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Effects of Cyclic Frequency and Pre-Loading on Behaviour of Plate Anchors

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ABSTRACT: This paper reports the response of embedded circular plate anchors to varying frequencies of cyclic loading. It also highlights the effect of pre-loading on anchor movement and post-cyclic monotonic pullout behavior using model circular plate anchor, buried at embedment ratio of six in soft saturated clay. The frequencies of loading cycle are found to have considerable effect on anchor movement. For a given duration of loading, high frequency cycle causes more anchor movement than that caused by low frequency cycles. Pre-loading causes a reduction of anchor movement in subsequent loading stages. Anchors subjected to cyclic loading and then monotonic pullout, show stiffer load-displacement behaviour at an initial stage compared to anchors not subjected to any cyclic loading. Pre-loading causes a reduction of anchor movement in subsequent loading cycles. When anchors are recycled at a load ratio level less than the pre-cycling load, the anchor movement in the recycling phase is very much reduced, but if the recycling is done at a higher load ratio level, the effect is not that pronounced, and the anchors behave as if they were not subjected to any cycling load in the past. The relative post-cyclic stiffness of anchors for the present test conditions varies from 1.169 to 1.327.

INTRODUCTION

Anchors form an important component of many civil engineering structures. The primary function of these anchors is to transmit upward forces to the soil at certain depth below the ground. In an offshore environment, these anchors are subjected to dynamic loadings caused by waves, wind, ocean current and tides in addition to sustained pulls. Additional complications of loading conditions are caused by cyclonic storms, which could last for several hours inducing different patterns of cyclic loading. The time period of loading cycles could vary depending upon the wave cycles prevalent in that locality and are also strongly influenced by the cyclonic storms and other environmental factors. During the in service life, the anchors are expected to be subjected to a number of cyclonic storms of varying intensity and duration. An attempt has been made to study the response of embedded circular plate anchors to these types of loadings. Although a real-time loading is best to evaluate the performance of anchors in the field, considerable limitations exist in replicating these loading patterns in laboratory model tests. Therefore, in the present work, uniform rectangular loading cycles are used to study the effects of time period of loading cycles and pre-loading on anchor behaviour.

REVIEW OF EARLIER WORK

Ponniah and Finally (1983) 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 (SLRL±CLRL), 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 a 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 proposed that the plate anchors should be designed for a load of 1/3rd of its static pullout capacity to take into account the effects of cyclic loading. Singh and Ramaswamy (2002) have studied the behaviour of plate anchors in soft saturated soil under sustained-cyclic loading to highlight the relative influence of static load ratio level (SLRL) and cyclic load ratio level (CLRL) on permanent anchor movement as well as post-cyclic monotonic load-deformation behaviour of deep anchors. The movement of plate anchor was reported to be governed primarily by the amplitude of cyclic loading rather than the static load ratio level. Anchors subjected to cyclic loading and then monotonic pullout load showed stiffer load-settlement behaviour than anchors not subjected to any cycling loading. Singh and Ramaswamy (2008) reported the response of embedded circular plate anchors to varying frequencies of cyclic loading (0.30 and 0.45, with cyclic time periods of 2 sec, 6 sec, 12 sec and 24 sec). The frequency of loading cycles was shown to have considerable effect on the movement of anchors. For a given duration of loading, high frequency cycles caused more anchor movement than that caused by low frequency cycles. However, a marginal loss of anchor capacity up to an extent of 12% was observed due to cyclic loading. Literature review shows that the available information on the behavior of plate anchors under cyclic loading is limited. Little attempt has been made to understand the influence of cyclic time period and pre-loading on the behavior of plate anchors.

EXPERIMENTAL PROGRAMME

The experimental program undertaken in the present study was broadly divided into two distinct phases. In the first phase, the anchors were subjected to two different cyclic load ratio levels (CLRL) i.e. 0.30 and 0.45, with cyclic time periods of 2 sec, 6 sec, 12 sec and 24 sec. The cumulative anchor movements with loading cycles were recorded. After completion of 1000 loading cycle the anchors were pulled out at a rate of 5 mm/min to find out the post-cyclic monotonic pullout behaviour. In the second phase, the anchors were subjected to a given cyclic load ratio level, thereafter, the anchors were subjected to re-cycling load levels less than, equal to, and greater than the load applied in first cyclic phase. In between the first phase of cycling and re-cycling phase an unloading period of 22 hrs was allowed. Re-cycling at load ratio levels of 0.30, 0.45 and 0.60 were done for anchors subjected to a pre-cyclic load ratio of 0.45; whereas, load ratios of 0.15, 0.30 and 0.45 are used for anchors subjected to pre-cyclic load ratio of 0.30. In each stage of loading (i.e. pre-loading phase or re-cycling phase), the anchors were subjected to 500 rectangular loading cycles of 12 sec time period. This time period of loading cycles was based on the prevailing wave conditions along the Indian east coast. At the end of re-cycling, monotonic pullout tests were conducted to find out the post-cyclic pullout capacity of anchors. All the above tests were conducted using a circular plate anchor of 80 mm diameter, buried at a depth of 480 mm in saturated clay with an average moisture content of 57.3% (I_c = 0.40). A highly plastic commercial clay which exhibited a LL = 75% and PI = 44% was used in the present study. It contained 96.5% fines (< 75 micron) and a 3.5% coarse fraction. The X-ray diffraction pattern showed the presence of illite, kaolinite, chlorite & vermiculite clay minerals with quartz. The soil was classified as 'CH' as per the Indian Standard soil classification system (IS: 1498-1970).

