EFFECT OF ALTERNATIVE LATERAL LOADS ON PILE GROUPS

EFFETS PRODUITES PAR LES EFFORTS LATERAUX ALTERNATIFS SUR LES GROUPES DE PIEUX

ВЛИЯНИЕ ПЕРЕМЕННЫХ ГОРИЗОНТАЛЬНЫХ НАГРУЗОК НА СВАЙНЫЕ КУСТЫ

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SYNOPSIS. Alternative lateral loads may originate certain effects on foundations on piles little known up to this time, for which reason they are very seldom taken into account in the projects. With a view to studying these phenomena, various tests have been conducted on a reduced scale on groups of 3 x 3 piles set in sandy soils of different relative densities. The spacing between piles has been varied in order to take into account the group effect. Also, the influence of the presence of vertical loads on the horizontal and vertical deformability of the group has been studied. Repeated load cycles of the same sign and alternative (reverse) load cycles have been clearly differentiated.

As soon as the range of alternative loads increases appreciably (above one sixth of the ultimate load of the group), the result is an increase in the horizontal deformability of the group until this deformability reaches a maximum, beyond which it diminishes and may stabilize to magnitudes that are smaller than the initial ones. If the soil is not very compact, a settlement of the group, and the formation of important depressions on the ground surface around the group, can be observed. An analysis has been made of these phenomena and of the practical ways to take them into account.

INTRODUCTION

The pile foundations are very often subjected to very important horizontal loads. These loads may act with a magnitude and direction always constant (foundations of retaining walls) or instead with variable values and opposite directions (braking effects in bridges).

The effect of repeated loads has been studied experimentally in several instances, on a full scale as well as on model tests. However, only the case of cycles of loadings in a single direction has in general been analysed (PRAKASH, 1962; DAVISSON and SALLEY, 1970).

In harbour installations (Dolphines, etc) it is very frequent that the horizontal loadings should have an alternative nature, that is, that their direction be reversed, although the possible effects of this reversal are not usually taken into account. FEAGIN (1948), subsequent to a set of experiments conducted in connection with the construction of various docks in the Mississippi river, called attention to the fact that if a foundation on piles is subjected to horizontal loads of variable magnitude and direction, an unexpected settlement may take place.

This remark gave us the idea of the performance of some model scale tests on pile groups to investigate the effects of alternative lateral forces. In view of the fact that the results obtained were different from those corresponding to loads acting in a single direction, a set of tests on vertical piles with alternative loads was programmed in order to study these phenomena in detail At the same time tests have been made at full scale with 1270-millimeter diameter piles, in connection with the construction of various dolphines in the harbour of La Coruña (Spain). A report has already been presented previously about the latter tests by ROMANA, OTEO and FERNANDEZ-ALLER, (1972), which, as will be noted, serves to corroborate in general the results of model tests described in this report.

DESCRIPTION OF THE TEST

The experimentation on model tests has been carried out on groups of 3 x 3 piles set on homogeneous sandy soil. To this end, an installation was used which consisted schematically of: a) an elevated bin for sand storage, b) A 90 x 40 x 50 cm^3 tank, c) Some devices for depositing the sand measured by weight in the tank and d) The group of piles which can be located in their final position before depositing the sand around them. The grain size chart for the sand used may be seen in Fig. 1. The densities used have been: $\gamma_1 = 1,590$; $\gamma_2 = 1,675$; $\gamma_3 = 1,800\ t/m^3$ corresponding to relative densities of 49%, 67% and 91%.

These densities were obtained by varying the height of drop of the sands and making them pass through metal sieves before letting them drop freely to the test tank. In the case of higher densities, it was necessary, in addition, to compact the sand in 1 cm thick layers.

The piles, 8 mm diameter and 28,5 cm long, were made of aluminum in order to better detect their deformations. For the installation of the groups, metal boxes with a flat perforated bottom were used. The piles were introduced through these perforations and a mortar made of Plaster of Paris and sand was subsequently poured into the box. In this way the piles were kept together by the mortar, the metal boxes acting as a left-over formwork of the cap. Thus it was possible to set the piles in groups of 3 x 3, with a spacing between the piles equal to 3, 4 and 6 diameters.

