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Response of Plate Anchors to Sustained-Cyclic Loading

S.P. Singh* and S.V. Ramaswamy†

Introduction

The foundations of offshore structures are normally subjected to large magnitudes of uplift force coupled with fluctuating load, which are significant during storm conditions. The major design requirements for anchor foundations under such loading conditions are (i) the ability to develop sufficient resistance to either static or cyclic loading or a combination thereof and (ii) the ability to develop this resistance with movements, which are compatible with the design criteria of that particular structure.

Plate anchors are among the most popular types of anchor used in the field as they provide an economical alternative to gravity and other embedded anchor foundation (Bouzza and Finally, 1990). The behaviour of anchors in saturated clay subjected to sustained-cyclic loading is a complex interaction problem involving the soil, water, anchor and loading pattern. A clear understanding of the behaviour of anchors under such loading conditions is essential for the design of structures in offshore environment. Due to lack of sufficient information the design of anchors under repeated loading is generally based on a high factor of safety.

Review of Earlier Work

Only limited information has been reported in the literature on the behavior of anchors under sustained-cyclic loading. Bemben et al. (1973), Bemben and Kupferman (1975) have presented some results on the long term cyclic behavior of fluke anchors embedded in sandy and clayey soils.

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* Department of Civil Engineering, Regional Engineering College, Rourkela – 769008, India.

† Department of Civil Engineering, Anna University, Chennai – 600025, India.

Ponniah and Finally (1988) reported the long term behaviour of circular (50 mm dia) plate anchors subjected to sinusoidal loading of 10 sec time period. Based on the test results it was reported that anchors did not fail when the load cycled up to 50 ± 20% of the drained ultimate pullout capacity. With recycling the failure load increased to 70 ± 20% of the drained anchor capacity.

The short term cyclic behavior of deep circular (50 mm dia) plate anchor in soft cohesive soil was reported by Datta et al (1990). The principal parameters studied were the influence of mean load and the cyclic amplitude on the permanent anchor movement and post-cyclic static pullout capacity. Based on the experimental results they opined that the plate anchors should be designed for load of 1/3rd of its static pullout capacity to take into account the effects of cyclic loading.

This paper outlines the relative influence of the static and cyclic load ratio levels on the movement of anchors and the post-cyclic load-deformation behavior of anchors.

Experimental Programme

The experimental program undertaken in the present study is broadly divided into two distinct phases. In the first phase, the anchors were subjected to various combinations of static and cyclic load ratio levels. In the second phase, the anchors are monotonically pulled out at the rate of 5 mm/min and the post-cyclic monotonic behavior of anchors was studied. All these tests were carried out using rigid circular (80 mm dia) model anchors made up of brass plates of 6 mm thickness.

Soil Characteristics

Pulverized commercial clay of high plasticity was used in the test program. Grain size analysis indicates the presence of fine sand (3.5%), silt (47.5%) and clay (49.0%). The liquid limit (LL) and the plasticity index (PI) of the clay used was 75% and 44% respectively. The XRD pattern shows the presence of kaolinite, chlorite, illite and vermiculite clay minerals along with quartz particles.

Preparation of Test Sample

The pulverized clay was thoroughly mixed with required amount of water by hand kneading and stored in airtight containers. Care was taken to remove the entrapped air during the mixing operation. The wet soil was again remixed after 2 days and stored in airtight plastic containers for another 7 to 8 days before being used. This procedure was followed to ensure proper moisture equilibrium in soil sample. The wet soil was placed in the test tank in small quantities by hand and patted uniformly. Because of the low consistency of the soil used, no problem was faced to fill the test tank using this method. After filling the test tank to the base level of the anchor, the anchor with the connecting rod was placed and the filling operation continued till required embedddment depth (480 mm) was achieved. The test tank was kept undisturbed for 22 hours before the load being applied. All the tests of this series were carried out at an average moisture content of 57.4% (I_C = 0.40 %) with standard deviation of 0.2776. The average degree of saturation of test beds was 96.65 % with an in-situ undrained unit cohesion of 4.70 kPa. The unit weight of soil in test tank was 16.08 kN/m^3.

