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Pullout Behavior of Cyclically Loaded Piles in Clay

by

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Introduction

As the search for ocean resources forces the development of offshore structures into deeper waters, there are sound economic and technical reasons for the adoption of floating type compliant offshore structures. These structures require anchoring to the seabed in order to resist large mooring tensions. Tension piles are considered to be a viable means of providing this anchor facility, specially when large tensile forces are required to be resisted. These pile anchors are subjected to static uplift forces combined with cyclic forces.

Presence of significant petroleum resources has been registered off the east coast of India at the mouth of the river Godavari where water depths are of the order of 200 metres and the seabed soil comprises of very soft to soft clay. Tension leg platforms (TLPs) with pile foundations are envisaged as one feasible type of production structure for this location. An understanding of the pullout behaviour of offshore piles in very soft to soft clays, under cyclic uplift loading has thus been of growing concern to Indian engineers over the last few years. This aspect has been investigated in detail in this paper.

Cyclic Loads on Anchors

The tension leg platform is a floating structure held in position by anchoring it to the seabed. It consists of a floating hull which is connected to anchor foundations by tendons. Piles have been used as foundations in the Hutton TLP which was installed in 1983 in 150 metres water depth. After the successful installation and operation of the Hutton TLP, numerous TLPs have been proposed for deep water sites with "piles -with- template" as anchor foundations.

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Anchors of TLPs are subjected to vertical pullout loads which have a static component as well as a cyclic component. Cyclic loads occur due to platform movement on account of the effect of waves, wind, currents, tides and other environmental factors. The platform movement may be in the form of oscillations, slow drift or a steady offset. Due to variations in the platform movement, each leg of the TLP may be subjected to varying tensions with time in a cyclic manner. The nature and magnitude of pullout forces which are transmitted to the anchors of TLPs have been summarised by Datta et al. (1990). The typical range loads reaching the foundations of TLPs are:

(*a*) Static pretension at each leg = 3000 to 6000 tonnes,

(*b*) Minimum design tension at each leg = 7000 to 11000 tonnes, &

(*c*) Minimum design tension at each leg = zero to 2000 tonnes.

One notes that the cyclic tension induced in TLP foundations is significantly larger than the static pretension.

Literature Review

An attempt was made to survey the literature on the behaviour of piles under cyclic loading for soft clays. Since very limited data was available on soft clays, medium clays were also included in the literature survey.

Pullout behavior of piles under cyclic loading has been studied through laboratory model tests by Holmquist and Matlock (1976), Poulos (1979) and (1981), Steenfelt *et al.* (1981) and Matlock *et al.* (1982) as well as through field tests by Grosch and Reese (1980), Kraft *et al.* (1981), Puech (1982) and Karlsrud and Haugen (1985).

Many test results which have been reported are, however, not relevant for TLP foundations because of the following reasons:

(*i*) A majority of the cyclic tests have been conducted using two-way cyclic loading (tension – compression). This type of loading is not relevant for anchors of TLPs which experience only one-way cyclic loading in tension.

(*ii*) Some tests have been conducted under strain-controlled conditions. In these tests, cyclic loading has been applied between pre-specified displacement limits. The cyclic loading which is experienced by foundations of TLPs is stress-controlled in nature. Consequently, the results of strain-controlled tests are not of relevance for design of TLP foundations.

Only two studies have been reported under one-way stress-controlled cyclic loading in tension, one by Puech (1982) and the other by Karlsrud and Haugen (1985). The former is in a multilayered soil deposit (silty sand-loose sand – silty clay) and the later is in medium to stiff saturated clay.

Their findings can be summarised as follows :

(*a*) Below a threshold stress level of cyclic loading, piles show very low movement with number of cycles. The rate of movement rapidly falls to zero as number of cycles increases. The total accumulated movement remains below 4.0 percent of pile diameter.

(*b*) Above the threshold stress level, rapid accumulation of upward movement takes place with number of cycles, finally resulting in failure of the pile.

(*c*) The threshold level lies in the range of about 50 to 60 percent of ultimate static pullout capacity.

(*d*) The influence of cyclic loading on subsequent static behavior, in terms of degradation of pullout capacity, has not been delineated in these studies.

The review of literature reported here indicates that pullout behaviour of piles under cyclic loading in soft clays has not been a subject of detailed study in any investigation. The findings of Puech (1982) and Karlsrud and Haugen (1985) need to be verified for very soft to soft clays.

Aim

The aim of the present study was to understand the influence of cyclic loading on pullout behavior of piles buried in soft clay ; particularly to identify (*a*) the movement of piles under cyclic loading, and (*b*) the influence of the cyclic loading on subsequent static pullout behaviour.

Laboratory investigations were carried out on model aluminium tubular pile anchors buried in very soft saturated clay in model test tanks. The model piles were subjected to static pullout and cyclic pullout loads. Cyclic pullout tests were carried out at different water contents of soil, with variable number of load cycles and using different cyclic stress levels to identify the following:

(*a*) the influence of water content of soil on the movement of pile anchors under cyclic loading;

(*b*) the influence of number of cycles of loading on the movement of pile anchors,

(*c*) the influence of cyclic stress level on the movement of pile anchors, and

(*d*) the influence of cyclic loading on subsequent static pullout behaviuor of pile anchors.

