Response Prediction for Axially Loaded Fixed Head Pile Groups

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1. SUMMARY

The aim of this paper is to evaluate the influence of the interaction between the piles of a group fixed in a pile head on both bearing capacity and stiffness. For this purpose, numerical analyses were carried out to establish the load-displacement relationships for different 3*3 layouts of pile groups. The results are compared with those of the pile test carried out for the purposes of the project and the numerically established load-displacement curve of the single pile. Based on these non-linear analyses, the effect of the interaction was quantified for the pile group layouts examined, and was compared to proposed empirical relationships and reduction factors resulting from linear elastic analyses based on the principle of superposition.

2. INTRODUCTION

The effect of the interaction between the piles of a group under axial loading has been the subject of many researches during the past three decades. Based on the experience gained through these studies, empirical relationships were proposed to estimate the reduction factors on both, the bearing capacity and the stiffness of a group due to the interaction between the piles. Moreover, specific values for these factors have been proposed in tabular form resulting from simplified analyses based on elastic continuum analysis and the principle of superposition, Poulos and Davis /1/, Poulos /2/. An alternative approach is proposed by Lee /3/ in which the response of the single pile is simulated using the load-transfer (t-z) method, and the interaction between the piles is assessed using Mindlin's solution /4/. Another simplified approach providing a methodology for estimating the settlement of a pile group is the representation by an equivalent pier (Randolph /5/; Horikoshi and Randolph /6/). Most of the above methods involve soil profile simplifications and other idealisations rendering them computer cost-effective with the drawback however of limited accuracy in many cases. Numerical methods such as Finite Element or Finite Difference Method, taking advantage of powerful computer codes and hardware capabilities, provide us with the ability to efficiently analyse the effect of the interaction, covering two main aspects of the interaction problem for which the aforementioned approaches are not able to contribute. The first topic is related to the kinematic and stress field of the surrounding soil, when this information is required. The second one is the precise determination of a pile group response and its variation with the level of settlement.

The two topics above are examined in the present work. Numerical analyses have been carried out for various pile group arrangements with variable axial distance. In order to accurately investigate the effect of interaction, the responses of the piles constituting the groups were isolated for various level of settlement. In that way the contribution of each pile to the bearing capacity of the group was identified as a function of the settlement. Based on the results of the numerical analysis the bearing capacity efficiency factor was estimated for various group arrangements. The stiffness efficiency factor was also revealed as a function of both piles arrangement and settlement level.

3. SINGLE PILE ANALYSIS

The soil profile, Fig. 1, used in the analysis corresponds to that of the area of the new wharf at the harbour of Thessaloniki, where a long bridge based on a pile foundation was decided to be constructed. Given the magnitude and the importance of the project a pile load test was decided to be carried out. To numerically establish the load-settlement relationship of the single pile the computer code FLAC^{3D} /7/ was used. Full three-dimensional nonlinear analysis was carried out including the pile under compression and the four tension piles. The elastic perfectly plastic Mohr-Coulomb constitutive law in conjunction with a non-associated flow rule has been used to simulate the nonlinear elastoplastic material behaviour of the soil layers shown in Fig. 1. The bored piles consisted of class C30/35 concrete and their behaviour was considered as linear elastic. Its Poisson's ratio was taken equal to 0.20, while the modulus of elasticity was considered equal to 42000 MPa, including the stiffening due to the existence of steel reinforcement bars. In the case of bored piles in soft clays any anticipated failure takes place within the soil, just next to the interface. Therefore for the appropriate simulation a refined mesh, shown in Fig. 1, was utilised around the piles to allow plastification when the shear strength is attained, and no interface elements were incorporated in the analysis since no slip is expected for the anticipated level of settlements.