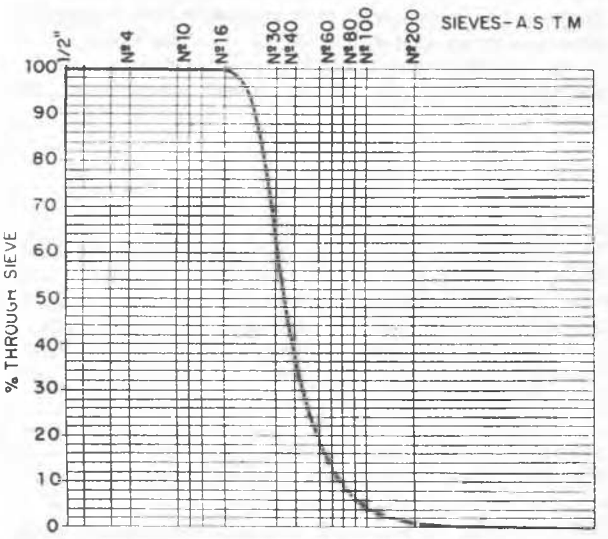

FIG 1 – GRANULOMETRY OF TESTED SAND

The horizontal loads were applied by means of a pull exerted by a cable fastened to the group being tested. The tension in the cable was developed, after taking it over a pulley, by means of a counterweight. Two devices were installed in order to be able to apply to the model foundation horizontal loads, one at a time, along the same line but in opposite directions.

In every test the following measurements were taken: a) Horizontal displacements of the pile cap reading to 0.005 millimeters, b) Vertical displacements on two points located on the upper plane of the cap and in line with the applied load, with the same accuracy of reading. With these latter measurements it was possible to determine the rotation of the cap and its average settlement. The piles had a free length of 40 millimeters and the height of the point of application of the load and of the points where horizontal displacements were measured, was 55 millimeters. The embedded length of the piles was 220 millimeters.

Before carrying out the test described herein, the same group of piles had been tested with horizontal loads acting in a single direction, which were increased until the ultimate strength of the sand was reached. Single piles were also tested in the same way for each type of soil. (OTEO, 1972a).

In the testing program that has been carried out, two types of tests can be distinguished: a) Those which we shall call of alternative load cycles, b) Those that we shall designate as cycles of loading. Both types of tests consist of the repetition of a sequence or complete cycle, different in each case. The sequence of the cycles of alternative load consists in the application of a horizontal load of a given magnitude, reduction of this load down to zero, new application of a load of the same magnitude but opposite direction, and subsequent reduction again to zero. In the other cycles of loadings the sequence consisted in the application of a horizontal load in a given direction and its subsequent reduction to zero.

The method of conducting all these tests has been as follows: A series of cycles was effected with a constant magnitude; thereafter another series of cycles wete applied with a higher magnitude and so on, until a horizontal load close to the ultimate lateral capacity of the group was reached. From this time on the load was increased in a single direction until failure of soil was attained. In all cases the loads were applied in succesive steps, which were kept constant until the resulting displacement were stabilized.

On the surface of the ground a fine layer of powder of Plaster of Paris was laid in order to observe the superficial form of failure of the ground.

RESULTS OBTAINED WITH ALTERNATIVE LOAD CYCLES.

As was already said, all groups tested consisted of 3 x 3 piles. In the soil with density 1.59 t/m^3 the spacing used (distance between axes of two adjacent piles) was equal to 3, 4 and 6 times the diameter (D). The tests with sands of density 1.675 and 1.800 t/m^3 were made on a group where the spacing was 3D. In this way the study of the group effect in relation to the alternative loads and the influence of the relative density of the sand, was made possible. A test was also made with a group of piles where the spacing "s" was equal to 4 D but with a vertical load permanently applied during the whole test, with a view to studying the interferences between the two kinds of loading to which the pile foundation was subjected.

The results of the tests whose characteristics may be considered average ($\gamma = 1{,}675\ t/m^3$ and s = 3D) are shown in Fig. 2. The maximum horizontal displacements and the residual displacements recorded in each cycle of the various series of alternative loads to which the group under consideration was subjected, have been represented. The ratio between the mean settlement and the number of cycles of each series has also been drawn. As can be noted, the horizontal displacement attained in each half-cycle increases in the first cycles, reaches a maximum value and then diminishes to a magnitude where it remains practically constant. When the module of the series is low-with respect to the failure load of the group- the displacement stabilizes rapidly at a value above the initial one of the series. But if the module is noticeable (above 30% of the failure load), a considerable number of cycles are required to reach this stabilization. The value attained may then be either equal or smaller than the one reached at the beginning of the series. This is also the case if the residual displacements are analyzed instead of considering the maximum displacements. The difference between these two types of displacements remains practically constant in each serie of cycles as can be noted from the diagram in Fig. 2.