Experimental Investigations

Tubular aluminium model pile anchors, 5 cm in outer diameter were buried in very soft saturated clay contained in circular model test tanks of 30 cm diameter and 40 cm height (Fig.1). The model piles used were 20 cm

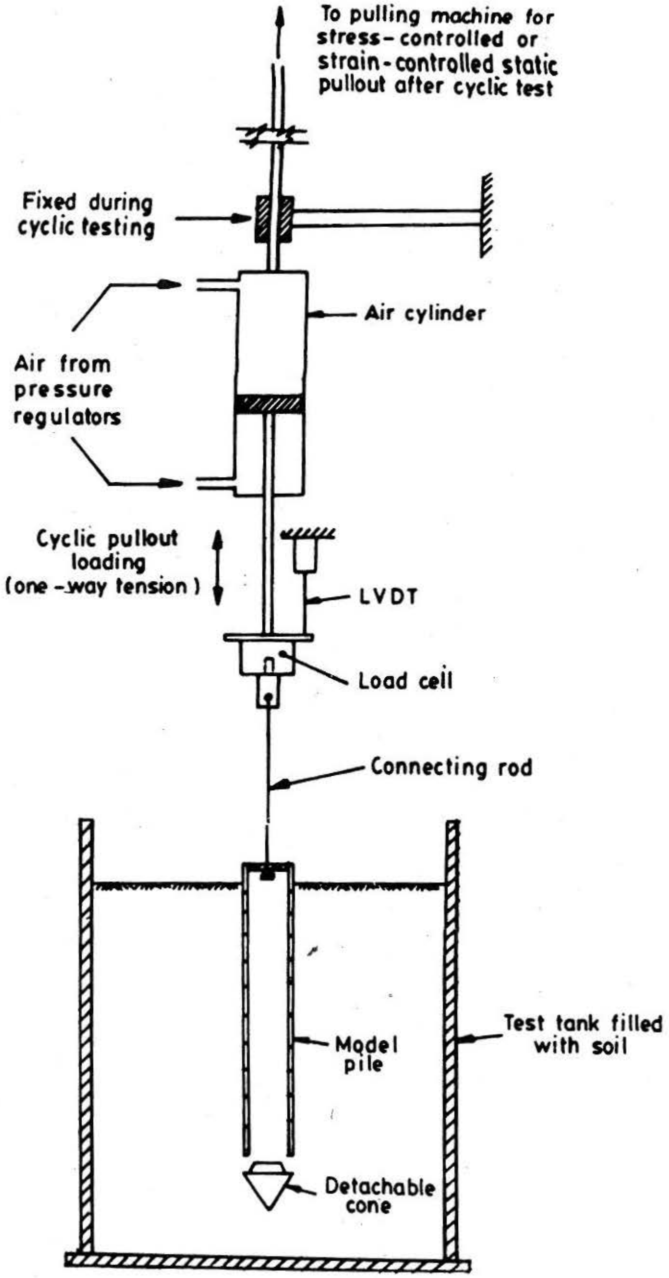

FIGURE 1 Testing arrangement for Cyclic Tests

in length and had their outer surface thoroughly and evenly roughened by knurling. These piles were installed in the soil by pushing from top and using a perspex cone fitted at the bottom end. The cone was detached from the bottom prior to applying pullout load.

Cyclic load was applied to model pile anchors using a pneumatic loading system (Fig.2) described by Datta et al. (1990). A square wave pattern tension cyclic loading was applied between prespecified maximum and minimum pullout load limits with a time period of 15 seconds. The upward movement of the pile was observed during cyclic loading.

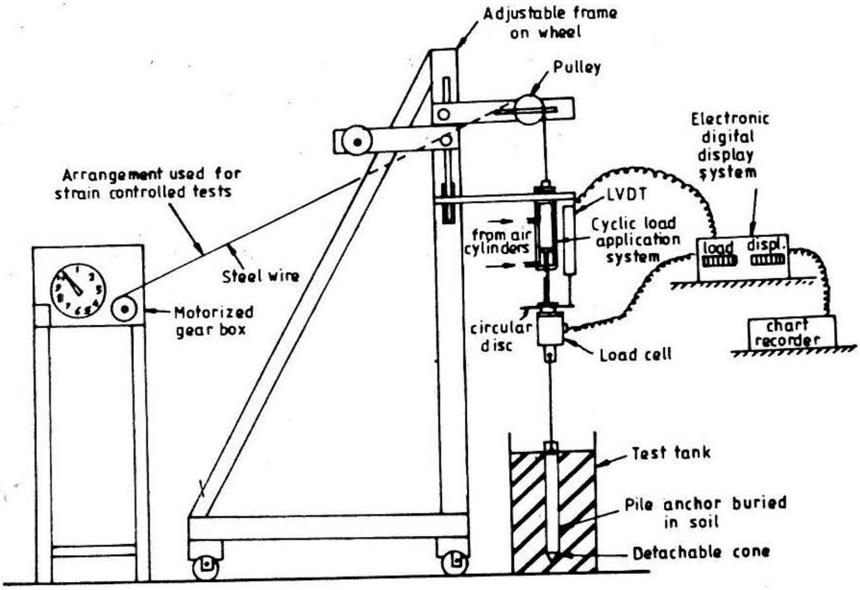

FIGURE 2 Experimental set-up for Pulling out Pile Anchors Under Cyclic Loading and Strain Controlled Static Loading

