures that when one valve is open, the other is closed. Consequently, chamber 2 is connected alternately to pressure regulators C2 and C3. The time period and the total number of cycles applied is controlled by the timer.

The cyclic load and the corresponding displacements are measured by a load cell and a LVDT respectively and are read on a digital display. A dial guage is also used to check the maximum and minimum displacements of the anchor under each cycle. A strip chart recorder is used to selectively record data during cyclic loading. At the end of cyclic load tests, static strain-controlled pullout tests are conducted on the same frame with the help of a motorized gear box as shown in Fig. 5.

Testing Programme

Tests were conducted on plate anchors embedded in Dhanauri clay at three water contents near the liquid limit—approximately 35%, 40% and 45%. Anchors alongwith pullout rods were embedded during filling operation of the model tanks. The tanks were filled with Dhanauri clay thoroughly mixed with water at the desired water content by hand kneading. Model anchors were placed in the tanks after filling the clay upto 10cm height above the base. The clay was then filled upto 30cm above the anchor level. Anchors and tanks were kept covered and undisturbed for seven days to allow thixotropic gain of strength. The undrained strength of the soil measured after 7 days by a large sized vane shear apparatus varied from 0.01 kg/cm^2 to 0.06 kg/cm^2 for the range of water contents used.

At each water content one static test and a number of cyclic tests were conducted. Reproducibility of test results was checked and only representative results are presented in this paper. A total of 500 cycles with a time period of 15 seconds were applied in each cyclic test after which a static pullout test was conducted at a strain rate of 5 mm/min. At each water content, tests were conducted under cyclic stress increments of 25%, 33%,

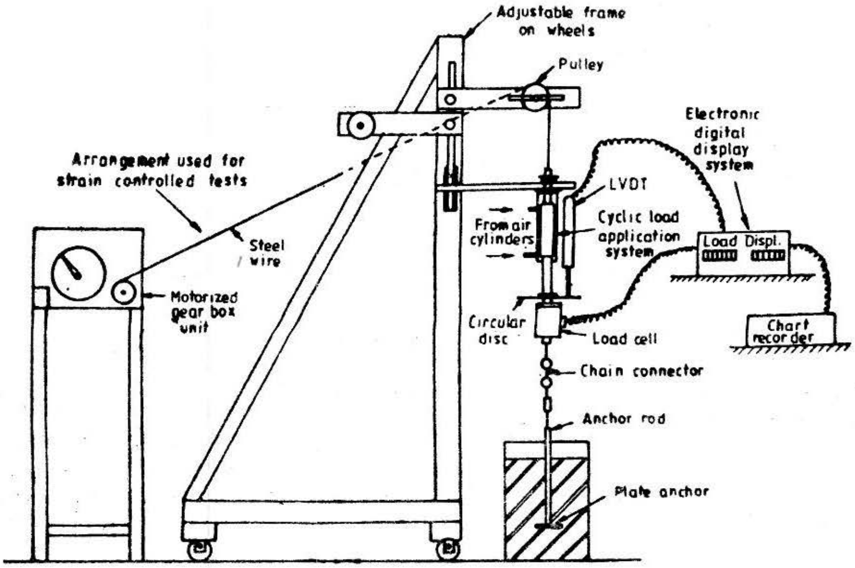

FIGURE 5 **Experimental Set-up for Pulling out Anchors under Cyclic loading and Strain Controlled Static loading**

50% and 66% of the static pullout load. The maximum cyclic stress level was kept at 25%, 33%, 50% and 66% of the static pullout load. Table 3 indicates the number of tests conducted at water content.

TABLE 2

Grain Size Distribution and Index Properties of Dhanauri Clay

Liquid Limit	=	51%
Plastic Limit	=	30%
Plasticity Index	=	21%
Sand Content	=	1%
Silt Content	=	64%
Clay Content	=	35%

Results

Movement

In all the cyclic tests conducted, plate anchors showed significant upward movement (Table 4). Figs 6 to 8 present some selected data from which it is evident that the rate of movement per cycle is maximum for the first