The testing sequence included an initial loading up to 4 MN and then unloading in steps of 1 MN (cycle A1). Then followed a second loading/unloading cycle to 10 MN using the same loading and unloading steps (cycle A2). Finally a third loading/unloading cycle to the maximum capacity of the hydraulic jacks (15 MN) was applied in steps of 1.07 MN and unloading steps of 2.14 MN (cycle A3). The load-settlement curves of loading cycles A1, A2 and A3 are given in Fig. 2. The simulation sequence of the load test included an initial step in which the initial stress condition was established, followed by 8 loading steps. More specifically, compression loads of 3, 6, 9, 12, 15, 16, 18 and 21 MN were applied on the test pile, while tension piles were simultaneously loaded with tension loads equal to one quarter of the compression load. The predicted load-settlement curve is presented in Fig. 2, together with the test results demonstrating remarkable agreement. Subsequently the same loading sequence was applied to numerically establish the load-settlement relationship for the case of a single pile. The analysis was performed using the same finite element mesh in which only the test pile was activated. This pile was loaded with gradual compression loads as previously stated. The results of the analysis are also given by the load-settlement curve in Fig. 2. It can be seen that there is a remarkable difference between the load-displacement curves of the test pile and the single pile for load levels lower than 15 MN, while for loads above this value the behaviour of the two piles is almost identical. It can be also seen that the stiffness of the test pile is almost double the stiffness of the single pile. Detailed presentation of the results is given by Comodromos *et al.* /8/. In that paper it is stated that due to the uplift forces applied by the tension piles, the contribution of the shaft resistance is significantly larger in the test pile than in the single pile until plastification occurs. Due to this fact the response of the test pile needs to be numerically assessed in order to be used for the design of foundations and superstructures.