A very interesting result is the constant increase of the mean settlement upon application of the successive alternative cycles. This settlement, as was already indicated, has been obtained taking the mean

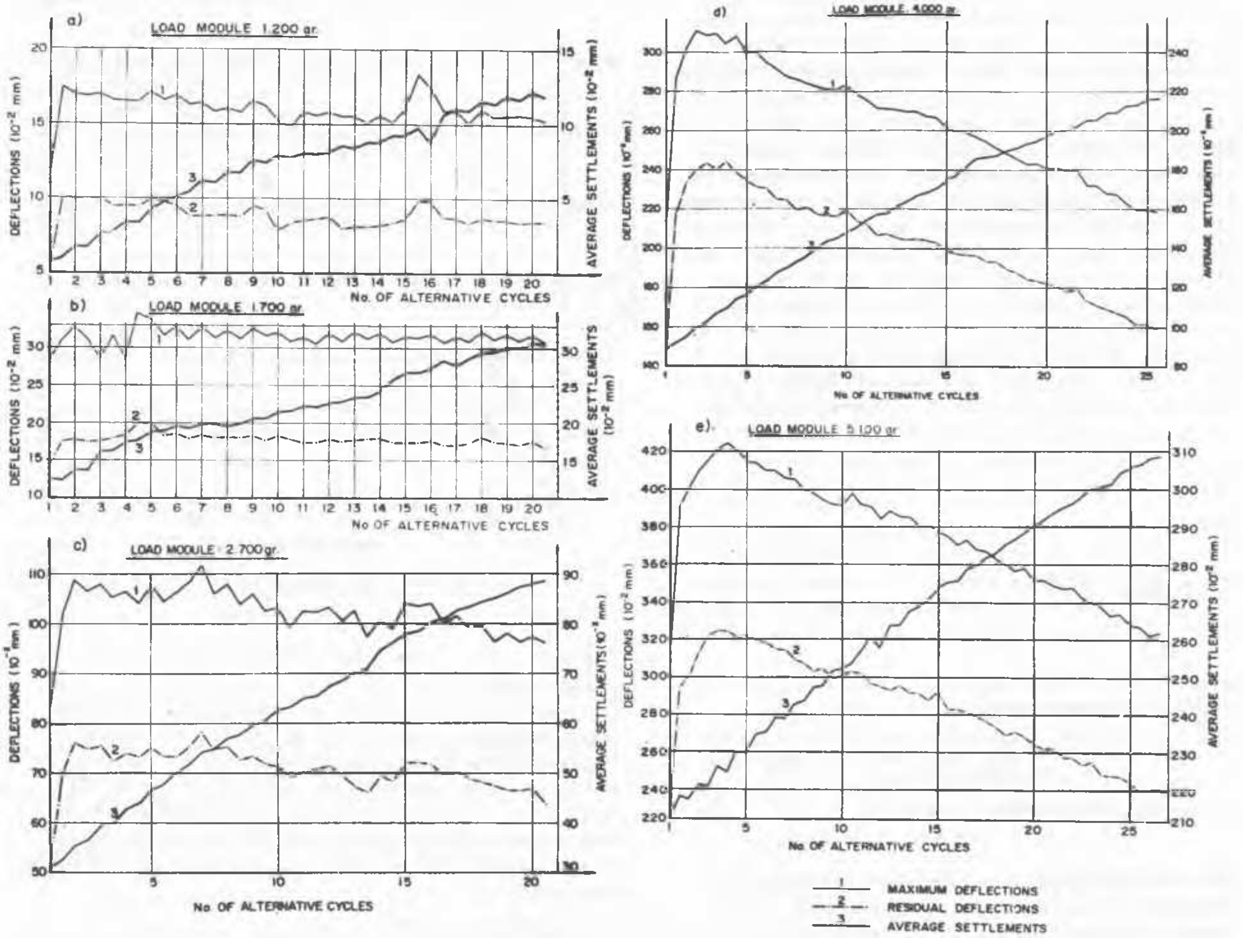

FIG 2 - MODEL TEST ON 3x3 PILE GROUP. WITH ALTENATIVE LOADS
S=3D $\gamma = 1.675\ t/m^3$

of the movement of two points of the cap when the cap passed in each half cycle through the same position, as to horizontal movements, that the cap occupied at the beginning of the test. In the case of Fig. 2 it can be observed that the mean settlement measured after application of the series of alternative loads, amounted to 3.09 millimeters. This movement is very important, taking into account the dimensions of the piles (D = 8 mm) and the fact that the same group in a soil of similar conditions reaches its ultimate vertical bearing capacity when the settlement is of the order of 1.00 millimeters.