Soil Used

The soil used in the model tests was Dhanauri clay, a river-bed clay deposit having grain size distribution and index properties as indicated in Table-1. The range of water contents used in model tests varied from 35 to 45 percent. In this range of water content the undrained strength, S_u, of the soil varied from 0.016 to 0.06 kg per sq.cm indicating that the soil strength fell within the range of strengths normally associated with very soft clays ($0 < S_u < 0.125$ kg per sq. cm.).

A detailed study was conducted to establish the variation of strength of remoulded Dhanauri clay with time. The study indicated that Dhanauri clay did exhibit thixotropic properties and that the undrained strength did not increase appreciably after 4 days. In all model tests, pullout loading was applied after allowing Dhanauri clay to remain undisturbed for 7 days.

TABLE 1
Grain Size Distribution and Index Properties of Dhanauri Clay

Liquid limit	=	51%
Plastic limit	=	30%
Plasticity index	=	21%
Sand content	=	01%
Silt content	=	64%
Clay content	=	35%
Specific gravity of solids	=	2.77

Test Procedure

The soil was first pulverized into a fine powder. Each model test took eight days. The complete test cycle consisted of the following stages:

(*a*) mixing pulverised soil with desired quantity of water,

(*b*) filling-up the test tank with saturated soil,

(*c*) leaving the soil in the tank undisturbed for 7 days to allow it to undergo thixotropic gain,

(*d*) installing model pile in the test tank on the eighth day,

(*e*) performing the pullout test soon after installation of pile,

(*f*) measuring undrained strength of the soil in the test tank immediately after the pullout test,

(*g*) taking samples for water content determination of the soil from the test tank immediately after measurement of undrained strength, and

(*h*) drying the soil and pulverizing for re-use.

Usually a few static strain-controlled pullout tests at each water content were performed just prior to starting a series of cyclic pullout tests at that water content. Cyclic tests consisted of applying 500 cycles of pullout load between pre-specified maximum and minimum load limits and observing the corresponding upward movement of the pile. The maximum and minimum load limits were prespecified as percentages of the static pullout capacity. Three sets of cyclic load limits were used namely 25 to 50 percent, 25 to 66 percent and 25 to 75 percent. The cyclic load was applied using pneumatic system described by Datta et al. (1990). The time period of cyclic loading was set as 15 seconds by means of the timers. The movement of the pile under cyclic loading was measured by an LVDT as well as a dial gauge fitted separately. Readings of displacements were taken for the following number of cycles; 1 to 10, 20 to 25, 50 to 55, 75 to 80, 100 to 110, 200 to

210, 300 to 310, 400 to 410 and 490 to 500. At the end of 500 cycles, the pullout load applied to the pile was decreased to zero. The pile was then pulled out statically under a strain rate of 0.2 mm/min.

Testing Programme

Table-2 presents the details of the testing programme of cyclic pullout tests. The influence of the following variables on pullout behaviour was studied:

(*a*) water content of the soil : 35, 40 and 45 percent

(*b*) number of cycles of loading : 0 to 500 cycles

(*c*) cyclic stress levels (one way, tension) :
25% (min.) to 50% (max.)
25% (min.) to 66% (max.)
25% (min.) to 75% (max.)

(*d*) strain rate in static test after cyclic loading : 0.2 mm/min.

Test Results And Discussion

Reproducibility of Test Results

Results of cyclic tests were checked for reproducibility by comparing the movement of pile in different tests under identical test conditions. From the test results it became evident that the first cycle movement in most tests was erratic. The non-uniformity in the first cycle movement appeared to reflect a seating adjustment that the pile underwent when subjected to pullout. Since this movement was sometimes larger than the movement in subsequent 500 cycles, it distorted the overall trend observed. Consequently, the first cycle movement was ignored to reduce the distortion of results and make the resulting plots more amenable to analysis.

Movement Under Cyclic Loading

Table-3 presents the magnitude of pile movement due to cyclic loading. The pullout behaviour of pile anchors under cyclic loading could be classified into two types – one in which there was insignificant movement even after 500 cycles of pullout load and the other in which the pile failed suddenly after some cycles of loading despite initially showing little movement. Which of these two type of behaviour was exhibited by a pile, depended on the cyclic stress level and water content of the soil. The influence of each of these parameters is described hereafter.