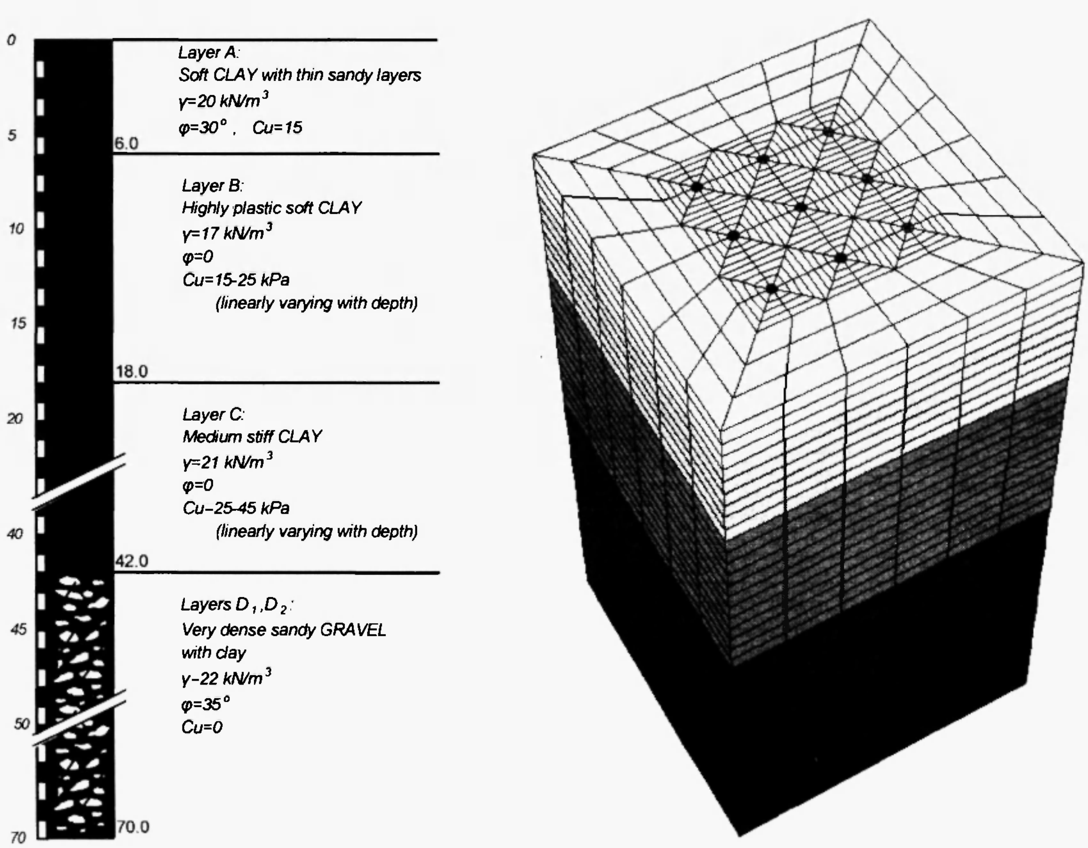

Fig. 1: Design soil profile and finite element mesh used in the analysis

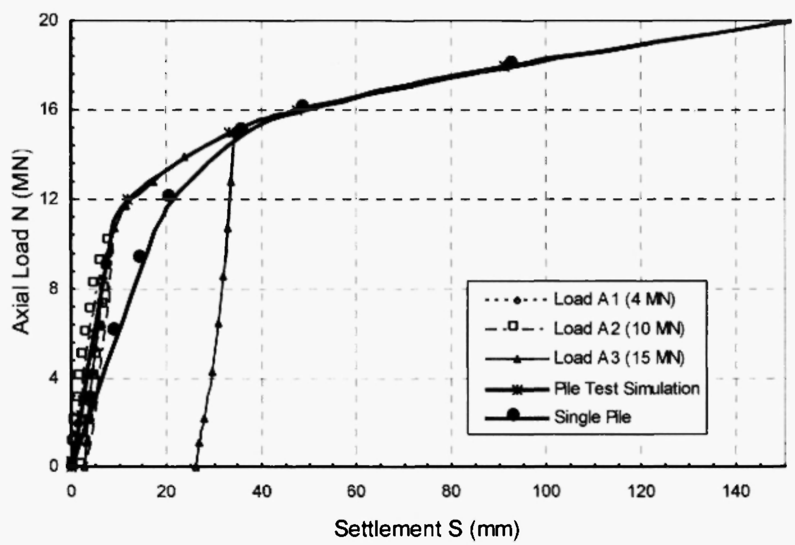

Fig. 2: Comparison of pile test load-settlement curve with the numerically established curves for pile test and single pile.

4. NUMERICAL ANALYSES OF PILE GROUPS WITH RIGID CAP

A parametric analysis was carried out in order to investigate the consequences of the interaction between the piles of a group with rigid cap on both the ultimate bearing capacity and the stiffness of individual piles and that of the entire pile group. The piles of the groups examined were identical to those of the pile test, having a diameter D=1.50m and a length of 45m. Initially three groups were studied; all of them in a 3*3 layout with the same geometrical features but at different axial distances. In the first group the axial distance of the piles was 3D, in the second one the axial distance was taken equal to 4.5 D, while in the third case the spacing was increased to 6D. The geometry of the mesh was parametrically defined in order to give the possibility for geometrical variations when needed. A mesh generator subroutine has been implemented using the FISH built-in programming language providing the possibility of mesh refinement and geometry variation.

The simulation sequence included an initial step in which the initial stress condition was established, followed by 8 loading steps. More specifically, a total load of nine times the mean compression load of 3, 6, 9, 12, 15, 18, 21 and 25 MN was applied on the central pile. To simulate the fact that the piles were fixed in a rigid pile head, the degrees of freedom of the nodes at the pile head corresponding to the directions x-x and y-y were eliminated, while in the z-z direction were considered slave to the node on which the load was applied. Figure 3a illustrates the numerically derived load-settlement curves for the single pile, and the various group configurations. As anticipated the group with axial distance of 6D presents the maximum stiffness, while the 3*3 group with a spacing of 3D was found as the less stiff. Considering as ultimate bearing capacity the load which causes a settlement equal to 10% of the pile diameter it can be seen that the bearing capacity efficiency factor, defined as the ratio of the ultimate bearing capacity of a pile in a group to that of a single pile, is greater than unity for the groups with spacing equal to 6D. It is well known that the bearing capacity efficiency factor is lower than unity for pile groups in clay and greater than unity for pile groups in sand. In the case analysed in the present investigation the value of the bearing capacity efficiency factor can be either above or below one. This behaviour can be attributed to the fact that in this case the soil profile contains both clay and sand layers. It is also clearly demonstrated that the bearing capacity efficiency factor is affected by the configuration of the piles. This is clearly stated by Fig. 3b showing the bearing capacity efficiency factors obtained from all the cases analysed in a column chart form.