TABLE 3

Tests Conducted at each Water Content

Test No.	Type	Maximum Cyclic Stress Level(%)	Cycle Stress Increment (%)	Strain Rate During Pullout (mm/min)	Time Period Per Cycle (Sec)
1.	Static	—	—	5	—
2.	Cyclic-then-Static	25	25	5	15
3.	Cyclic-then-Static	33	25	5	15
4.	Cyclic-then Static	33	33	5	15
5.	Cyclic-then-Static	50	25	5	15
6.	Cyclic-then-Static	50	33	5	15
7.	Cyclic-then-Static	50	50	5	15
8.	Cyclic-then Static	66	25	5	15
9.	Cyclic-then-Static	66	33	5	15
10.	Cyclic-then-Static	66	50	5	15
11.	Cyclic-then-Static	66	66	5	15

cycle and it reduces thereafter. For a given cyclic stress increment, the amount of movement is observed to increase rapidly as the maximum cyclic stress level increases. Figs 9 to 11 show that for a given maximum cyclic stress level, the amount of movement of plate anchors is of the same order of magnitude even though the cyclic stress increments vary from 25% to 66%. This observation highlights the fact that the magnitude of anchor movement under cyclic loading is controlled primarily by the maximum cyclic stress level.

Figs 12 and 13 show the variation of rate of movement per cycle after 450 cycles as a function of the maximum cyclic stress level and the cyclic stress increment. One notes that the rate of movement increases as the maximum stress level increases for a given stress increment. However, for a given maximum cyclic stress level, the rate of movement does not show any consistent trend with increase in cyclic stress increment.

TABLE 4

Movement of Plate Anchors under Cyclic Loading

Water content %	Max. cyclic stress level (%)	Cycles stress increment (%)	Total movement the (in mm) after cycles				Total Movement after 500 cycles as a % of anchor dia
			1	10	100	500	
33.52	25	25	0.5	2.0	5	6.8	14
34.04	33	25	1.0	3.0	7.5	9.5	19
33.77		33	1.0	3.5	10.0	30.0	60
33.69		25	4.0	8.0	17.5	22.0	44
34.97	50	33	2.0	6.0	16.0	22.5	45
35.15		50	5.0	9.0	20.0	42.5	85
32.58		25	6.0	12.0	32.5	61.0	122
14.63		33	4.0	9.0	24.0	42.0	84
34.48	66	33	11.0	15.0	30.0	42.0	84
36.29		50	7.5	13.0	31.0	43.0	86
34.75		66	7.5	11.5	25.0	50.5	101
35.51	25	25	0.5	1.5	3.5	4.0	8
39.62	33	25	1.0	2.0	4.0	6.0	12
36.91		33	1.0	4.0	12.0	13.0	26
37.39		25	2.5	6.0	17.0	20.0	40
37.30	50	33	7.0	11.0	23.0	30.0	60
36.95		50	6.0	12.0	28.5	33.0	66
37.70		25	9.0	15.0	39.0	49.0	98
38.61		33	5.0	7.0	15.0	34.0	68
39.58	66	33	5.0	10.0	30.0	47.0	94
36.61		50	9.0	14.5	35.5	47.0	94
37.18		66	9.5	14.0	35.0	46.0	92
40.86	25	25	0.5	1.0	2.0	2.5	5
42.92	33	25	0.5	1.2	3.0	5.0	10
40.78		33	1.5	2.8	5.0	6.5	13
41.40		25	5.5	9.0	11.0	13.0	26
40.05	50	33	3.0	9.0	10.5	14.5	29
40.19		50	8.0	9.0	10.5	14.5	29
40.79		25	7.5	12.0	27.5	35.0	70
43.82		33	5.0	7.0	13.0	16.0	32
43.21	66	33	4.0	6.0	8.0	12.0	24
39.72		50	10.5	12.5	17.5	25.0	50
39.92		66	10.0	13.0	24.0	31.0	62

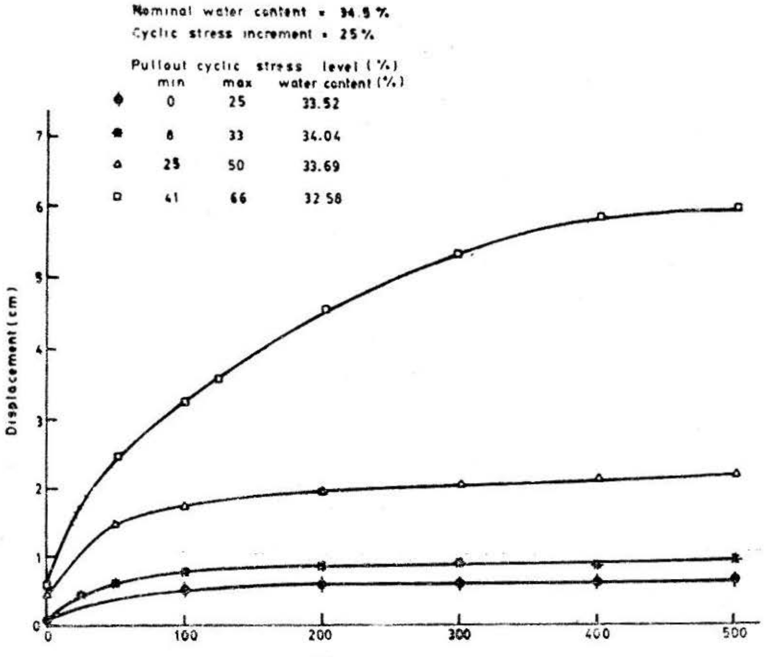

FIGURE 6 Movement of Plate Anchors with Number of Cycles for a Constant Cyclic Stress Movement