In the tests with a fixed load in a single direction, the cap rotates, due to which the two points whose vertical movements have been measured would move in opposite directions. In principle, this same phenomenon takes place with the half-cycles of alternative loads but the ascending movements are of little importance when compared with the descending movements of the next half-cycle, due to which both reference points descend with respect to the initial position.

A phenomenon worthy of note is the variation of the load-displacement diagram of the initial cycle of each series, depending on the characteristic modulus of the cycle. The first cycle of various alternative series, together with the final cycle up to failure and the new diagram (fixed load, with no cycles) corresponding to the group of 3 x 3 piles with S = 3D and a sand of $\gamma = 1{,}675$ t/m^3, have been represented in Fig. 3. As can be seen, upon increasing the value of the modulus of the series the diagrams depart more and more from the noval, chaging its curvature with respect to the latter. It can be said that this last phenomenon takes place until the horizontal load reaches the value of the modulus of the previous series of cycles and from that moment on the curvature changes, with its concavity in the same direction as the noval diagram. The final failure load differs very little from that of the fixed load test.

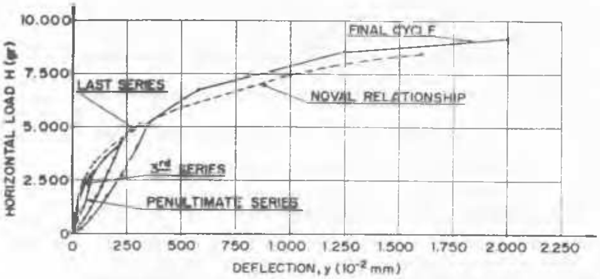

FIG 3 - 3x3 PILE GROUP. $\gamma = 1{,}675$ t/m^3

The effect of this change of curvature (refered of noval cycle) was also observed in the full scale test described by ROMANA, OTEO and FERNANDEZ-ALLER (1972). The results obtained with a prestressed cylindrical pile diameter D = 1370 mm, driven through 3.80 meters of fine sand and 1.50 meters through foliatable slates, are shown-in Fig. 4. This pile was subjected to 10 cycles of 2.4 t alternative loads (applied 18.00 meters above ground surface), to 7 cycles of 4.8 t and, afterwards, the load was increased up to 5.9 t. The change in the curvature of diagram referred to can be noted in Fig. 4. The behaviour of the pile during the application of the alternative load cycles was similar to the one just noted, that is: Increase of the displacement of each half-cycle and subsequent stabilization at a value smaller than the maximum; although the displacement at the end of the series was closer to the maximum than to the initial one (this phenomenon can be noted from Figs. 2a and 2b.)

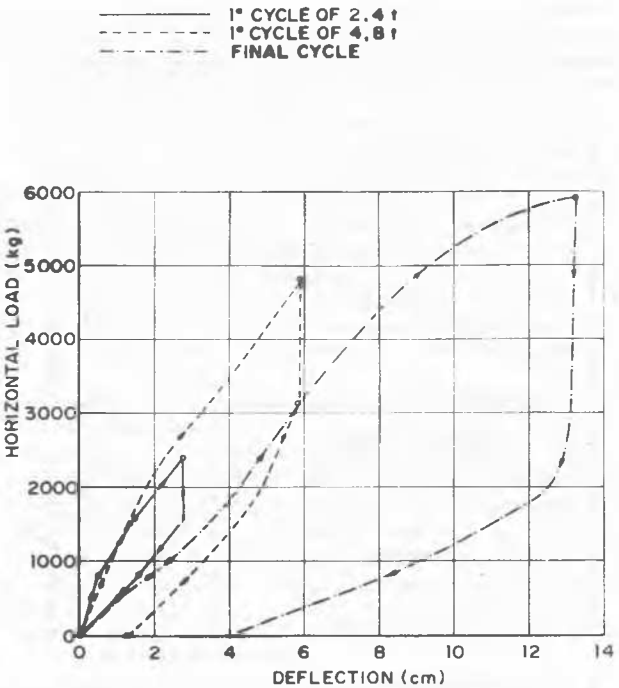

FIG. 4 - FULL SCALE TEST. SINGLE PILE

The behaviour of the other groups tested was in general similar to that of the group just mentioned. The most interesting results obtained are summarized in Figs. 5 and 6. In Fig. 5, the maximum displacements among the ones attained in each series of cycles have been represented, in terms of the modulus of the serie, while in Fig. 6, the relationship between this modulus and the mean settlement attained at the end of each series and in all the tests is given.