Influence of cyclic stress level

Figs. 3, 4 and 5 depict the movement of piles versus number of cycles, each at a constant cyclic stress level and at three water contents of the soil. From these figures it is apparent that at low cyclic stress level (25-50 per cent, Fig. 3), the movement of piles is extremely low, being less than 0.2

TABLE 2

Testing Programme : Cyclic Tests

Sl. No.	Attempted water content	Test type	Minimum cyclic stress level (%)	Maximum cyclic stress level (%)	Time Period per cycle in cyclic test	No. of cycles in cyclic tests	Strain rate during static pullout (mm/min)	No. of tests conducted
1	35	Static	-	-	-	-	0.2	3
2	"	Cyclic	25	50	15	500	"	2
3	"	"	"	66	"	"	"	2
4	"	"	"	75	"	"	"	2
5	40	Static	-	-	-	-	"	3
6	"	Cyclic	25	50	15	500	"	2
7	"	"	"	66	"	"	"	2
8	"	"	"	75	"	"	"	2
9	45	Static	-	-	-	-	"	3
10	"	Cyclic	25	50	15	500	"	2
11	"	"	"	66	"	"	"	2
12	"	"	"	75	"	"	"	2

TABLE 3
Movement of Pile Anchors Under Cyclic Loading

Sl. No.	Water Content (%)	Cyclic stress level (%)		Total movement of anchor in mm (excluding 1st cyclic movement after cycles			Total movement after 500 cycles as a percentage of pile dia. (excluding 1st cycle movement)
		Min	Max	10	100	500	
1	33.62	25	50	0.000	0.002	0.068	0.136
2	33.88	"	"	0.006	0.008	0.008	0.016
3	35.82	"	"	0.000	0.000	0.012	0.024
4	36.25	"	"	0.018	0.068	0.068	0.136
5	38.02	"	"	0.016	0.016	0.016	0.032
6	37.20	"	"	0.014	0.016	0.016	0.032
7	32.48	"	66	0.000	1.488	(Failed at 240 cycles)	--
8	33.42	"	"	0.068	0.102	0.102	0.204
9	35.10	"	"	0.000	0.000	0.000	0.000
10	35.46	"	"	0.052	0.104	0.126	0.252
11	35.25	"	"	0.000	0.000	0.000	0.000
12	36.93	"	"	0.010	0.096	0.300	0.600
13	32.90	"	75	0.680	(Failed at 70 cycles)	--	--
14	34.01	"	"	0.290	3.400	(Failed at 200 cycles)	--
15	34.92	"	"	0.000	0.054	0.054	0.108
16	35.48	"	"	0.030	0.726	1.660 (On the verge of failure)	3.32
17	37.60	"	"	0.168	0.318	0.418	0.836
18	37.29	"	"	0.110	0.112	0.114	0.228

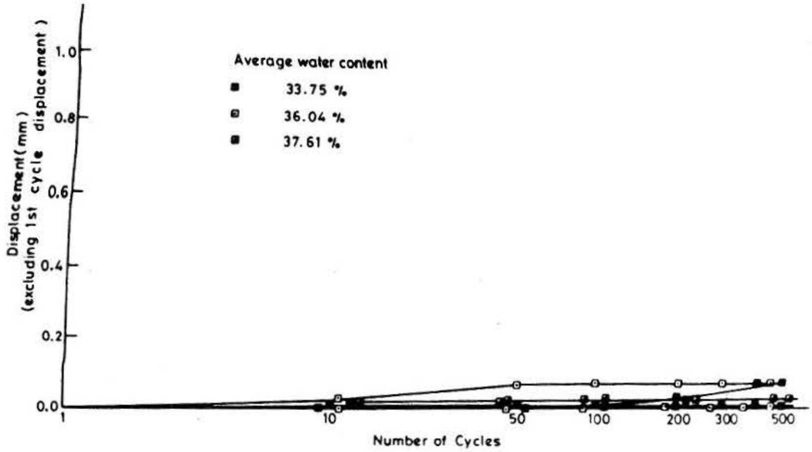

FIGURE 3 Movement of Pile Anchors with Number of Cycles (cyclic stress level : 25 to 50%)