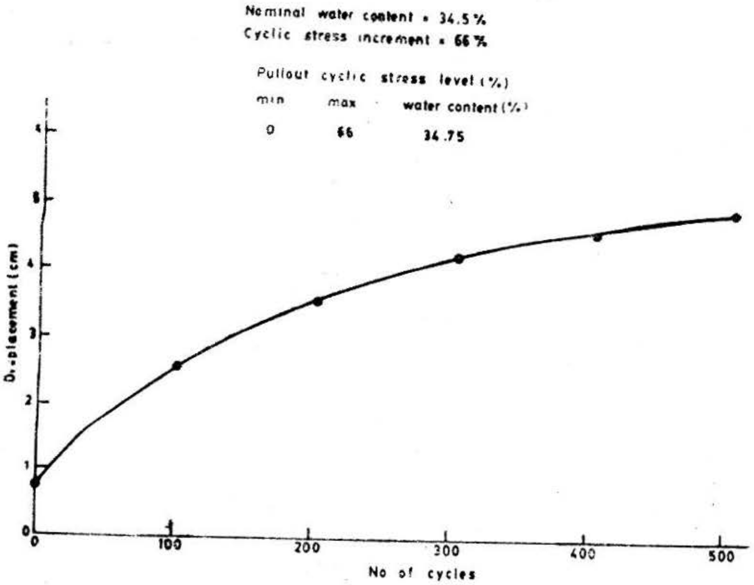

FIGURE 7 Movement of Plate Anchors with Number of Cycles for a Constant Cyclic Stress Increment

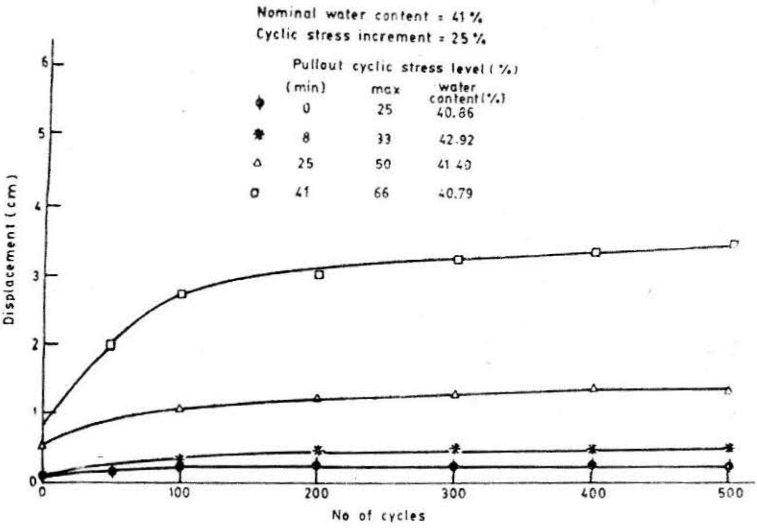

FIGURE 8 Movement of Anchors with Number of Cycles for Constant Stress Increment.

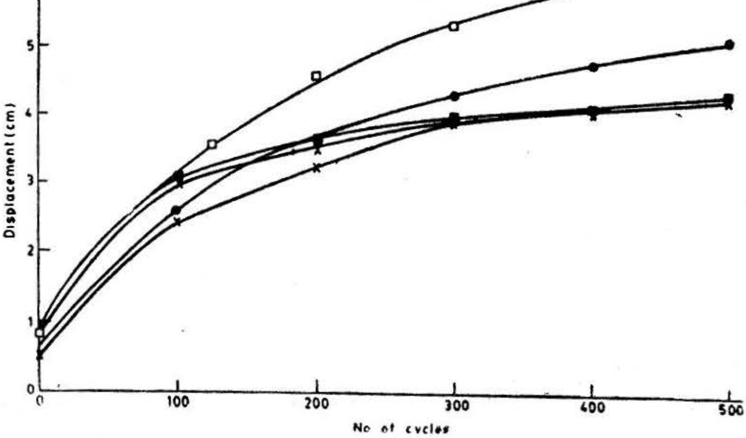

FIGURE 9 Movement of Plate Anchors with Number of Cycles for a Maximum Cyclic Stress level of 66%.

