CHAPTER IV

APPLICATION OF THE FINITE ELEMENT METHOD TO THE PROBLEM OF PILE-GROUP SETTLEMENT

Introduction.

Settlement prediction is an important part for the design of a pile foundation, especially for mat foundations or pile groups with a number of piles in a group. The settlements of these foundations may be excessive and differential settlements may occur. In the following section, the suitable parameters to be used in the analysis will be discussed and then the settlements of the square-configuration pile groups will be investigated by the proposed method. The behavior of these pile groups will be discussed and the results will be compared with those predicted by Poulos's method. For the verification of the proposed method, the observed settlements of a highrise building constructed in Bangkok are used in comparison with those predicted by the proposed method.

Determination of Parameters.

1. Introduction.

The computer program developed in this research will be used to analyse the idealized finite element model of the pile-soil interactions. The material parameters to be considered are only

Young's modulus and Poisson's ratio. In the following section, the material properties of the pile and soil mass are considered and their parameters are discussed.

2. Pile Parameters.

The Young's modulus and Poisson's ratio of piles depend on the type of material of the pile. In this research, only the concrete pile will be considered and its parameters can be found from those of the concrete properties. From ACI 318-83 (17), the Young's modulus of the concrete can be related to concrete's compressive strength by the following formula:

$$E_c = 4270\, w^{1.5} \sqrt{f_c'} \qquad (4.1)$$

$$= 15210 \sqrt{f_c'} \qquad (4.2)$$

where w = unit weight of concrete (t/m^3)

f_c' = ultimate compressive strength of concrete (kg/cm^2)

E_c = Young's modulus of concrete (kg/cm^2)

Equation(4.1) is for the values of w between 1.45 to 2.48 t/m^3, and equation(4.2) is for normal weight concrete. Normally, the value of E_c ranges from $2x10^5$ ksc to $3x10^5$ ksc.

Poisson's ratio of concrete is usually found to be in the range between 0.15 to 0.20. The lower value is for the high-strength concrete.

3. Soil Parameters.

The application of the theoretical solution to practical problems generally requires a knownledge of the representative values of the deformation parameters, they are E_s and ν_s of the soil. Although soil is not an ideally elastic material in that its stress and strain are not linearly related, and strains are not fully recoverable on reduction in stresses and strains are not independent of time as well. However, strains in soil increase as stresses increase. To avoid unduly complicated theory, a linear elastic theory which is sufficiently accurate can be used for engineering purposes, provided that elastic constants are selected appropriately to that particular problem. The methods of determining soil parameters presented here closely follow those appearing in references (4,18,19), there appears to be three means to obtain these parameters.

(a) From laboratory tests

(b) From pile-loading tests

(c) From empirical correlations

3.1 Laboratory Tests. Generally, the deformation parameters are determined in laboratory triaxial test, the stress paths of typical elements in the field are reproduced in the laboratory test and the resulting strains are measured. The procedure of the test can be found in reference (20).

The other laboratory test which can be used to approximate the deformation parameters is the oedometer test. Other names for this test are the one dimensional compression test, the confined compression test and the consolidation test. Once the values of m_v and ν_s' have been determined, the drained soil modulus E_s' for three dimensional analysis can be approximated as follows:

$$E_s' = \frac{(1 + \nu_s')\ (1 - 2\nu_s')}{m_v\ (1 - \nu_s')} \qquad (4.3)$$

where ν_s' = Poisson's ratio of soil in drained condition

m_v = Coefficient of volume compressibility

By assuming that the soil is an ideal two-phase elastic homogeneous isotropic material, the undrained soil modulus E_u can be related to the drained soil modulus E_s' as follows:

$$E_u = \frac{3E_s'}{2(1 + \nu_s')} \qquad (4.4)$$

The ranges of values of ν_s have been suggested in Table 4.1 .

The selection of drained and undrained parameters for the settlement analysis can be classified into two cases. First, for piles in sand or unsaturated soil, the final settlement may be considered to occur immediately on application of the load, so that the values of E_s and ν_s used in calculating the settlement of the pile should be the drained values, that is the moduli of the soil skeleton, E_s' and ν_s'. Second, for piles in saturated clay, an immediate settlement, ρ_i , occurs under undrained conditions followed by a time-dependent consolidation settlement. After dissipation of the excess pore pressures resulting from loading of the piles is complete, the total settlement of the pile is ρ_f. The immediate settlement ρ_i is calculated by using the undrained soil modulus, E_u, and the undrained Poisson's ratio, ν_u, which is 0.5 for a saturated soil. The final settlement ρ_f is calculated by using the drained soil modulus, E_s', and the drained Poisson's ratio, ν_s'.

However, for pile foundation analysis, such tests are not possible to measure the accurate value of E_s because of the difficulty in the determinination of the appropriate stress path during installation of the pile and that resulting from the applied load on the pile as well. Poulos (4) has found that the values of E_s determined from laboratory test are much lower than the backfigured values obtained from model-pile tests, he then concluded that more appropriate forms of laboratory testing remained to be explored.