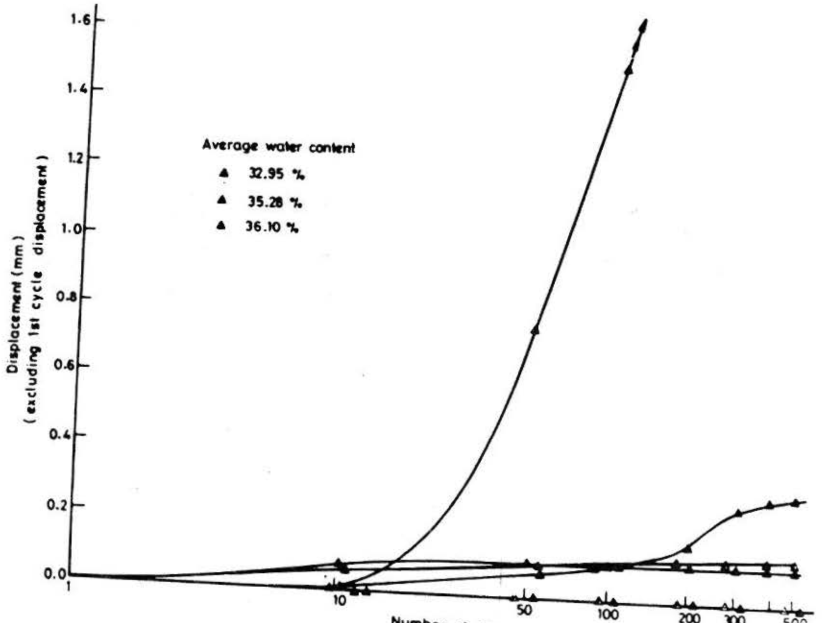

FIGURE 4 Movement of Pile Anchors with Number of Cycles (cyclic stress level : 25 to 66%)

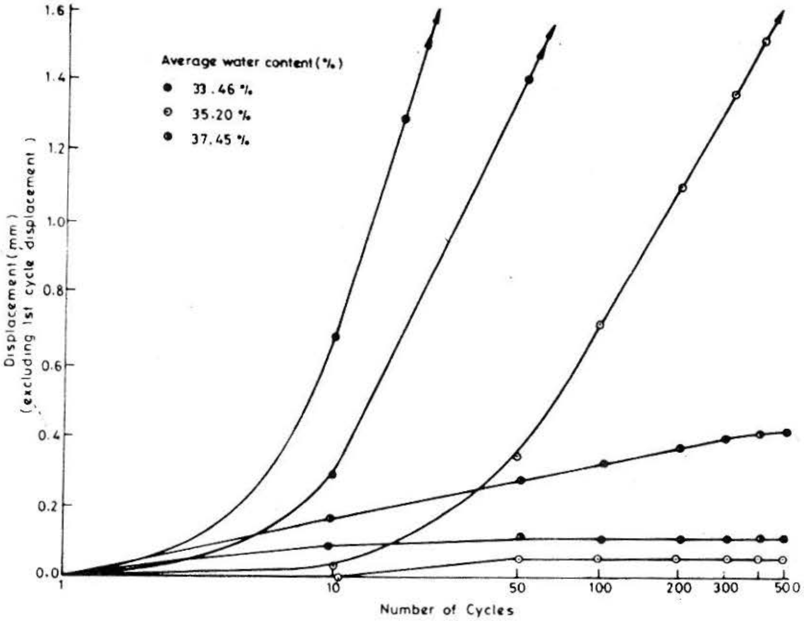

FIGURE 5 Movement of Pile Anchors with Number of Cycles (cyclic stress level : 25 to 75%)

mm i.e. 0. 40 percent of the pile diameter. At high cyclic stress level (25-75 percent Fig. 5), some piles exhibit failure after showing very low movement in the initial few cycles. These piles fail without any warning and move up rapidly in few cycles. This trend is not observed for piles installed in soil with the highest water content - in which no failure is observed. Fig. 4 depicts the results at the intermediate cyclic stress level in which the only pile anchor observed to fail is the one at the lowest water content.

That the movement under cyclic loading is a function of maximum cyclic stress level becomes evident from Fig. 6 which depicts the total displacement after 500 cycles versus the maximum cyclic stress level for the entire range of tests conducted. It is evident from this figure that the movement of piles anchors increase with the maximum cyclic stress level and that the movement registers a very sharp increase near a threshold value of the maximum cyclic stress level beyond which failure of the pile occurs. This threshold value; designated as the critical maximum cyclic stress level; appears to be about 70 percent for piles embedded in soil at low water content and above 85 percent for piles in soil at higher water content.

Influence of water content

Figs. 7, 8 and 9 depict the movement of pile anchors with number of cycles, each for a given water content and under three different stress levels of cyclic loading. From the figures, it is evident that at high water content (Fig. 9) there is no failure for the entire range of cyclic stress levels, whereas at low water content (Fig. 7) one observes failure even at the intermediate