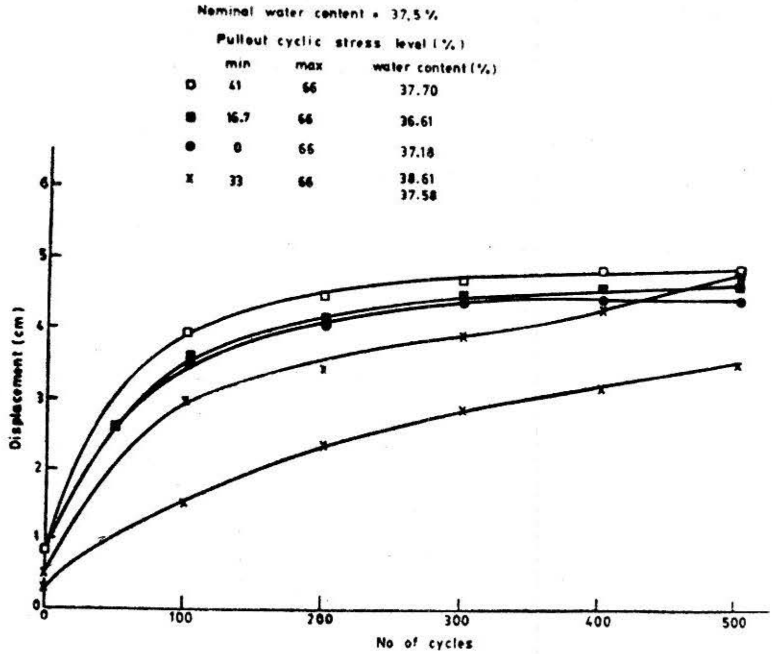

FIGURE 10 Movement of Plate Anchors with Number of Cycles for a Maximum Cyclic Stress level of 66%.

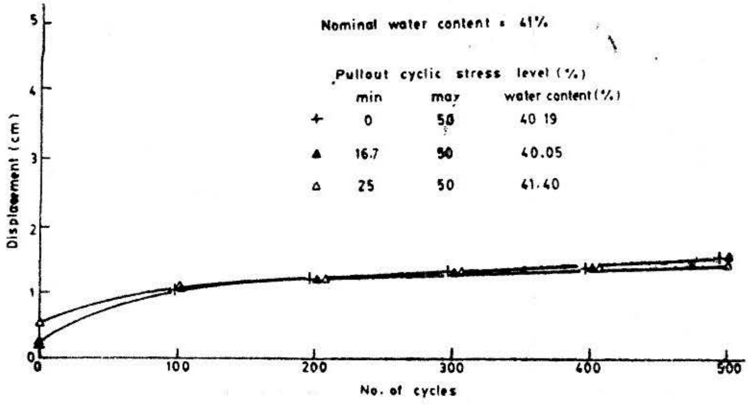

FIGURE 11 Movement of Plate Anchors with Number of Cycles for a Maximum Cyclic Stress level of 50%.

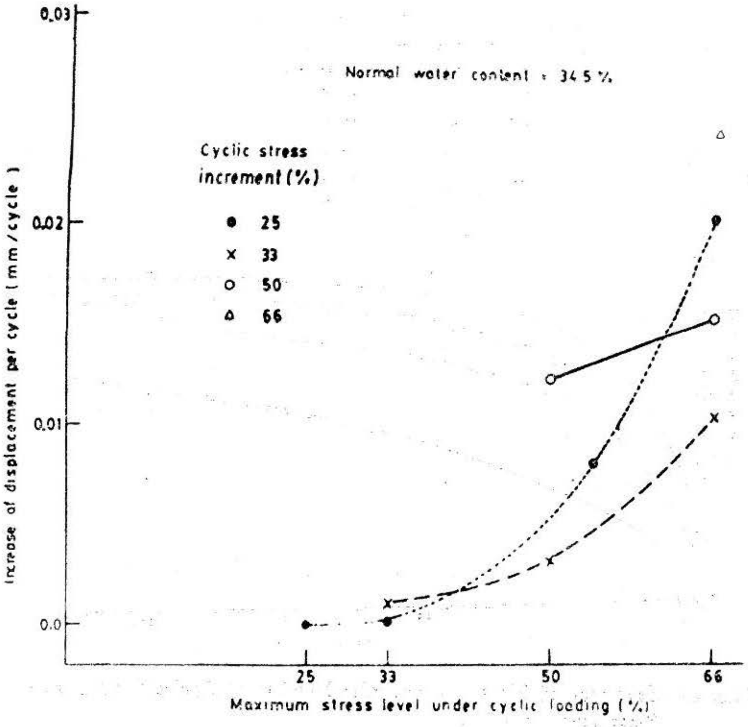

FIGURE 12 Variation of Plate of Displacement under Cyclic loading after 450 Cycles.