Cyclic Loading Tests

In this investigation, one-way vertical cyclic pullout load on anchors was imparted by using a pneumatic loading apparatus. This consists of (i) an air compressor of adequate capacity with a reservoir (ii) pressure regulator with indicator (iii) double acting pneumatic power cylinder with 40 mm bore diameter and 150 mm stroke length (iv) three-way solenoid valve and (v) an electronic timer capable of operating the solenoid valve in the frequency range of 1/24 to 1 Hz.

Two types of cyclic loading pattern were used in this test programme. In the first loading pattern, the CLRL was varied from zero to a desired loading level. The maximum cyclic loading level used was 75% of the static ultimate pullout capacity of anchor. In the second loading pattern, the anchors were subjected to a sustained load of the desired intensity with the help of a loading hanger and dead weights superimposed by one-way cyclic load. In this test programme, the anchors were subjected to a maximum of 1000 loading cycles or loading cycles which cause permanent movement equal to the diameter of anchor. The details of the sustained-cyclic loading tests conducted is presented in Table 1. The cyclic loading on the anchor was imparted by the piston of the double acting pneumatic power cylinder which was connected to the anchor rod by a flexible wire through a system of frictionless pulleys. The piston of the pneumatic power cylinder was actuated by regulated compressed air, passing through a solenoid valve system controlled by an electronic timer. Schematic diagram of the cyclic loading set-up used is shown in Fig.1. All these tests were conducted using rectangular cyclic loading of 12 sec time period which is based on the prevailing wave conditions along the Indian east coast.

Post-Cyclic Monotonic Loading

The post-cyclic monotonic behavior of anchors was studied by adopting strain controlled pullout tests. The test set-up comprises of a (i)

TABLE 1 : Details of Sustained Cyclic Loading Tests

S.No.	Type of Loading	SLRL	CLRL	Cyclic Load Increment	Max. No. of Loading Cycles	Pullout Rate During PCML Tests (mm/min)	Cyclic Time Period (sec)
1.	Monotonic	–	–	–	–	5	–
2.	Cyclic then monotonic	0	0.15	0.15	1000	5	12
3.	Cyclic then monotonic	0	0.30	0.30	1000	5	12
4.	Cyclic then monotonic	0	0.45	0.45	1000	5	12
5.	Cyclic then monotonic	0	0.60	0.60	1000	5	12
6.	Cyclic then monotonic	0	0.75	0.75	100	5	12
7.	Cyclic then monotonic	0.15	0.15	0.15	1000	5	12
8.	Cyclic then monotonic	0.15	0.30	0.30	1000	5	12
9.	Cyclic then monotonic	0.15	0.45	0.45	1000	5	12
10.	Cyclic then monotonic	0.15	0.60	0.60	200	5	12
11.	Cyclic then monotonic	0.30	0.15	0.15	1000	5	12
12.	Cyclic then monotonic	0.30	0.30	0.30	1000	5	12
13.	Cyclic then monotonic	0.30	0.45	0.45	500	5	12
14.	Cyclic then monotonic	0.45	0.15	0.15	1000	5	12
15.	Cyclic then monotonic	0.45	0.30	0.30	1000	5	12
16.	Cyclic then monotonic	0.60	0.15	0.15	1000	5	12