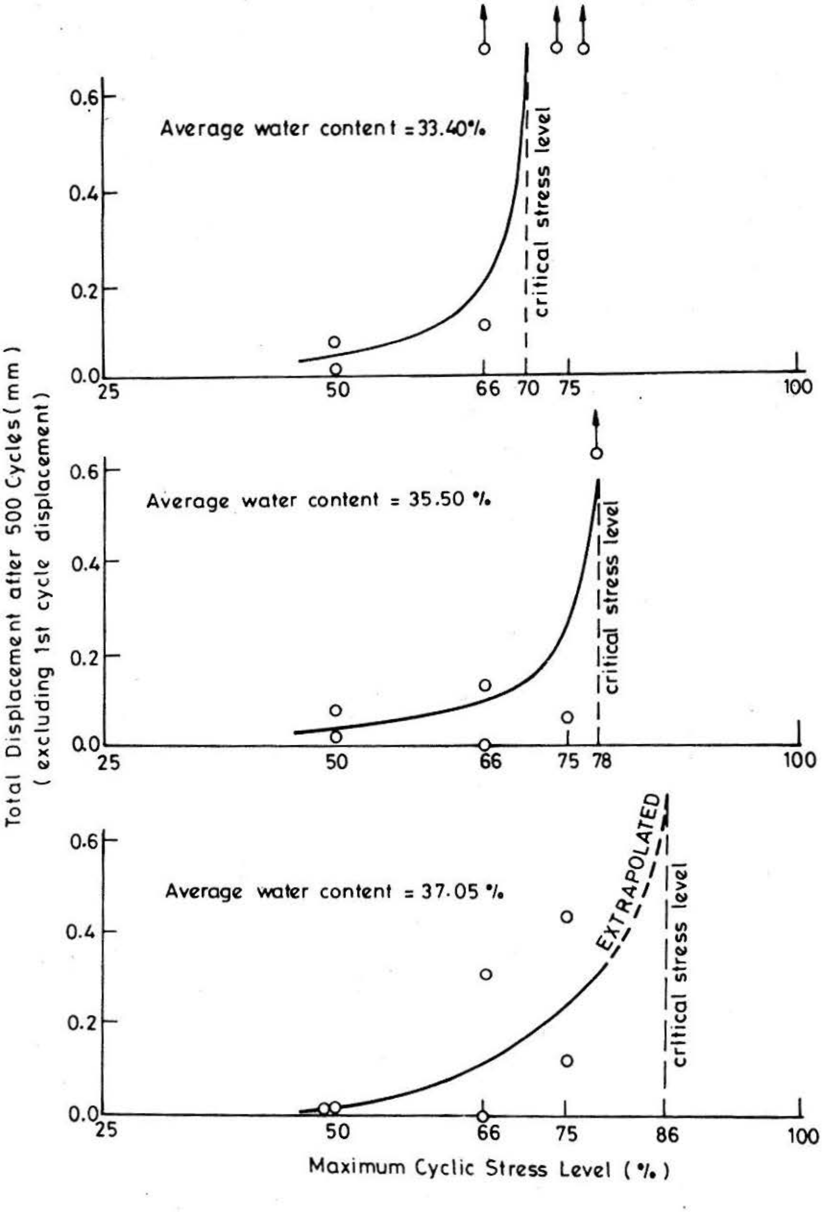

FIGURE 6 Influence of Maximum Cyclic Stress Level on Movement of Pile Anchors

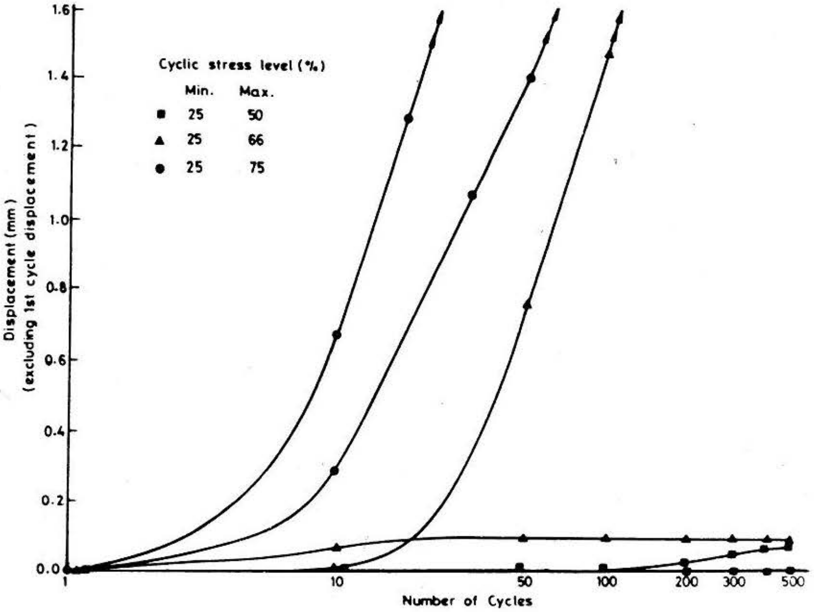

FIGURE 7 Movement of Pile Anchors with Number of Cycles (average water content = 33-40%)