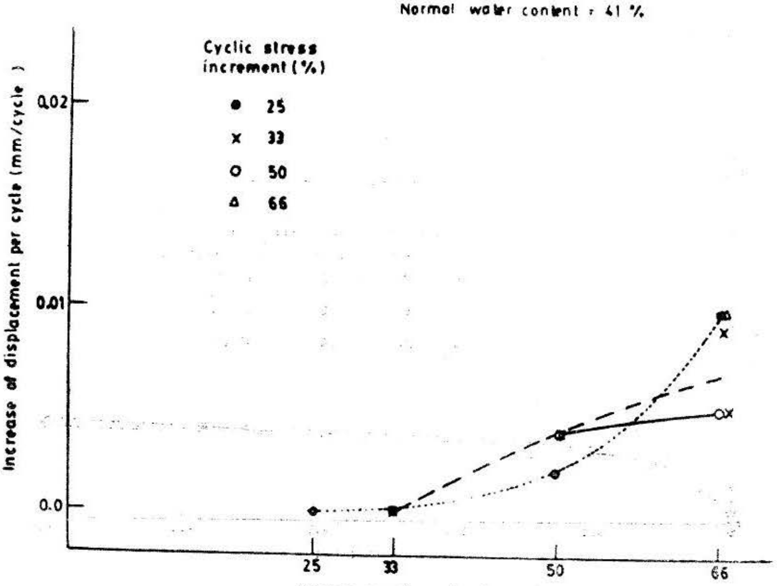

FIGURE 13 Variation of Rate of Desplacement under Cyclic loading after 450 Cycles.

Figs 14 to 16 depict the number of cycles required to achieve rates of displacement of 0.02, 0.01 and 0.0 mm/cycle at different cyclic stress levels and cyclic stress increments. It is evident from these figures that for the three water contents, a zero rate of displacement is achieved only when the maximum cyclic stress level is 33% or lower and the cyclic stress increment is 25%. The total anchor movement recorded under these cyclic stress levels and increments varies from 5% to 20% of the anchor diameter (Table 4). At higher cyclic stress levels and increments, the plate anchors show larger movement and continue to move even after 450 cycles.

Figure 17 shows a plot of total movement of plate anchors after 500 cycles for different water contents. The data indicates that for the same range of cyclic stresses the total movement decreases as the water content increases. This appears to be perhaps on account of the fact that as water content increases, the breakout capacity decreases. As a result, the cyclic load at higher water contents for a given range of stress levels also reduces resulting in decrease of anchor movement.

Static Pullout Capacity

Figs 18 and 19 show the results of static pullout tests conducted on anchors after completion of 500 load cycles in cyclic tests. The figures also show the results of static pullout tests conducted on anchors which were not

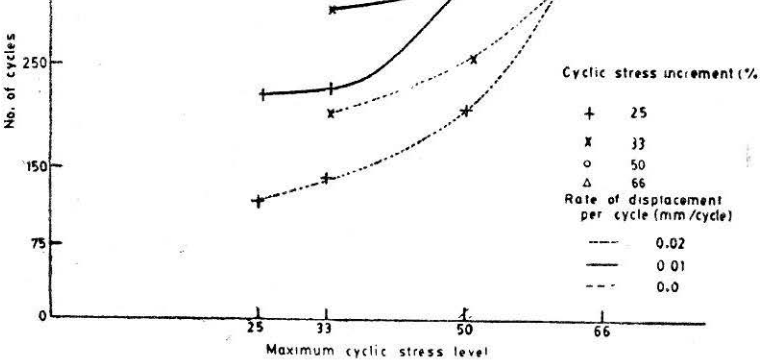

FIGURE 14 **Number of Cycles Required to Achieve a Specified Rate of Displacement under Cyclic loading.**