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 the 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. The cylindrical test tank used for the model tests had an internal diameter of 560mm and 710mm deep. The diameter of the test tank was seven times bigger than that of the least dimension of the anchor in order to avoid boundary effect of the test tank on the anchor. 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 embedment depth (480 mm) was achieved. The test tank was kept undisturbed for 22 hours before the load being applied. The average unit wet weight and the undrained unit cohesion of clay in the test tank was 16.08 kN/m^3 and 4.70 kPa, respectively.

Cyclic Loading Test

One-way vertical cyclic pullout load on anchor the imparted was by using a pneumatic loading apparatus. This consisted of (i) an air compressor 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. 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. A schematic diagram of the cyclic loading set-up used is shown in Fig. 1.

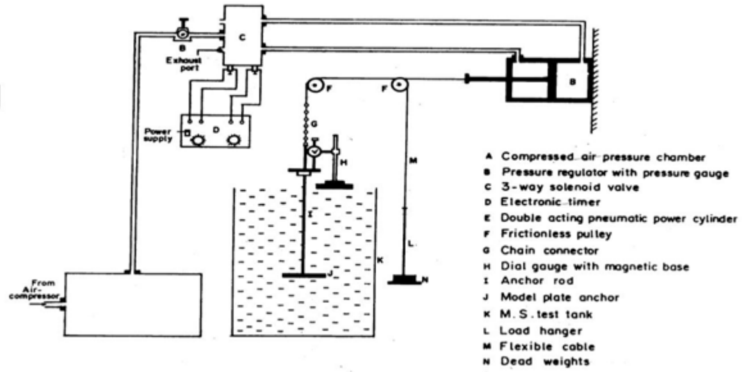

FIG. 1. Schematic layout of the cyclic loading test set-up.

Post-Cyclic Monotonic Pullout Test

The post-cyclic monotonic pullout tests were carried out by using a strain controlled test set-up. After completion of the cyclic loading, the anchors were monotonically pulled out at a rate of 5 mm/min. 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

Effect of Time Period of Loading Cycles on Movement of Anchors

Typical variations of anchor movement with number of loading cycles are illustrated in Fig. 2 for CLRL of 0.45. The movement of the anchor was found to increase continuously with cycles of loading. However, the rate of increase of anchor movement tended to slow down with an increase of loading cycles. It is further noticed that the rate of movement of anchors with number of loading cycles tended to stabilize earlier when subjected to lower frequency cycles. For anchors subjected to 2 sec loading cycles, the movement was found to be almost linear until the cyclic loading was stopped (i.e. after 1000 cycles of loading). Rao (1988) found similar results from the undrained triaxial tests conducted on marine clays and reported that at high frequency of loading, the built-up cyclic strain per load cycle was slow and more or less uniform, whereas at low frequency loading it was quite high and the movement tended to stabilize at a smaller number of loading cycles. The movement of the anchor during cyclic loading was related to the development and dissipation of excess pore water pressure. The cyclic pore water pressure increased during the cyclic loading phase and subsequently dissipates under cyclic unloading. The dissipation of excess pore water pressure in the soil mass above the anchor results in the upward movement. The movement of an anchor after 1000 loading cycles with 24 sec period is 1.75 times that of anchors subjected to a period of 2 sec for a CLRL of 0.45. This value is 1.93 for CLRL of 0.60. But, it was to be noted here that the loading duration for 1000 cycles with a 2 sec period was 33.33 minutes compared to 400 minutes for a 24 sec period. The curves in Fig. 3 indicated a non-linear relationship between the movement of anchor and duration of loading. Initially, the rate of anchor movement was high, which tended to stabilize with time. For a given duration of time, cyclic loadings of lower time period produced higher anchor movement than movements caused by cycles of higher time period.