3.2 <u>Pile-loading Test.</u> Since many uncertainties may be associated with laboratory tests, it is desirable where possible to deduce the deformation parameters from a full-scale pile-loading test. Such factors as the method of installation of the pile and layering of the soil profile are then largely taken into account. The appropriate theoretical solutions to backfigure these parameters can be found in references (4,18,19). However it is probably sufficient either to estimate the value of ν_s or to dertermine it from a laboratory triaxial test.

For settlement analysis of pile group, Poulos (4) strongly recommended that in founding layer, the value of E_s should be backfigured from pile load test. For the values of E_s in underlying layers, they should be determined from laboratory triaxial tests.

3.3 Empirical Correlation. When pile-loading test data are not available, the values of E_s in founding layer may be approximated by the empirical correlation based on the previous experience. The ranges of values of E_s have been summarized as follows:

3.3.1 Piles in Clay: Poulos suggested that the values of drained soil modulus, E_s' , can be correlated with the values of undrained cohesion, c_u , of the clay. For driven pile, two trends have been observed;

(a) For soft to medium clay. ($c_u < 12$ t/m^2) The values of E_s' range from 300 c_u to 400 c_u, the lower values tend to be associated with very soft clay and the higher values with medium clay.

(b) For stiff clays. E_s' appears to reach a limiting value about 4000 t/m^2.

To predict the immediate settlement, the undrained soil modulus, E_u , determined from the relationship as shown in equation (4.4) can be used.

3.3.2 Pile in Sand: For driven pile, the suggested ranges of average values of E_s are summarized in Table 4.2.

Behavior of Square-configuration Pile Groups.

1. Introduction.

The group effect among piles which are relatively closely spaced and loaded vertically is manifest in two main ways; the ultimate load capacity and the settlement of the group. In the following section, the settlement of the group which is not necessary the same as that of a single pile carrying the same average load as a pile in the group will be considered. The effect of group action on settlement is most conveniently considered in terms of a group settlement ratio, R_s , which is the ratio of the average settlement of the group to the settlement of a single pile at the same average load as a pile in a group. Generally, R_s is greater than unity.

2. Method of analysis.

The developed computer program for nonlinear static finte element analysis which accounts for large displacement and large strain has been employed in the analysis. The soil mass and the pile are idealized using 8 node isoparametric hexahedral element as shown in Figure 2.2.

The plan and elevation of a 2x2 pile group are shown in Figure 4.1. The plan of 3x3 and 4x4 pile group are shown in Figures 4.2 and 4.3 respectively. All piles in the group are loaded equally with the load of 80 ton per pile. The finite element models accounted for the symmetry in x and y axes of these pile groups are shown in Figures 4.4, 4.5 and 4.6 respectively.

As shown in Figures 4.4, 4.5 and 4.6 the boundary of the entire model is located at a distance of 15.5D, where D is the width of the pile group. The effect of the variation in position of the outer boundary has been investigated by Pressley and Poulos (9), and can be concluded that there is little effect in increasing the distance from 4D to 8D in most cases. However, in this research the distance of 15.5D is recommended because the mesh of the presented model is relatively coarse.

For the analysis of a single pile, the outer boundary of the entire model is located at a distance of 31.5d, where d is the width of the single pile which is in agreement with Pressley's model where the outer boundary of the entire model is located at a radius of 35 pile diameter. The finite element model for a single pile with the symmetry in x and y axes is shown in Figure 4.7.

3. Pile and Soil Paremeters.

A summary of the pile and soil parameters chosen for the analysis is given in Table 4.3. These soil parameters are good representative of the Bangkok soil properties. In founding layer, the undrained soil modulus is assumed to be the value which backfigured from pile load test. Thanin (19) has analysed the settlements of three driven pile foundations constructed in Bangkok area and the backfigured values of undrained soil modulus of these foundations are 1600 t/m^2, 2900 t/m^2 and 4450 t/m^2 respectively. For this analysis, the average value is selected. In underlying layers, the soil moduli are assumed to be the average soil moduli of Bangkok soil which obtained from laboratory tests. Only immediate settlement has been considered in the analysis, as a result, for cohesive soil, attention is confined to the case of undrained condition. For the proposed method, the Poisson's ratio of cohesive soil is taken as 0.49 rather than the correct value of 0.5 in order to avoid numerical difficulties. For Poulos's method, it should be noted that when this method is applied to the settlement problem of piles installed such that the pile tip bears on to a soil stratum that is stiffer than the soil along the shaft of the pile, the ratio of soil modulus between base layer and founding layer, E_b/E_s , will be an important factor in the analysis. This effect has been studied by Thanin (19) and he suggested that for driven pile groups, constructed in Bangkok area, with pile tip embedded in the first sand layer, the value of E_b/E_s should range from three to five. For this analysis, the value of E_b/E_s equals five is applied.