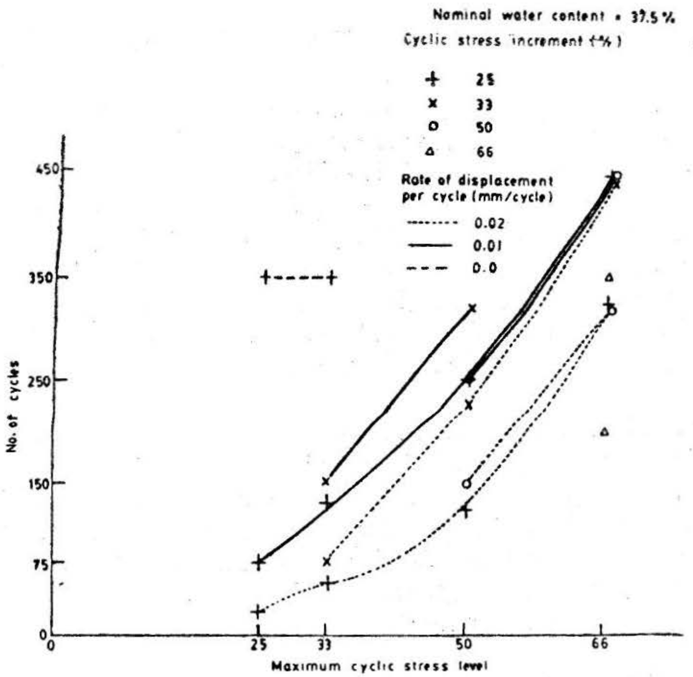

FIGURE 15 Number of Cycles Required to Achieve a Specified Rate of Displacement under Cyclic loading.