It seems that from the observation of said diagrams it may be inferred that the relation between the displacement y_M in each series and its modulus H, is of the parabolic type. The relative density of the sand, D_r, has a considerable influence. When D_r varies from 91% to 67% and to 49%, for equal values of the load, the y_M is multiplied by 2.5 and by 5.0 respectively; in other words, the relation of D_r to y_M is almost lineal for equal loads. The degree of compaction of the sand also affects appreciably the mean final settlement of each series (Fig. 6), inasmuch as a highly diminished settlement corresponds to a higher compaction. For a value of D_r equal to 91%, the mean resulting settlement is practically nil; whereas for a value between 67% and 49%, the settlement of the pile capping is multiplied by 6.

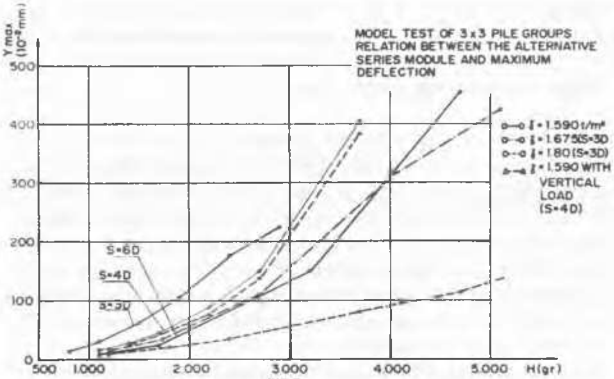

FIG 5

This shows that the influence of the relative density of the sand in the deformability of the group of piles, when the loads are alternative, is very important and even greater than in the case of a fixed load. (OTEO, 1972a). The group effect is also notable, in the sense that an increase in the spacing of the piles has as a consequence a reduction of the horizontal displacement and of the average settlement. Considering the tests with sands of $\gamma = 1.590$ t/m³ (with "s" equal to 3, 4 and 6 D), if the maximum displacement y_M of each series refers to the displacement due to a fixed load and corresponding to the same modulus, it can be observed that the greater value of the ratio (y_M/y) is practically independent of the spacing. The value of the horizontal load required to attain this maximum value of y_M/y has been equal to approximately one half of the failure load of the group tested.

All the results discussed herein have been obtained by subjecting the group of piles exclusively to horizontal loads. The only vertical load that was acting during the test was the self-weight of the cap, whose value is very small compared to the vertical failure load of the groups. In order to analyze the influence of vertical loads, tests have been conducted with one group of 3 x 3 piles (with s = 4 D and using sand of $\gamma = 1.590$ t/m³) to which a vertical load of the order of 50% of its bearing capacity was previously applied. The results are shown in Figs. 5 and 6.

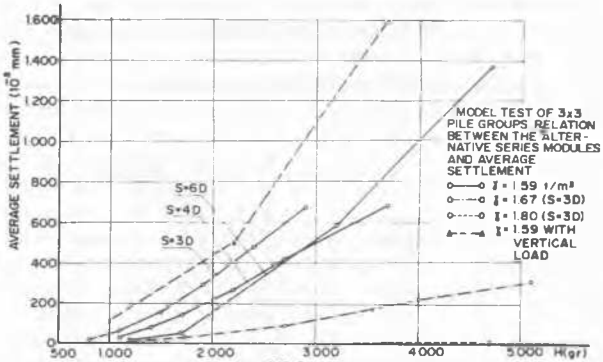

FIG 6

The presence of this vertical load has the effect of diminishing the maximum displacements of each series. The difference with respect to the case where no vertical loads are acting is only 7%. However, its influence on settlement is considerably greater, inasmuch as the mean settlement becomes doubled when compared with that of the test with no vertical load.

RESULTS OBTAINED WITH REPEATED LOAD CYCLES.