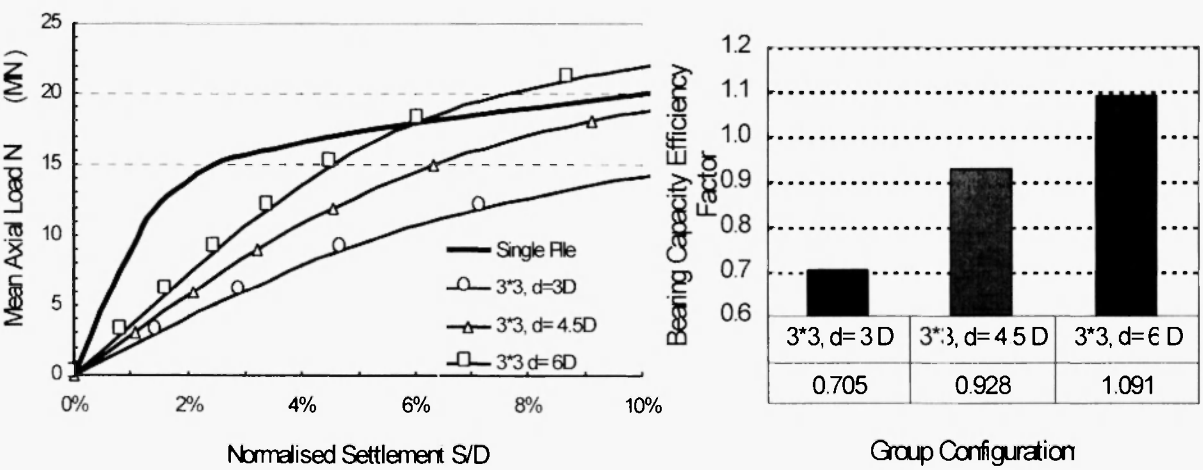

Fig. 3: a: Numerically established load-settlement curves for the single pile and a 3*3 group layout with axial distance of 3, 4.5 an 6 pile diameters, b: Bearing capacity efficiency factors

5. EVALUATION OF PILE GROUPS RESPONSE

Although the bearing capacity efficiency factors presented in Fig. 3b are close to one, the interaction between the piles has a much greater effect on the foundation stiffness. The stiffness efficiency factor can be defined as:

$$R_G = \frac{S_{ml,s}}{S_{mG}} \qquad (1)$$

in which S_{mG} and $S_{ml,s}$ stand for the mean settlement of the pile group and the single pile settlement under an axial mean load N_m, respectively. The mean load N_m is defined as the total load of the group divided by the number of piles in the group. The stiffness of a pile group for a given mean load N_m, can then be calculated using equation,

$$K_G = R_G * K_S \tag{2}$$

in which K_S is the stiffness of the single pile for a given load and K_G denotes the stiffness of the pile group for a load equal to that of the single pile multiplied by the number of piles in the group.

Obviously both the stiffness of the pile group and the stiffness efficiency factor depend on the level of settlement. Figure 4 illustrates the variation of this factor with the pile group settlement. It can be seen that by decreasing the pile spacing, the interaction among the piles of the group increases resulting in the reduction of the pile group stiffness. The application of higher loads that can produce settlements of the order of 10%D leads to the plastification of the surrounding soil. Since plastification minimises the effects of interaction, the stiffness efficiency factors approach unity when plastification occurs. This reason can be attributed to the fact that the stiffness efficiency factor increases when settlement increases, achieving the values of 0.7 and 1.1, for the group with spacing of 3D and 6D, respectively, when the settlement reaches the level of 10%D. The stiffness efficiency factor of the 3*3 group with a spacing of 6D is greater than unity since the bearing capacity of that group is 10% greater than that of the single pile as it is shown in Fig. 3b. In order to accurately investigate the effect of interaction, the responses of the piles of the 3*3 layouts were isolated. Figure 5 illustrates the variation of the response of the piles with the level of settlements in a revealing way. On the same figure the load-settlement curves proposed by Poulos and Davis /1/ are shown for the case of L/D=100 and relative compressibility pile/soil K=100.