4. Comparisons with Poulos's Method.

Comparisons are made between the finite element solutions and the elastic solutions obtained by Poulos method (3,4). Figure 4.8 shows values of the settelment ratio, R_s , of three pile-group configurations from both analyses. The agreement is generally good at closer spacing, although the finite element analysis predicts smaller values of R_s. The solutions tend to diverge at larger pile spacings, probably because of the relative coarseness of the finite element mesh. Both solutions show that the values of group settlement ratio R_s tend to increase as the number of piles increases and these values tend to decrease as the pile spacing s/d increases. The pile spacing effect for 4x4 pile group is more pronouced than that for 2x2 pile group. The comparisons for relative settlement of pile within 3x3 and 4x4 pile group are also made. The general behavior is found to be similar, that is smaller settlements occur in the corner piles and larger settlements occur in the middle piles. However, the average settlements should be the best representative of pile-group settlements. The average settlements of these pile groups are sumarrized in Table 4.4.

In this comparison, both methods use the same parameters in the analysis and it is obvious that the proposed method tends to give lower values of settlements than those obtained by Poulos's method. There are three reasons , firstly, the proposed method is based on the finite element method which gives lower bound to displacement solution. The solution will converge to the exact one if the suitable element is used and the mesh of the model is more refined. Secondly, Poulos's method uses an assumption that all piles are circular piles while the proposed method considers them to be square piles. If the width of the pile considered is the same, the pile used in the proposed method will be stronger and the settlement of this pile should be smaller. Thirdly, the presented finite element model has been considered a finite layer depth of soil mass while Poulos's method applied to this case by considering a soil mass of infinite depth. The presence of the finite layer depth tends to reduce the settlement of pile group and this effect is more pronouced as the size of the group increases.

Illustrative Application.

1. Introduction.

To show the effectiveness of the proposed method, the settlement analysis of a highrise building in Bangkok has been investigated. The Tower C Building has 26 stories. Its piling foundation consists of a mat foundation for the service core and combined footings for the columns arranged as shown in Figures 4.9 and 4.10. The number of piles in this foundation system is 272. They are prestressed concrete pile with I shape cross section, the width of the pile is 0.40 meters and its length is 25 meters. The pile tip and pile top are at the levels of 29 meters and 5 meters below the ground surface. At the end of the construction, the total load on this foundation is approximated to be 11,500 tons. The other essential details of the foundation and the observed settlement data can be found in reference (19).

2. Method of Analysis.

In the previous sections, the settlements of a square-configuration pile group have been analysed in such a way that all piles in the group are represented explicitly in the model. Herein, the same method will be performed with some modification. For mat foundation or pile groups with a large number of piles in a group, it is more appropriate to subdevide the whole group into smaller pile groups and then replace each smaller pile group by an equivalent single pier that settles equally. Each smaller pile group is analysed seperately to find the width of an equivalent single pier, B_e. This arrangement has been suggested by Poulos (3,4) as well. The equivalent single piers with circular shape cross section are performed in the Poulos's method while those with square shape cross section are used in the proposed method. By this method of idealization, the whole groups are analysed without computational difficulty and their settlements are determined.

Figure 4.9 shows the typical floor plan of the building with the points to observe settlement, Figure 4.10 also shows the plan of the piling arrangement. To analyse this foundation, the equivalent pile group method has been performed. The subdevided pile groups and the equivalent model of these groups are shown in Figures 4.11 and 4.12 respectively. The smaller subdevided pile groups, i.e. 5x6, 6x7, 6x8 numbers of pile, have been analysed seperately to find the equivalent width of them. Then the equivalent single piers with the variation in width have been analysed and the relations between the immediate settlements and their widths at specific load have been shown in Figure 4.13. The equivalent pier width of the pile groups are interpolated by using these curves and the results are summarized in Table 4.5. Then the complete model containing the equivalent groups has been analysed to determined the settlements of this building.

3. Pile and Soil Parameters.

The parameters E_p, ν_p, E_s, ν_s are summarized in Table 4.6. It should be noted that the value of E_u in founding layer (laryer 1 and 2) is backfigured from pile load test and the value of E_s' is calculated by using equation (4.4). For underlying layers, the values of E_s are approximated from oedometer test using equations (4.3) and (4.4). Both immediate and final settlements are considered in this case. For cohesive soil, the immediate settlement prediction is based on undrained condition while the final settlement prediction will be associated with drained condition. For cohesionless soil, only drained condition is applicable, as a result, both settlement predictions are dependent upon the same parameters.

4. Comparisons with Field Measurements and Poulos's Method.

Comparisons between the results from the proposed method, those of Poulos's method and observed settlement data have been shown in Table 4.7. It is obvious that the predicted settlements by the proposed method are in good agreement with the observed data and the results obtained by Poulos's method. It should be noted that the effect of pile cap rigidity which tends to reduce the settlement has been considered in the Poulos's method. The proposed method does not consider this effect, therefore, the comparisons of settlements for this foundation tend to be better than the comparisons of those of pile groups which have been studied in previous section. However, the settlements predicted by the proposed method are still less than those obtained by Poulos's method.