In the introduction to this communication, reference has been made to some tests conducted with repeated load cycles of horizontal forces. The application of a considerable number of cycles (> 50) marks the increase of the displacement of the group in relation to the initial position without load. The tests on load cycles discussed further on were not intended to verify this fact but, instead, the purpose was only to distinguish the behaviour of a group subjected to loads always acting in one direction as compared with the behaviour with loads acting in alternatively reversed directions.

For this study a group of 3 x 3 piles, with spacing of three diameters and sand of $\gamma = 1.675$ t/m³ has been selected as corresponding to the average characteristics of the groups tested. This group has been subjected to 10 cycles of loads of 1228 grams and to 10 cycles of 2288 grams, which loads were subsequently increased to failure.

Represented in Fig. 7 are the load displacement diagrams of the group corresponding to the first 10 cycles. As can be noted, a hardening of the ground takes place, as a consequence of which each new cycles produces displacements less than those in the previous cycle, until beginning with cycle No. 6. all diagrams have similar shape.

The absolute displacement (referred to the initial position, unloaded) increases, due to the fact that in every cycle a certain residual displacement is produced. But the relative displacement (that originated by each cycle) diminishes from the first cycle on, until it stabilizes beginning with the sixth cycle, approximately. This result was obtained for the 1228 gr cycle as well as for the 2288 gr cycle. In neither case was a change of curvature produced, as was the case with the alternative cycles.

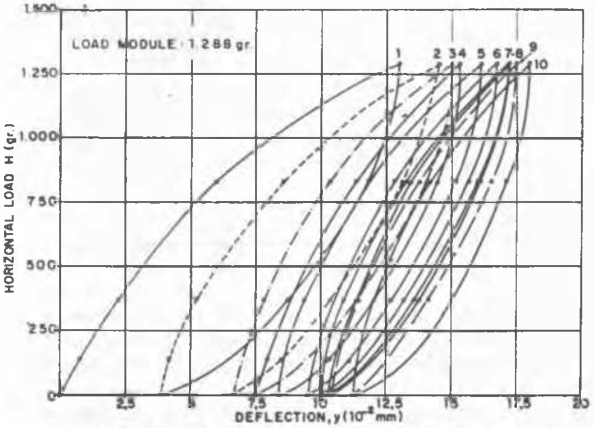

FIG.7.-CYCLIC LOAD TEST OF A 3x3 PILE GROUP. γ = 1.675 t/m^3

If a load of 1200 gr is considered, slightly below that applied in the ten first cycles, the relative horizontal displacement would vary from 12.00 x 10^{-2} mm to 5.85 x 10^{-2} mm (48.70% of the initial displacement), which value may be considered to remain constant for the last cycles.

In the tests using the same load but alternative, the displacement in the first cycle was similar to 12.00 x 10^{-2} mm, increasing afterwards up to a maximum value of 17.50 x 10^{-2} mm (146% of the previous displacement) and finally stabilizing at 15.50 x 10^{-2} mm (129% of the displacement of the first cycle). If the results corresponding to the other type of cycle loading are analyzed, the stabilization of the relative displacement takes place when it attains a value equal to 51% of the displacement corresponding to first cycle of this type. It can be said that in the alternative load test, the initial value is similar to that of the cycle loading, with a maximum value in the series of 125% of the initial value and a stabilizing value equal to 94% of this magnitude

By means of these data the effects of the cycle loading and of the alternative loads can be clearly differentiated. The first ones tend to increase the absolute displacements but to diminish the relative displacements on each cycle, stabilizing them at 50% or less of the values on the first cycle. The alternative loads originate displacements in each half-cycle higher than the normal (fixed load) until the displacements reach a maximum beyond which the displacement in each cycle diminishes, stabilizing at values which are as a minimum of the order of 80% of the displacement of the first half-cycle.

ANALYSIS OF THE RESULTS

In the foregoing articles we have described the tests that have been performed, distinguishing the phenomena originated by cycles of alternative loads from those caused by repeated load cycles. In both cases the loads were wholly of the static type with regard to the way they were applied. For this reason, any sort of explanation that we may try to give to the observed phenomena should have a similar character. When a horizontal load acts in a certain direction on a group of piles, two zones in the soil around the piles may be distinguished (OTEO, 1972 b): a) The forward zone (towards which the force mover), with a "passive" character, b) the backward or "active" zone. The stress spectrum in each of these zones is definitely different as is made evident by the formation of a crater in the backward zone and an upheaval in the forward zone when the soil-piles complex attains its ultimate resisting capacity.