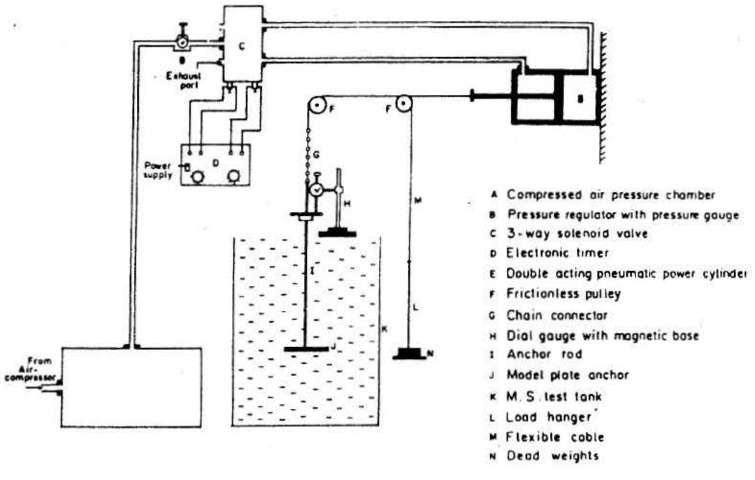

FIGURE 1 : Schematic Diagram of Cyclic Loading Test Set-up

loading frame (ii) 5 H.P., D.C. motor with speed control unit (iii) gear box unit with pulley drive and (iv) load and displacement measuring facilities. After completion of the cyclic loading the anchors were monotonically pulled out at a rate of 5 mm/min using the above test facility. The pullout resistance of anchors at required displacement levels was measured using a tension proving ring. Both cyclic loading tests and post-cyclic monotonic pullout tests were carried out without eliminating adhesion and suction force.

Results and Discussions

Anchor Movement

The cumulative anchor movement with loading cycles is shown in Figs.2 and 3. In these tests, the CLRL are varied from 0.15 to 0. 75 while keeping the SLRL at zero. From these curves, it is evident that the rate of movement per loading cycle is maximum for first few cycles and it reduces thereafter. For CLRL of 0.15 and 0.30 the movement of anchor gets stabilized after few loading cycles, subsequently only elastic movement is observed during each loading cycle i.e. without causing any net permanent anchor movement. The movement of anchor during cyclic loading is related to the development and dissipation of excess pore water pressure. The cyclic pore water pressure increases during the loading phase of cycle and subsequently dissipates. The dissipation of excess pore water pressure from

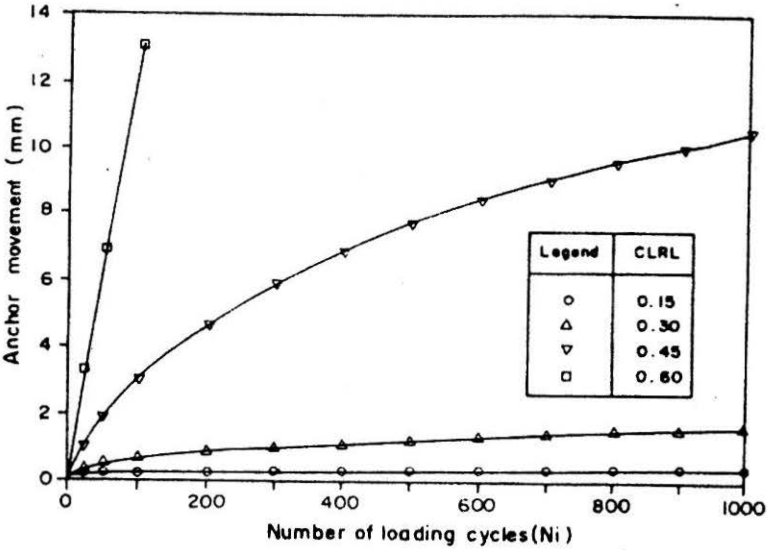

FIGURE 2 : Movement of Anchors with Number of Loading Cycles at CLRL of 0.15, 0.30, 0.45 and 0.60