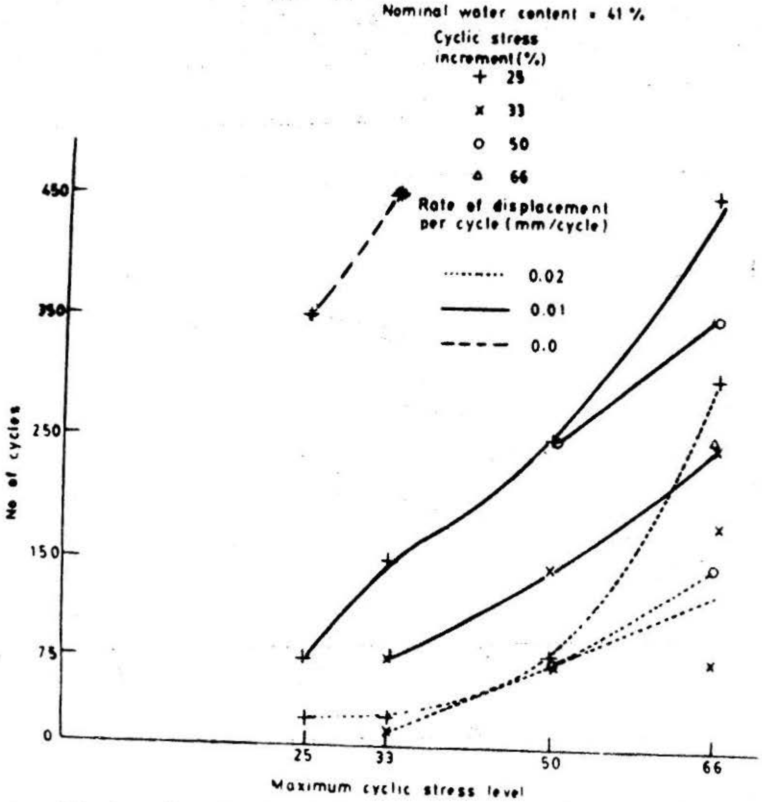

FIGURE 16 Number of Cycles Required to Achieve a Specified Rate of Displacement

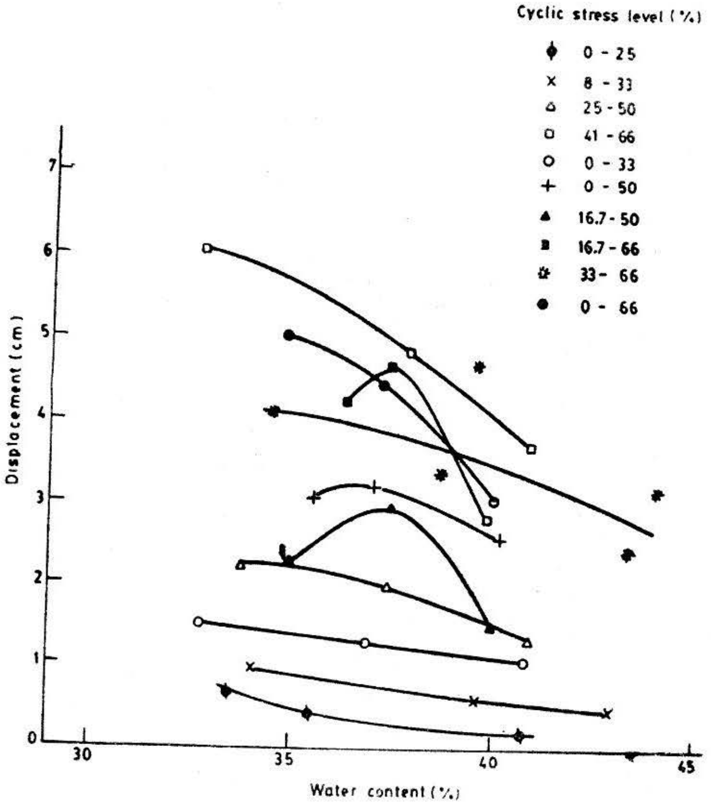

FIGURE 17 Variations of Anchor Movement (after 500 cycles) with water content.

subjected to cyclic loading. In the former set of tests, the load-displacement curves have been plotted after depicting the total movement of the anchors under cyclic loading on the displacement axis.

The figures show that the breakout force-displacement behaviour of anchors subjected to cyclic loading and then static pullout is more stiff in comparison to the behaviour of anchors not subjected to cyclic loading. This may be on account of strain hardening of the soil which occurs under cyclic stresses.

One notes from the results that there is no significant difference in the pullout capacities of anchors which have been subjected to cyclic loading and those which have not been subjected to cyclic loading. This is so because there is no significant decrease in pullout loads even when anchors under static tests were subjected to large displacements similar to those which are observed in cyclic tests. However, if significantly greater number of loading cycles are given, higher displacements than those recorded in the present tests would occur. These may result in a decrease in the static