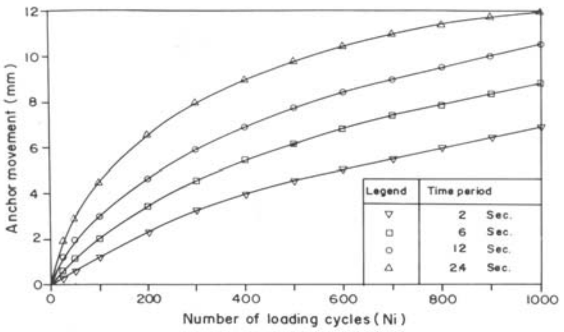

FIG. 2. Movement of anchors with number of loading cycles at CLRL of 0.45

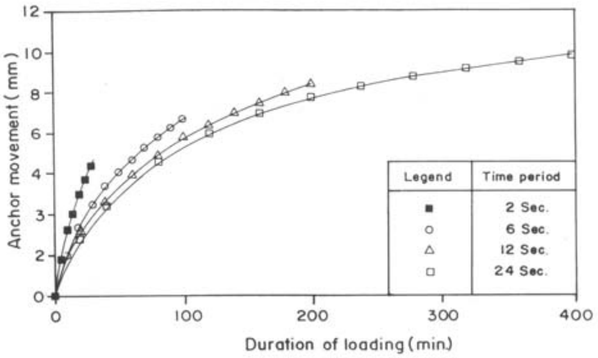

FIG.3. Movement of anchors with loading time at CLRL of 0.45

Effect of Pre-Loading on Movement of Anchors

For studying the effect of pre-loading on anchor movement in subsequent loading stages, two sequences of cyclic loading were adopted. In the first phase, the anchors were cycled 500 times at CLRL of 0.30 or 0.45. In the next phase i.e. after an unloading period of 22 hours the anchors were again cycled at a CLRL value less than, equal to or more than that of the first stage of loading. This is referred to as re-cycling. The re-cyclic load ratio levels of 0.15, 0.30 and 0.45 were used for anchors cycled at load ratio level of 0.30. Whereas, re-cycling load ratio levels of 0.30, 0.45 and 0.60 are used for anchors cycled at CLRL of 0.45. The movements of anchor with number of loading cycles in re-cycling phase were compared with the movements registered during the cycling phase with same intensities of loading (Fig. 4). When anchors are cycled at load ratio level of 0.30 and further recycled at load ratio levels of 0.15, 0.30 and 0.45 the anchor movements obtained after 500 cycles of loading in re-cycling phase were 25.7%, 52.3% and 72.8% of anchor movements those were obtained in the initial cyclic stage with CLRL of 0.15, 0.30 and 0.45 respectively. Similarly, the anchor movement obtained in re-cycling stage for load ratio levels of 0.30, 0.45 and 0.60 with pre-loading intensity of 0.45 was 31.3%, 58.8% and 86.6% of the movement registered in cycling stage with comparable loading intensities. This showed that when anchors were re-cycled at a load ratio level less than the pre-cycling load, the movement of anchor in re-cycling phase were very much reduced, but if the re-cycling was done at a higher load ratio level, the effect was not that pronounced, and the anchors behaved as if they were not subjected to any cycling load. The movement during cyclic loading was related to the development and dissipation of pore water pressure. The cyclic pore water pressure increased during the loading phase of a cycle and subsequently dissipates. The dissipation of excess pore water pressure from the soil just above the anchor created a locally consolidated soil mass with comparatively higher shear strength. For low cyclic load amplitudes the anchor movement was arrested by the stiffer soil mass, formed above the anchor during the initial few cycles of loading. At higher cyclic load levels, this phenomenon also occurred but due to substantial movement of the anchor in each cycle of loading, a localized consolidated soil zone could not be formed as in each cycle, the anchor moved upward through undisturbed soil. This resulted in a decrease in anchor movement in the re-cycling phase. However, if the CLRL in re-cycling phase was higher than of the pre-cycling phase, the effect is not pronounced, and the anchors behaved as if they had not been previously subjected to any cycling load.

Effect of Pre-Loading on Post-Cyclic Pullout Behaviour

Typical pullout load displacement behaviour of anchors subjected to a pre-cyclic load ratio level of 0.30 and subsequently re-cycled at load ratio levels of 0.15, 0.30 and 0.45 is shown in Fig. 5. Load-displacement curve for an anchor, which has not been subjected to any cyclic loading, is also plotted in both this figure for comparison. For all these cases of cyclic loading, there was a marginal reduction in peak pullout load, while the initial stiffness of the anchor increased compared to the anchor which was not subjected to any cyclic loading. For a given pre-cyclic load the peak pullout load decreases when the re-cycling load ratio level increases, whereas, the relative cyclic stiffness increases. The relative stiffness is the ratio of initial stiffness of anchors subjected to cyclic loading to that of the anchor without any cyclic loading. The relative post-cyclic stiffness was found to vary from 1.169 to 1.282, and the degradation factor varied from 0.946 to 0.981. The increase of initial stiffness of anchors is related to the local consolidation of the soil above the anchor during cyclic loadings and depends upon the intensity and duration of cyclic loading. Datta et al. (1990) also reported the increase of initial stiffness of anchors in remoulded clay and attributed this to the strain hardening of soil caused by repeated loading.