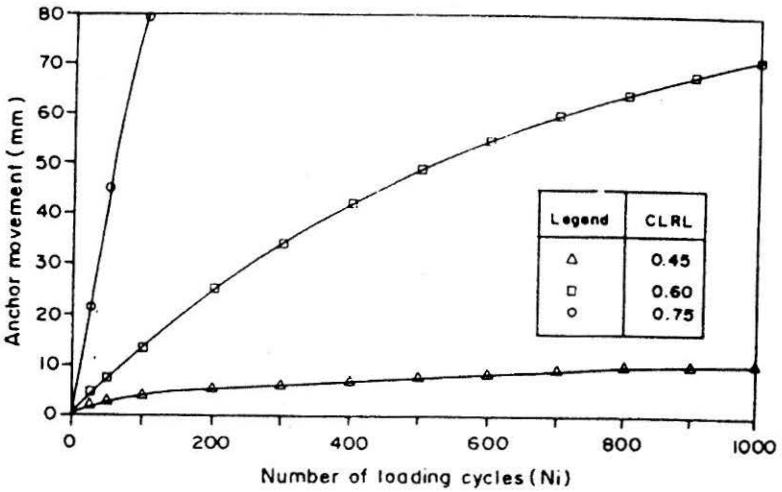

FIGURE 3 : Movement of Anchors with Number of Loading Cycles at CLRL of 0.45, 0.60 and 0.75

the soil just above the anchor plate, creates a locally consolidated soil mass with comparatively higher shear strength. For low cyclic load amplitude the movement of anchor is arrested by the stiffer soil mass formed above the anchor during initial few cycles of loading. At higher cyclic load levels this phenomenon also occurs but due to substantial movement of anchor in each cycle of loading, a localized consolidated soil zone can not be formed as in each cycle, the anchor moves upward through undisturbed soil. So for higher CLRL, the complete stabilization of movement is not observed within 1000 loading cycles, although the rate of movement is found to decrease with loading cycles. Similar behaviour is also observed by Datta et al. (1990) for plate anchors in normally consolidated clay.

Cyclic Stiffness

The cyclic stiffness of anchor soil system is defined as the ratio of CLRL to the cumulative cyclic displacement at a given loading cycle. The variation of cyclic stiffness with the number of loading cycles is shown in Fig.4. The cyclic stiffness is found to degrade with loading cycles. However, for low intensities of cyclic loading, i.e. CLRL of 0.15 and 0.30 the cyclic stiffness stabilizes within 1000 loading cycles, while for higher CLRL the degradation continues beyond 1000 loading cycles. The results are further analyzed in terms of normalized cyclic stiffness which is the ratio of cyclic stiffness at (N_i) cycles of loading to the cyclic stiffness of first loading cyclic. The rate of degradation of normalized cyclic stiffness is found to increase with the intensity of cyclic load (Fig.5).