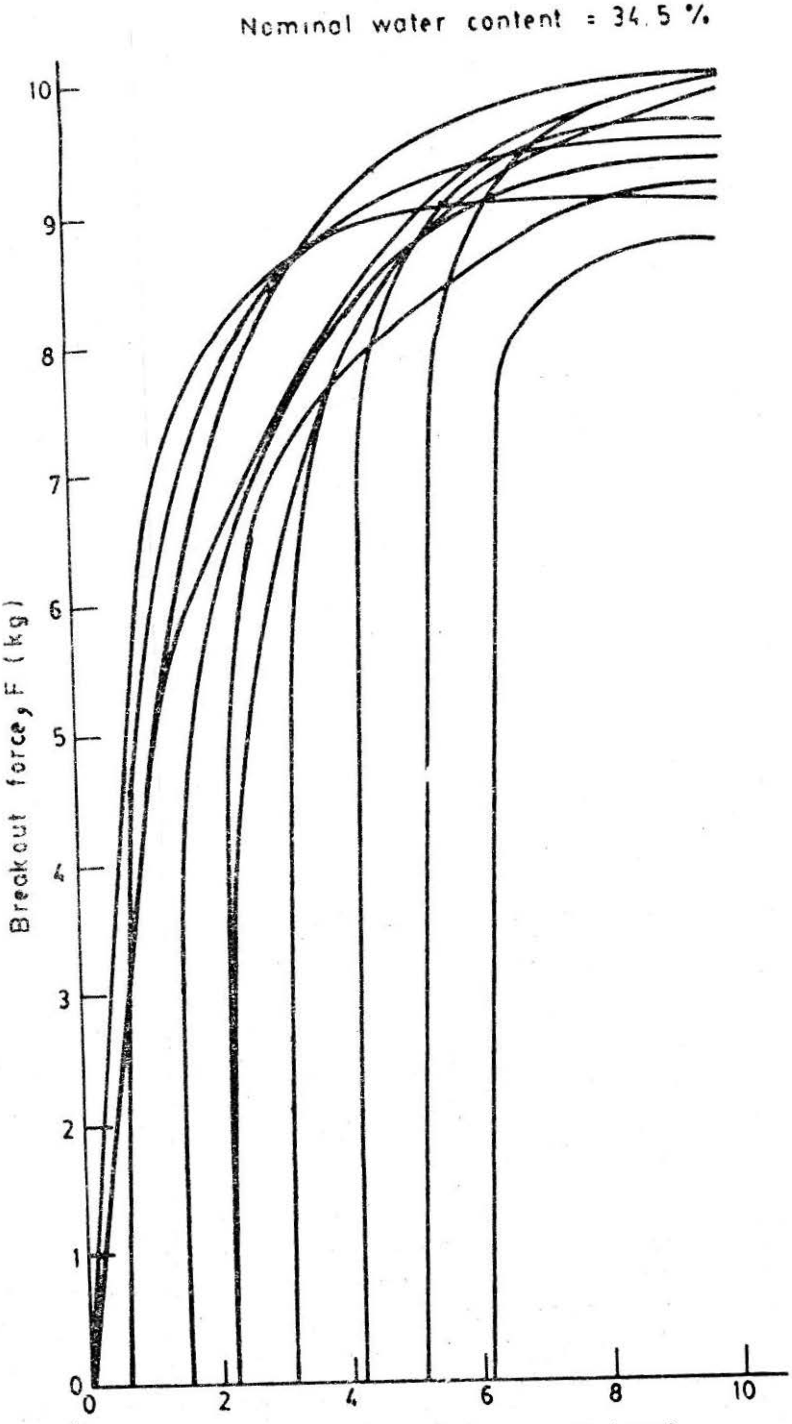

FIGURE 18 Breakout Force-Anchor Displacement Curves under Static Pullout Conditions.

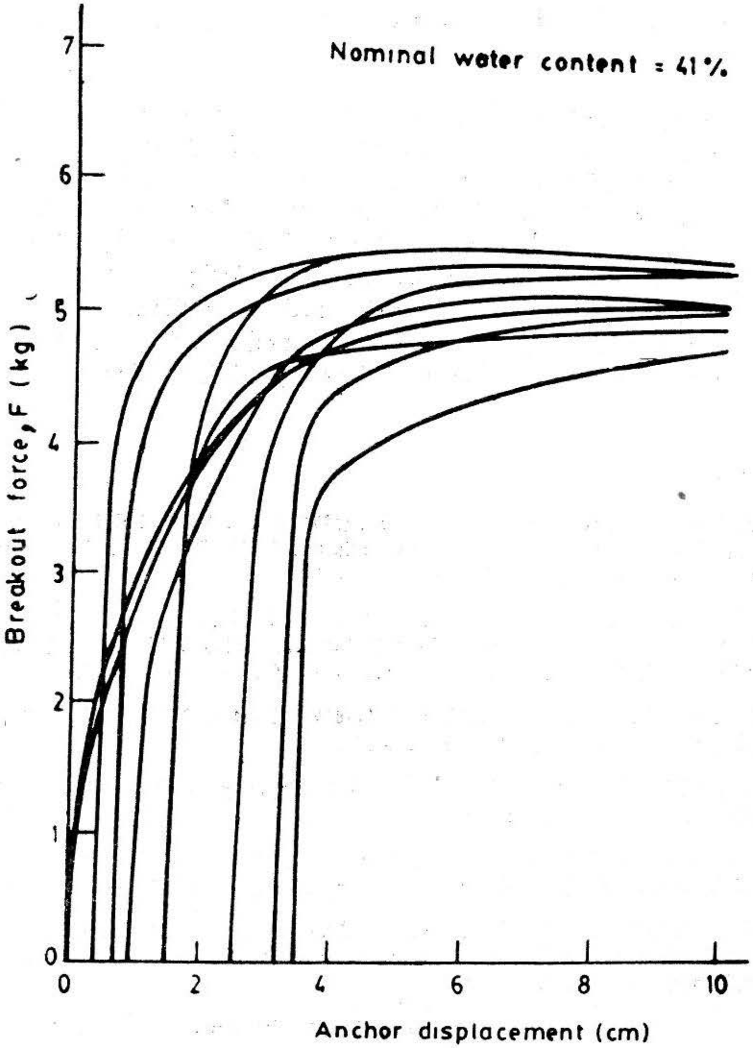

FIGURE 19 Breakout Force—Anchor Displacement Curves under Static Pullout Conditions.

pullout capacities of anchors on account of either (*a*) decrease in soil strength or (*b*) pullout behaviour changing from that of deep anchor to one of shallow anchor.

In submarine clays which exhibit strength on account of their insitu structure, cyclic loading may cause degradation of structure and loss of strength. However, since in the present study remoulded clay was used, no degradation was observed.

Conclusions

Plate anchors show significant movement under cyclic loading. The magnitude of movement is governed primarily by the maximum cyclic stress level.

Plate anchors undergo movement of upto 20 percent of the anchor diameter under a maximum cyclic stress level of 33 percent of the static pullout capacity and under a cyclic stress increment of 25% of the static pullout capacity. The magnitude of movement does not increase with number of cycles after 500 cycles. If a displacement of 20% of anchor diameter is acceptable, plate anchors must be so designed that their static pullout capacity is at least three times the maximum cyclic stress level. To prevent any movement of the anchor under cyclic loading the maximum cyclic stress level will have to be well below 25% of the static pullout capacity.

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