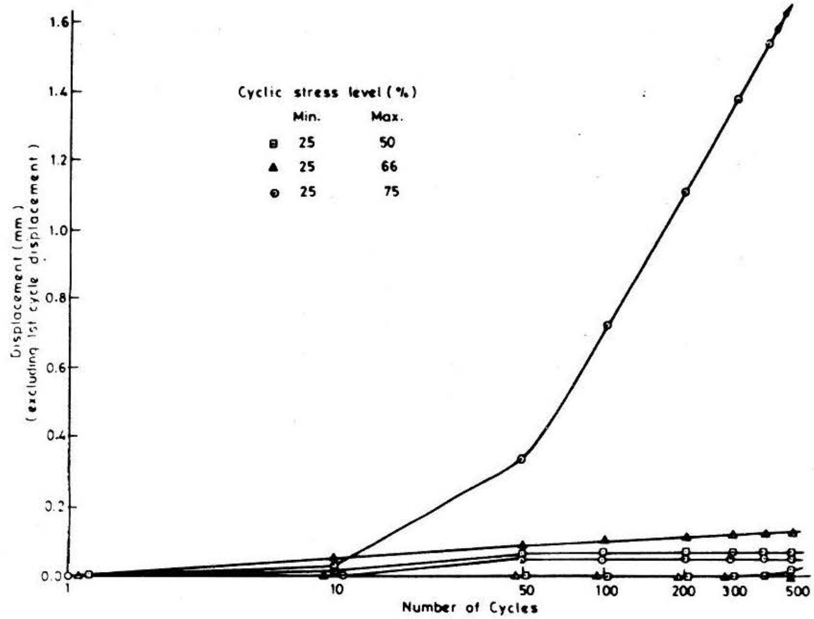

FIGURE 8 Movement of Pile Anchors with Number of Cycles (average water content = 35.50%)

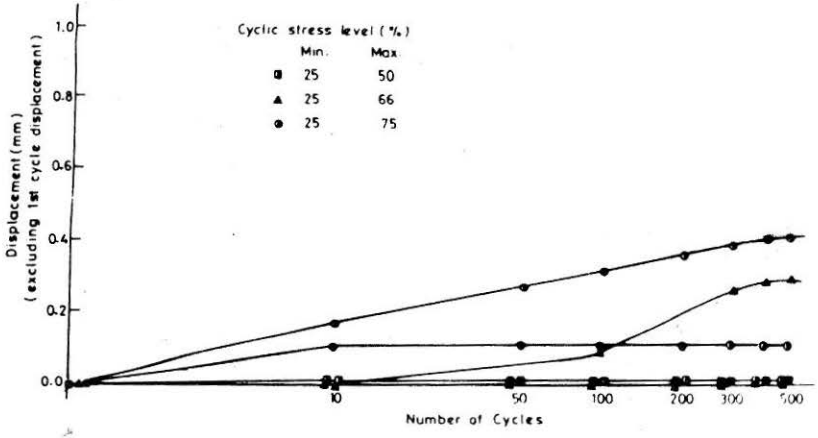

FIGURE 9 Movement of Pile Anchors with Number of Cycles (average water content = 37.05%)

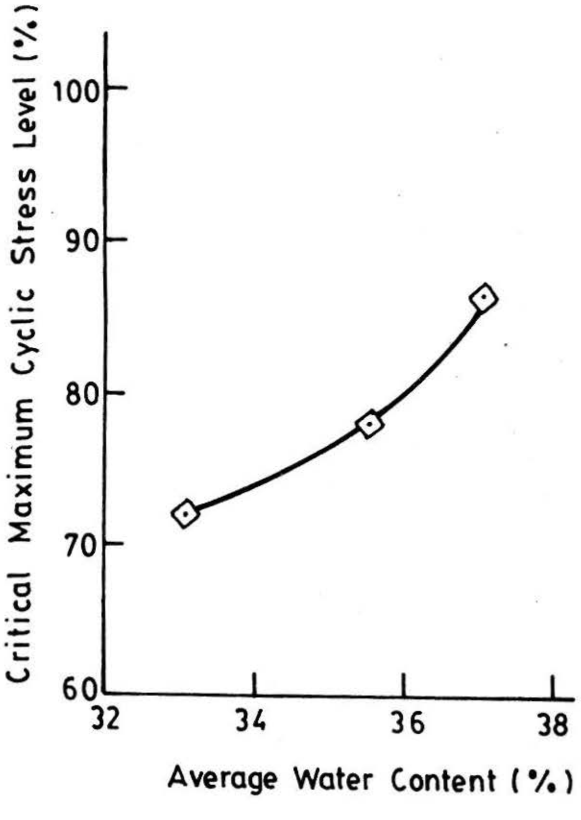

FIGURE 10 Influence of Water Content on Critical Maximum Cyclic Stress Level

cyclic stress level (25-66%). That increasing water content causes an improvement in the performance of a pile under cyclic loading becomes evident from Fig. 10 which shows that the value of the critical maximum cyclic stress level increases with the water content of the soil.

Static Behavior After Cyclic Loading

Load - displacement Behavior

Fig.11 shows the pullout load-displacement Behavior observed in static tests as well as in cyclic -then - static tests performed at an average water content of 37.05 percent for all the cyclic stress levels. No static test could be performed on piles which failed under cyclic loading. From the figure it is evident that so long as a pile does not fail under cyclic loading, there is no influence on the subsequent static behavior of the pile. The same trend was observed at other water contents.