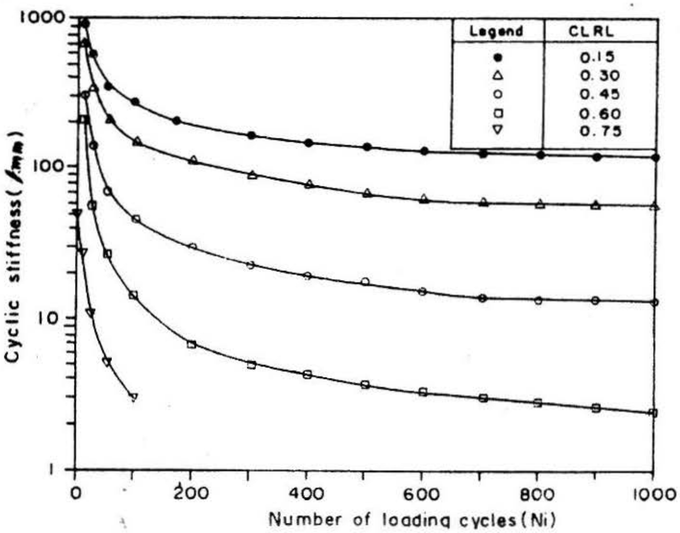

FIGURE 4 : Degradation of Cyclic Stiffness with Number of Loading Cycles

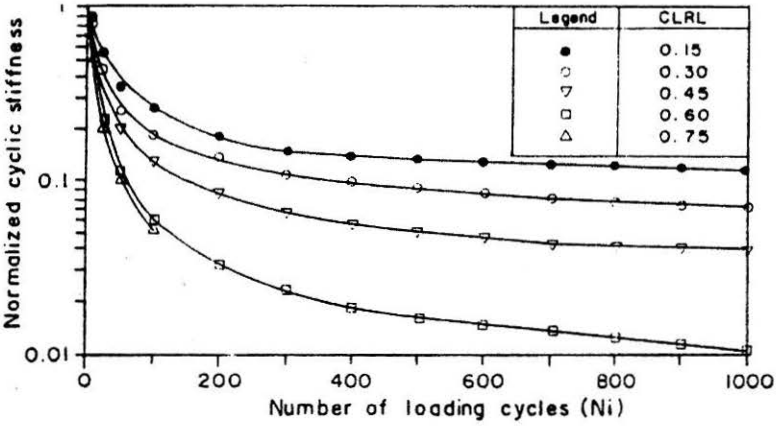

FIGURE 5 : Variation of Normalised Cyclic Stiffness with Number of Loading Cycles

Relative Influence of Load Ratio Levels

In order to examine the relative influence of load levels on the movement of anchors, the anchors were subjected to various combinations of cyclic and static load ratio levels, keeping the total load ratio level (TLRL) constant. TLRL is the sum of SLRL and CLRL Figs.6 and 7 show