If the direction of the applied horizontal load (alternative cycles) is reversed, the zone that in the previous half-cycle was "active" becomes "passive" and reciprocally. The horizontal load is then transmitted to a soil wherein some changes (deformations, local plastifications, etc) have taken place. The zone that was "active" before, now experiences a considerable change in its way of acting, due to which it behaves as if it were a soil different from the previous one for this reason the displacement of the group of piles in the second half-cycle becomes greater under equal load. Actually, the new "passive" zone was already deformed due to which it now acts as a soil having less resistance; which means that the displacements of the soil will now have to be greater to mobilize the portion of "passive resistance" required to equilibrate the exterior forces.

The application of succesive cycles of alternative loads discloses another phenomenon: The sandy soil around the piles is becoming more compact. The particles rearrange themselves into more stable positions, due to which the external thrust is now being resisted by a more dense soil (at least in the neighborhood of the ground surface); as a consequence, the displacements required to mobilize the soil passive resistance to equilibrate the said external force are smaller. The compaction of the sand around the piles may cause the settlement of the group in two ways: a) By diminishing the void ratio in the nearby zone and consequently producing settlement which is followed by the piles. b) By increasing the vertical loads acting on the piles through development of a negative skin friction (drag force) caused by the downward displacement of the sand particles.

The ground surface also settles, which is an evident indication of its compaction, as can be inferred from the tension crack lines that can be detected at the surface of the layer of Plaster of Paris that was laid around the piles. Craters around the group are being formed successively, resembling ellipses with ever greater axes. The depth of said craters is much greater than the maximum recorded settlement of the cap (it may be as much as three times larger). It may be thught that these settlements of the group and of the ground surface are the cause of the increment of the horizontal displacement observed in the alternative series through a lenhthening of the portion of pile above the ground. This hypothesis, however, cannot fully explain the phenomenon. (Fig. 8).

Let us analyze, for example, an average case: A group of 3 x 3 piles, with s = 3 D and a sand of $\gamma = 1.675$ t/m^3. Considering the last series of alternative loads: The increment of settlement originated in this series is 1.00 millimeters. The free length of the piles was 40 millimeters. As the length of these elements affects the horizontal displacement proportionaly to a third degree power, the reduction of the displacement, at least in relative value, should have been $(40^3 - 39^3)/40^3 = 0.073 = 7.3\%$. The reduction of the displacement at the end of the series, compared with the maximum value has been: $(422 - 262)/422 = 0.38 \simeq 38\%$. In other words, the measured relative reduction of the horizontal displacement is much larger than the reduction that the settlement of the group could have produced, considering moreover that only the length of the free portion of the piles has been taken, whereas in reality and for calculation of the deformations a length of the order of at least twice that value should have been taken.

With regard to settlement of the surface a similar reasoning may be made, considering moreover the fa fact that the increase in horizontal displacement (up to 46% for positive increment, as already indicated) takes place with small ground surface settlements ($\simeq$ 3 millimeters) which could only correspond, at most, to a 10% increase. The great surface settlements take place at the end of the series with a modulus near the value of the failure load of the group.

If the relative density of the sand is very high (90%), the possibilities of compaction are very limited, for which reason the effects of the alternation of loads are not noticeable until the loads are rather high in relation to the failure load of the group. With these loads, superficial plastification and softening of the soil is possible. In other words, two stages may be considered during the application of alternative loads cycles: 1. Increase of the deformability of the soil due to loading and unloading of the "active" and "passive" zones (Softening). 2. Compaction and stiffening of the sandy material (Hardening).

This process takes place even in each half-cycle alo along a series, as shown by the change of curvature of the load-displacement diagrams. This twofold process does not happen when only repeated load cycles are applied, inasmuch as in that case the forces act in a single direction without reversal. Due to this, only the stage of the hardening of the material takes place. The "passive" zone behaves with increasing resistance, due to which the displacements required to equilibrate the outside forces are smaller, until the number of cycles is such that the soil particles occupy stable positions and the whole behaves in a single way when acted upon by succesive cycles of exterior loads.

PRACTICAL RECOMMENDATIONS

Some of the phenomena discussed in this Report (variation of displacements in a series of alternative cycles) have been confirmed at full scale (ROMANA, OTEO and FERNANDEZ-ALLER, 1972) due to which they should be kept well in mind when projecting deep foundations subjected to horizontal alternative forces. Nevertheless, the increment of settlement has not been yet verified systematically, although the remarks from FEAGIN (1948) should be taken into account. The extrapolation to full scale of the results of model tests is a problem in the realm of Soil Mechanics much discussed and not yet solved. It may be possible that the settlement would not actually be so important, although it is apt to depend mainly on the system of construction that has been followed, the presence of stiff layers close to the tip of piles, etc. The test at full scale already mentioned have served to confirm that the increment in driven length of the piles tend to diminish the effects of alternative loads, although the number of tests that have been conducted so far does not allow us to ascertain such influence quantitatively.