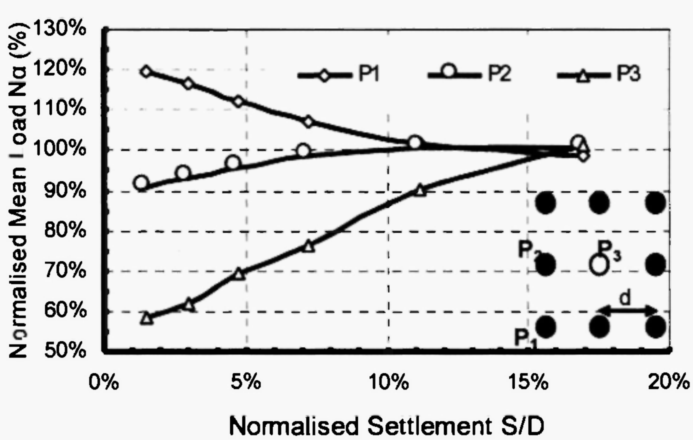

Fig. 4: Variation of normalised load with normalised settlement for piles P1, P2 and P3 in a 3*3 layout with a spacing of 3D

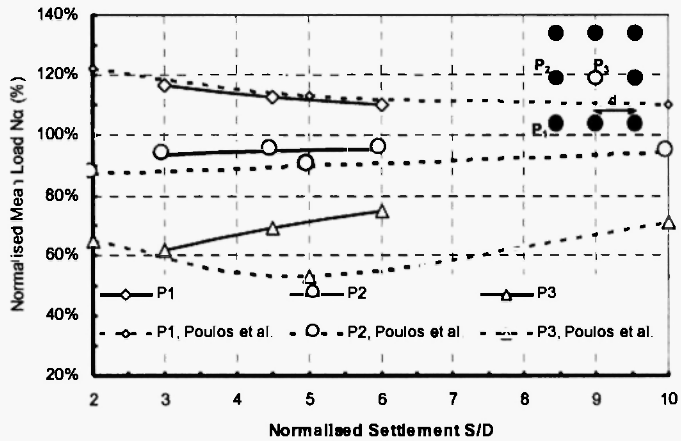

Fig. 5: Variation of normalised load with normalised settlement for piles P1, P2 and P3 in a 3*3 layout with normalised settlement

The interaction between the piles becomes insignificant and the central pile undertakes 100% of the mean load when settlements rise to 15%. On the other hand, pile P1 initially undertakes 120% of the mean load. This percentage gradually decreases with settlement level, becoming 100% when settlement rises to 15%. The variation of the load of pile P2 is considerably smaller, initially being 90% and becoming 100% when settlement rises to the above levels. Figure 5 presents the variation of the mean axial load with normalised spacing for the settlement of 3%D, which could be considered as the maximum level to which the allowable load corresponds. Comparison between the curves corresponding to the external pile P1 and the central pile P3 demonstrated that pile P1 undertakes 1.88 times the load of that of pile P3 for the 3*3 layout with spacing of 3D. The P1/P3 ratio decreases as spacing increases, being 1.62 for 4.5D and 1.47 for 6D.

6. CONCLUSIONS

In this paper the effects of the interaction to the response of a pile group fixed in a rigid cap was examined for various group configurations. From the analysis carried out and the evaluation of the results it can be concluded that the interaction between the piles of a group, fixed in a pile head, can affect the response of the pile group. While the effect on the bearing capacity lies within the framework of the world-wide proposed relationship, the stiffness reduction factor was found to vary with the level of settlement and evidently with the applied load.

More specifically it was found that the application of the stiffness obtained from single pile analysis, or even from a pile load test, in the design of structures based on pile foundation, would significantly underestimate the settlement of the pier and the bending moments of the structural members of the structure.

It was also demonstrated that, in the case of a 3*3 layout with axial distance of 3D, for a common level of settlement of the order of 3% of the pile diameter, the corner piles carry twice the load carried by the centre pile. This difference decreases with an increase of the axial distance. In all cases, the difference decreases when the settlement and the applied load increase, achieving the same final response when the settlement reaches the order of 10 to 15% of the pile diameter, at which the plastification level of the surrounding soil eliminates the effects of the interaction between the piles.

7. REFERENCES

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