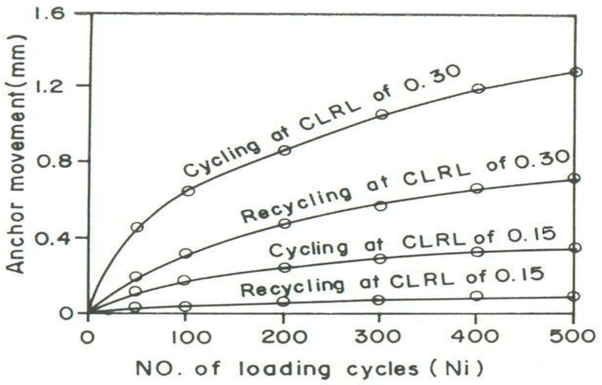

FIG. 4(a). Effect of pre-cycling on anchor movement (with pre-cycling load ratio level of 0.30 and re-cycling load of 0.15 and0.30)

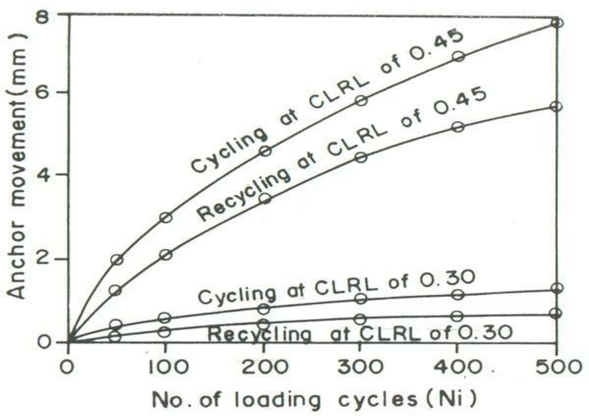

FIG. 4(b). Effect of pre-cycling on anchor movement (with pre-cycling load ratio level of 0.30 and re-cycling load of 0.30 and0.45)

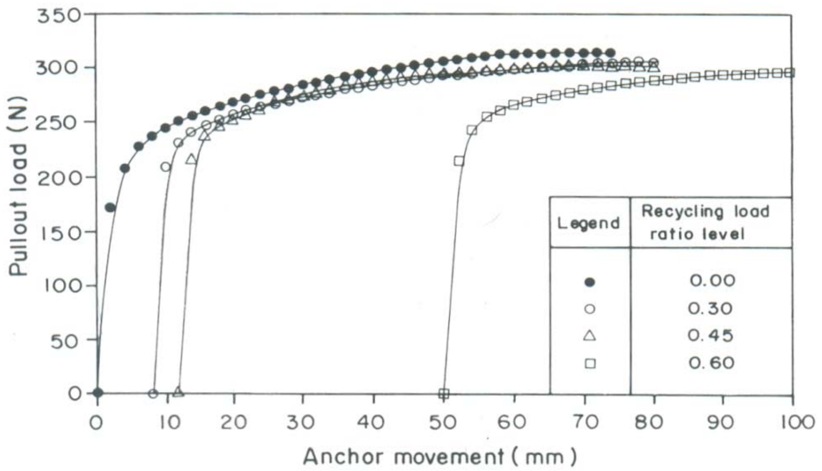

FIG.5. Post-cyclic pullout load-displacement curves for anchors subjected to pre-cycling load ratio level of 0.45

CONCLUSION

Based on the results of the present investigation it was concluded that the magnitude of anchor movement was primarily governed by the amplitude and frequency of cyclic loading and for a given duration of loading, high frequency cycle caused more anchor movement than that caused by low frequency cycles. Pre-loading reduced anchor movement in subsequent loading stages. When anchors were re-cycled at a load ratio level less than the pre-cycling load, the movements in the re-cycling phase were very much reduced, but if the re-cycling was done at a higher load ratio level, the effect was not highly evident, and the anchors behaved as if they were not subjected to any cycling load in the past. Anchors subjected to cyclic loading and then monotonic pullout load showed stiffer load-displacement behaviour than anchors not subjected to any cyclic loading. For the present test conditions (remoulded clay) a marginal loss of anchor capacity up to 12% was observed due to cyclic loading. This was believed to be due to the loss of embedment depth during cyclic loading. However, marine clays which exhibit strength on account of their in-situ structure, may experience degradation of the soil structure during cyclic loading and thus experience subsequent loss of anchor stiffness as well as anchor capacity.

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