Settlements Under Footings on Rammed Aggregate Piers

Tassements sous des semelles sur pieux d'agrégats battus

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ABSTRACT: This study uses a 3D finite element program, calibrated with the results of a full scale instrumented load test on a limited size footing, to estimate the settlement improvement factor for footings resting on rammed aggregate pier groups. A simplified 3D finite element model (Composite Soil Model) was developed, which takes into account the increase of stiffness around the piers during the ramming process. Design charts for settlement improvement factors of square footings of different sizes (B = 2.4m to 4.8m) resting on aggregate pier groups of different area ratios (AR = 0.087 to 0.349), pier moduli (E_{column} = 36MPa to 72MPa), and with various compressible clay layer strengths (c_u = 20kPa to 60kPa) and thicknesses (L = 5m to 15m) were prepared using this calibrated 3D finite element model. It was found that, the settlement improvement factor increases as the area ratio, pier modulus and footing pressure increase. On the other hand, the settlement improvement factor is observed to decrease as the undrained shear strength and thickness of compressible clay and footing size increase.

RÉSUMÉ : Cette étude utilise un modèle de calcul en éléments finis 3D, calé à partir sur les résultats d'essais de chargement grandeur nature , totalement instrumentés, sur une semelle de dimensions limitées, dans le but d'estimer le facteur d'amélioration du tassement des semelles reposant sur des groupes de pieux en agrégats, battus. Un modèle simplifié par éléments finis 3D (modèle de sol composite) a été développé ; il prend en compte l'augmentation de la rigidité autour des piles pendant le processus de battage. Les abaques des facteurs d'amélioration de tassement d'une semelle carrée de dimensions variables (B = 2,4 m à 4,8 m) reposant sur des groupes de pieux en agrégats battus, avec des rapports de surface variés (AR = 0,087 à 0,349), modules de pile (Ecolumn = 36MPa à 72MPa), et avec différentes couche de renforcement d'argile compressible (c_u = 20 kPa à 60 kPa) et épaisseurs (L = 5m à 15m) ont été préparés en utilisant ce modèle en éléments finis 3D. D'une part, il a été constaté que le facteur d'amélioration du tassement croît en fonction de l'augmentation du rapport de la surface, du module de pile et de la pression des semelles. D'autre part, le facteur d'amélioration du tassement diminue lorsque la résistance au cisaillement non drainé, l'épaisseur de l'argile compressible ainsi que les dimensions des semelles croissent.

KEYWORDS: rammed aggregate pier, stone column, settlement improvement factor

1 INTRODUCTION

This study uses a 3D finite element program, calibrated with the results of a full scale instrumented load test on a limited size footing, to estimate the settlement improvement factor for footings resting on rammed aggregate pier groups. A simplified 3D finite element model (Composite Soil Model) was developed, which takes into account the increase of stiffness around the piers during the ramming process. Design charts for settlement improvement factors of square footings of different sizes (B = 2.4m to 4.8m) resting on aggregate pier groups of different area ratios (AR = 0.087 to 0.349), pier moduli (Ecolumn = 36MPa to 72MPa), and with various compressible clay layer strengths (c_u = 20kPa to 60kPa) and thicknesses (L = 5m to 15m) were prepared using this calibrated 3D finite element model.

2 CALIBRATION OF THE FINITE ELEMENT MODEL

The finite element model that is going to be used for the parametric studies that will be presented in the proceeding chapters of this study is calibrated with the results of full-scale field load tests detailed in Özkeskin (2004). The full scale field tests consist of load tests on both untreated soil and on three different groups of rammed aggregate piers with different lengths on the same site, and therefore offers the unique opportunity of calibrating geotechnical parameters for a finite element model.

The test area which is approximately 10m x 30m is located around Lake Eymir, Ankara. Site investigation at the test area included five boreholes which are 8m to 13.5m in depth, SPT tests, sampling and laboratory testing, and four CPT soundings. (see Figure 1)

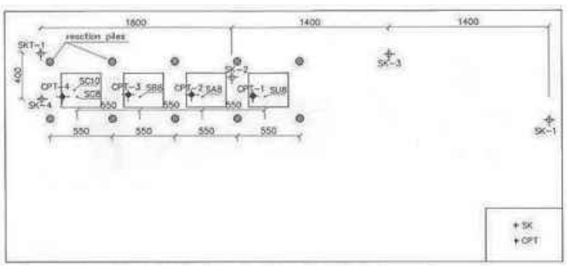

Figure 1. Location of boreholes and CPT soundings at the test site.