In view of these uncertainties, and if the alternative forces are considerable in comparison with the horizontal service loads, it would be advisable that flexure tests be carried out on single piles similar to those to be used in the final design. In this way it would be possible to determine the characteristic parameters of the soil and of the pile corresponding to the most representative periods of a series of cycles, based on the displacements and rotations of a point on the pile corresponding to each peiod. To this end, working-stress or ultimate-strength methods may be used, which may be utilized later to calculate the group of piles that constitute the foundation, considering their mutual interferences (OTEO, 1972b).

In case flexure tests could not be conducted, the calculation of the group of piles can be effected on the basis of parameters determined geomechanically from borings, laboratory tests, etc, in order to evaluate the noval estate (first cycle of loading). The effect of alternative loads may be taken into account considering, for the case of maximum displacements in a series of cycles, a length of pile above the ground surface longer than the actual. Even though this may not be the true cause of the increase of the horizontal displacement, it could be adopted as an equivalent model for its simplicity.

The increment in length depends on the modulus of the loads applied and on the relative density of the soil. Based on the test performed, it seems adequate to take for the increment a value ranging from 1.5 to 2 times the diameter of the pile, when considering a service load (between 1/2 and 1/3 the failure load) and as to density of the soil ($45\% < D_r < 65\%$).

can be considered as an average. This figure hasbeeb been arrived at by considering the pile as equivalent to built-in (fully restrained) cantilever beams embedded to such a depth that the deflection would be equal to the measured horizontal displacement. The decision of using 1.5 or 2 times the diameter may be made taking into account the actual alternative character of the loads, the compaction of the soil, etc.

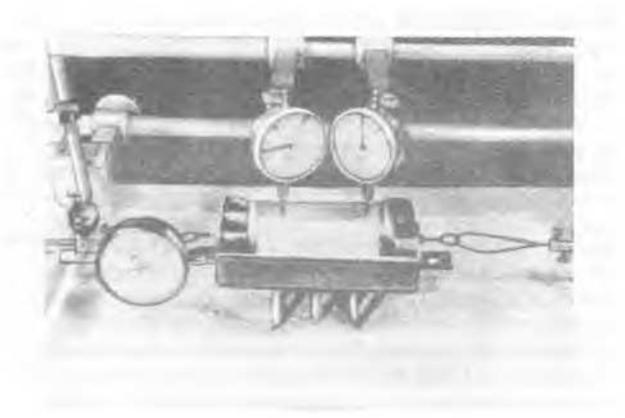

Fig. 8. Craters in the soil around the piles, caused by alternative loads.

CONCLUSIONS

It has been made evident that the effects on groups of piles of lateral alternative loads, having a modulus substantially below the failure load, are important. These effects may be summarized as follows:

(a) Increase of lateral deformability upon application of cycles of alternative loads of constant module, with subsequent reduction and stabilization to lower values that may be smaller than those at the beginning.

(b) Continuous increase of the vertical deformability even for very small loads.

These phenomena point to the existence of two continuous stages during the application of each series of alternative cycles and at the same time in the sucessive application of different series of cycles:

1. Increase of the deformability of the soil, through loading and unloading of the "active" and "passive" zones (Softening).
2. Compaction and stiffening of the sandy material (Hardening).

The cycles of loading in a single direction originate a response from the soil entirely different from that produced by alternative cycles. Single direction cycles give rise to the 2nd stage just mentioned. After several cycles of loading (6 to 8), the soil attains a stable equilibrium and presents a response, to exterior horizontal forces, that is maintained constant in spite of subsequent applications of new cycles of loads.

The relative density has a great importance in relation with the effects produced by alternative loads, in the sense that an increase in density would diminish the increments of settlement and horizontal displacement. Settlement is practically nil for relative densities of the order of 90%.

To take these phenomena into account in a deep foundation project, obtention of actual data may be resorted to, by means of tests on single piles. Likewise, it is possible to establish quantities considering that the free length of the piles increases proportionately with 1.5 and 2 times the diameter.

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