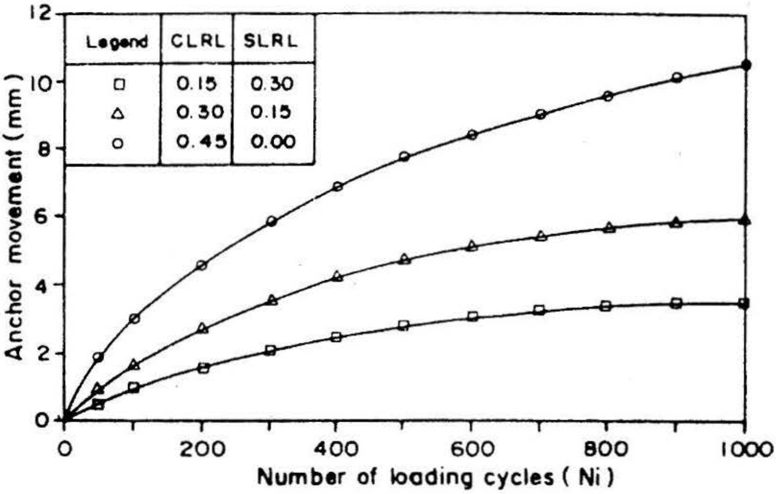

FIGURE 6 : Movement of Anchor with Number of Loading Cycles at TLRL of 0.45

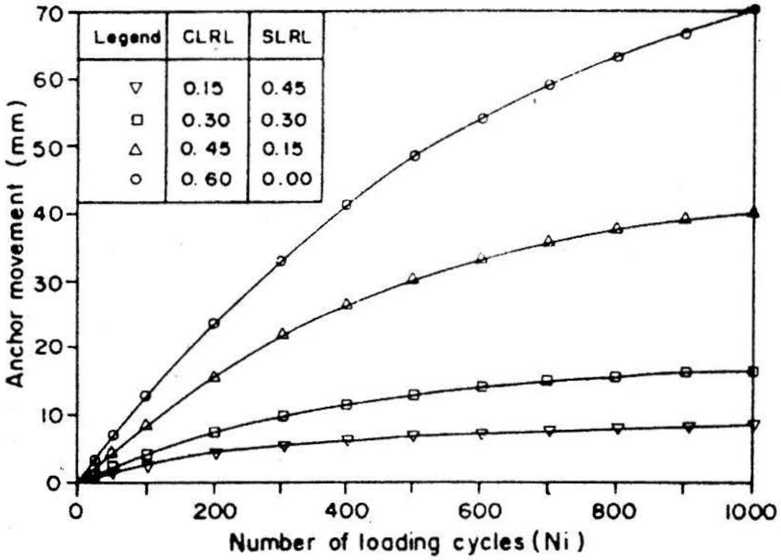

FIGURE 7 : Movement of Anchor with Number of Loading Cycles at TLRL of 0.60

the movement of anchor with the number of loading cycles for TLRL of 0.45 and 0.60 respectively. For TLRL of 0.60 the relative anchor movement after 1000 cycles is 11.5% and 88.8% for CLRL of 0.15 and 0.60 respectively. This shows that the movement of anchor is primarily governed by the amplitude of cyclic loading rather than the component of static loading. Further one notes that after given cycles of loading the rate of anchor movement is more, for anchors subjected to higher cyclic load levels although, the TLRL is kept constant. All these highlight the relative influence of CLRL component on the movement of anchors.

Post-Cyclic Monotonic Behaviour

Load-displacement behaviour

Typical load displacement curves for anchors subjected to CLRL of 0.15, 0.30 and 0. 45 are shown in Fig. 8 along with that without any cyclic loading. The accumulated movement of anchors after 1000 loading cycles is also illustrated along the displacement axis. The plots indicate that the pullout load displacement behaviour of anchors subjected to cyclic loading and then monotonic pullout loads are more stiffer in their initial part compared to anchors without any cyclic loading. The relative post cyclic stiffness (ratio of initial stiffness of anchors subjected to cyclic loading to that of the anchor without any cyclic loading) is presented in Table 2. The relative post-cyclic stiffness of anchors are found to increase with intensity of cyclic loading upto CLRL of 0.45, thereafter it decreases. The loss of post-cyclic stiffness of anchors at higher cyclic loading levels may be attributed to the loss of embedment ratio of anchors during the cyclic loading phase. Moreover at higher cyclic loading levels, substantial magnitude of anchor movement occurs at each loading cycle, thus preventing the development of a localized consolidated soil mass above the anchor plate. Irrespective of the loading combinations the relative movement at