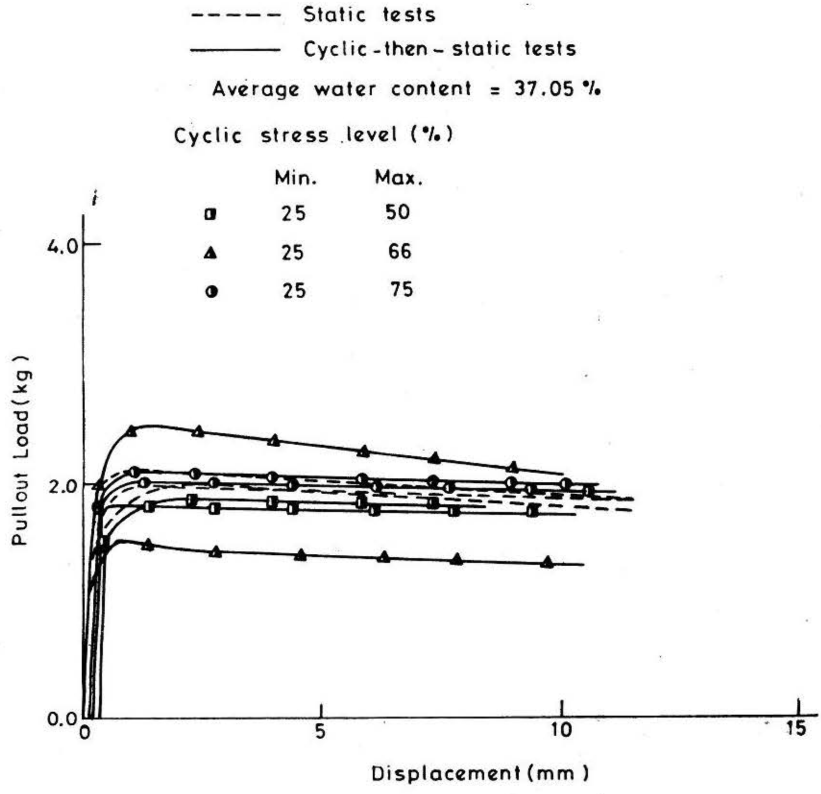

FIGURE 11 Pullout Load-Displacement Behaviour Under Static Tests and Cyclic-Then-Static Tests

α - Values

The adhesion factor α between the soil and the pile was evaluated at the end of each static as well as cyclic - then- static pullout test. Fig. 12 shows the plot of α - values versus water content for the entire set of tests conducted under both static tests as well as cyclic - then - static tests. No significant difference is observed in the α - values and after cyclic loading. The degradation of pile capacity due to cyclic loading, as reported by some investigators for two-way loading, was not observed in this entire test series which consisted of one-way loading.

Concluding Remarks

The results of the present study seem to follow the trends observed by Puech (1982) and Karlsrud and Haugen (1985). The following significant conclusions can be drawn regarding the pullout behaviour of piles if soft clay under cyclic loading:

(*i*) At low cyclic stress level, the upward movement of model piles is observed to be less than 0.4 percent of the pile diameter.

(*ii*) The critical maximum cyclic stress level beyond which failure of the pile occurs appears to be about 70 percent of its static pullout capacity in soil at low water content and about 85 percent at high water content for the range of water contents investigated.

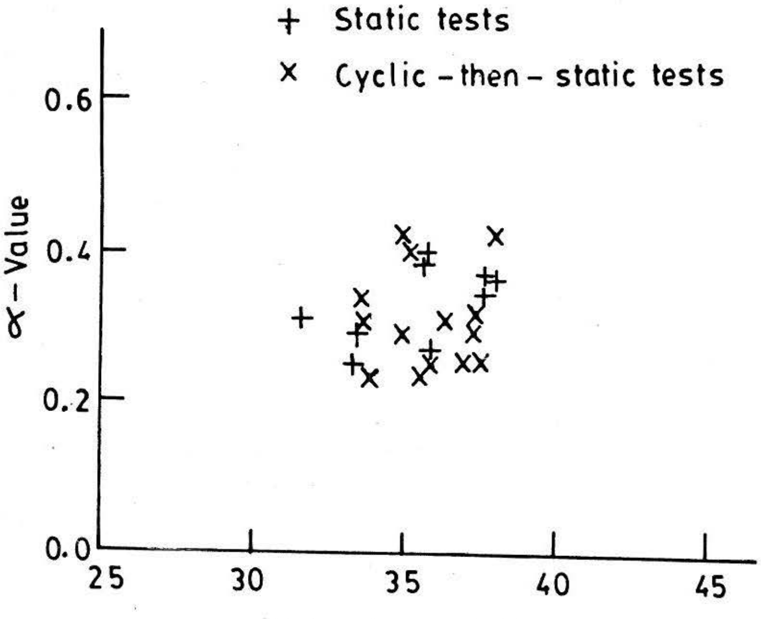

FIGURE 12 α-Values Obtained From Static Tests and Cyclic-Then-Static Tests.

(*iii*) A high maximum cyclic stress level, piles exhibit sudden failure without warning except when the pile is embedded in soil of high water content.

(*iv*) No degradation of static pile capacity due to cyclic loading is observed in post cyclic-static behaviour as long as the pile does not actually fail during cyclic loading itself.

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