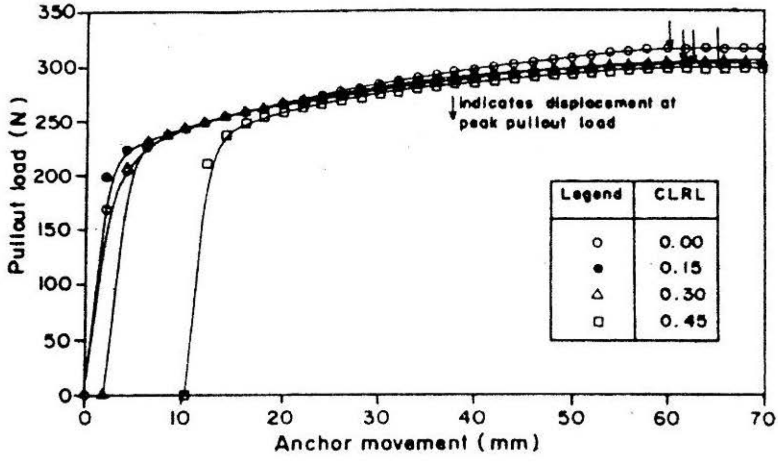

FIGURE 8 : Post-Cyclic Pullout Load-Displacement Behaviour of Anchors

TABLE 2 : Summary of Post-Cyclic Monotonic (PCML) Tests

S.No.	SLRL	CLRL	Cycles of Loading	E.R. at the Beginning of PCML Test	Pullout Rate (mm/min)	Peak Load (N)	Displacement at Peak Pullout Load (mm)	Relative Displacement at Peak Load (%)	Initial Stiffness (N/mm)	Relative Post-Cyclic Stiffness	Cyclic Reduction Factor
1.	0.00	0.00	–	6.00	5	315	62	77.5	122.0	1.000	–
2.	0.00	0.15	1000	6.00	5	304	64	80.0	143.7	1.178	0.965
3.	0.00	0.30	1000	5.89	5	301	62	77.5	150.2	1.231	0.956
4.	0.00	0.45	1000	5.87	5	297	56	70.0	154.2	1.264	0.943
5.	0.00	0.60	1000	5.11	5	292	58	72.5	151.3	1.240	0.927
6.	0.00	0.75	100	5.00	5	290	57	71.3	143.4	1.175	0.920
7.	0.15	0.15	1000	5.99	5	301	61.5	76.9	142.0	1.163	0.956
8.	0.15	0.30	1000	5.93	5	296	64	80.0	152.0	1.246	0.940
9.	0.15	0.45	1000	5.50	5	304	58	72.8	165.2	1.354	0.965
10.	0.15	0.60	200	5.10	5	289	63.0	78.8	139.0	1.140	0.918
11.	0.30	0.15	1000	5.96	5	300	65	81.3	146.3	1.199	0.952
12.	0.30	0.30	1000	5.79	5	303	60	75.0	161.9	1.327	0.962
13.	0.30	0.45	500	5.23	5	293	62.5	78.1	158.2	1.297	0.930
14.	0.45	0.15	1000	5.89	5	305	61	76.3	149.7	1.227	0.968
15.	0.45	0.30	1000	5.53	5	309	59.5	74.4	155.0	1.270	0.981
16.	0.60	0.15	1000	5.72	5	308	58.5	73.1	157.5	1.291	0.977

peak pullout load is found to vary within a small range i.e. from 70% to 81%. These values are almost comparable to that of anchors initially not subjected to any cyclic load, which showed peak at relative movement of 77.5%. So, it can be concluded that for the present soil conditions, an anchor movement of the order of 70% to 80% of the diameter of the anchor is required to mobilize the full anchor capacity and the relative anchor movement at peak pullout load is not influenced either by the number of loading cycles or load combinations as long as the anchors are in deep locations.

Cyclic reduction factor

The cyclic reduction factor (ratio of peak pullout load of anchors subjected to cyclic loading to that of anchors not subjected to cyclic loading) is found to decrease marginally with increase in the amplitude of cyclic loading (Table 2). For the present test condition the minimum value of cyclic reduction factor obtained is 0.92 i.e. 8% reduction of strength over the non-cycled peak pullout load. This may be due to loss of embedment depth of anchors during the cyclic loading phase. The results of the present study is based on model tests on remolded insensitive clay. However, in undisturbed naturally cemented clays, cyclic loading may cause degradation of soil structure and loss of strength.

Conclusion

The magnitude of anchor movement is primarily governed by the amplitude of cyclic loading rather than the component of static loading. The rate of movement of anchor per loading cycle is maximum for first cycle and it reduces thereafter. The normalized cyclic stiffness is found to decrease with increase of amplitude of cyclic loading.

Anchor subjected to cyclic loading and then monotonic pullout shows a stiffer load-displacement behavior at its initial stage compared to anchor not subjected to any cyclic loading. The relative post-cyclic stiffness of anchors for the present test conditions varies between 1.169 to 1.327.

The magnitude of ultimate uplift capacity is found to remain almost constant even with the imposition of cyclic load, however the magnitude of anchor displacement increases significantly with cyclic loading intensity.

For the present test conditions a marginal loss of anchor capacity up to an extent of 8% is observed due to cyclic loading. However, in undisturbed naturally cemented clays cyclic loading may cause degradation of soil structure and subsequent loss in anchor capacity.

From the present investigations, it is recommended that the design of plate anchors subjected to cyclic loading should be based on the allowable movement of structure rather than the breakout capacity of anchors. To prevent, any substantial movement, the amplitude of cyclic loading should be kept below 30 % of the static anchor capacity.

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