The variation of SPT-N values with depth is given in Figure 2. It can be seen that, SPT-N values are generally in the range of 3 to 10 in the first 8 m. After 8 m depth, SPT-N values are greater than 20, and the samples are identified as weathered graywacke. Based on the laboratory test results, the compressible layer, first 8 m, is classified as low plasticity clay (CL) and clayey sand (SC) according to USCS. The liquid limit of the compressible layer changes predominantly in the range of 27% to 43% with an average of 30%, and the plastic limit changes in the range of 14% to 20% with an average of 15%. The ground water is located near the surface.

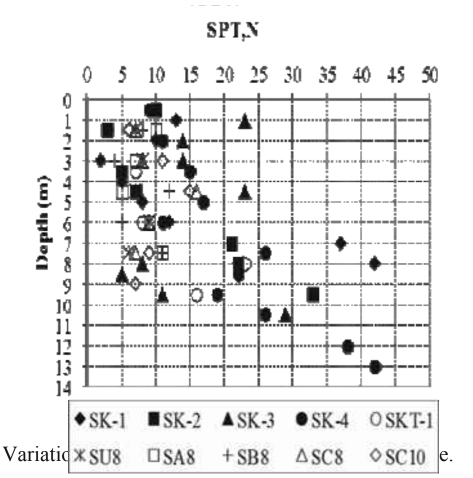

Figure 2. Variation of SPT-N values with depth at the test site.

Four large plate load tests were conducted at the load test site. Rigid steel plates having plan dimensions of 3.0m by 3.5m were used for loading. First load test was on untreated soil. Second load test was Group A loading on improved ground with aggregate piers of 3.0m length, third load test was Group B loading on improved ground with aggregate piers of 5.0m length and finally fourth load test was Group C loading on improved ground with aggregate pier lengths of 8.0m. Each aggregate pier groups, i.e. Group A, Group B, and Group C, consisted of 7 piers installed with a spacing of 1.25 m in a triangular pattern. The pier diameter was 65cm. (See Figure 3)

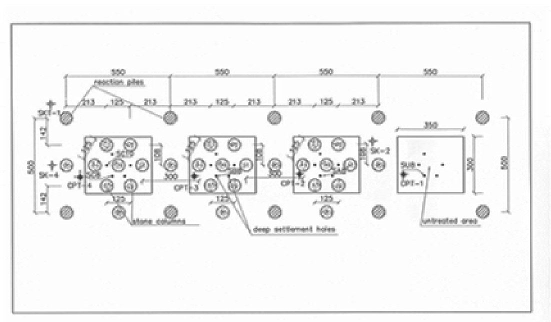

Figure 3. Location of aggregate piers at the test site.

For each group of aggregate piers, deep settlement plates were installed at 1.5m, 3m, 5m, 8m and 10m depths. 10cm thick fine sand layers were laid and compacted to level the surface before placing the total pressure cell on top of the center aggregate pier. The loading sequence for untreated soil load test was cyclic and at each increment and decrement, load was kept constant until the settlement rate was almost zero. For aggregate pier groups, the loading sequence was 50, 100, 150, 200, 250, 150, 0 kPa. Two surface movements, one at the corner and one at the center of the loading plate, and five deep movement measurements were taken with respect to time.

The data of the plate loading test on untreated soil was used for calibrating the finite element model. Geotechnical finite element software PLAXIS 3D Foundation which offers the possibility of 3D finite element modeling was used for the analysis. Loading plate, which has dimensions of 3.0mx3.5m, was modeled as a rigid plate and the loading was applied as a uniformly distributed vertical load on this plate according to the loading scheme used during the actual field test. The boundaries of the 3D finite element mesh was extended 4 times the loading plate dimensions in order to minimize the effects of model boundaries on the analysis. The height of the finite element model was selected as 12meters. The first 8 meters was the compressible silty clay layer and the remaining 4 meters was the relatively incompressible stiff clayey sand (weathered greywacke) layer. An isometric view of the 3D model is given in Figure 4.

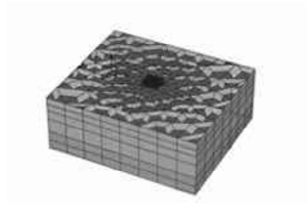

Figure 4. Isometric view of the 3D finite element model.

Both the compressible and relatively incompressible soil layers was modeled using the elastic-perfectly plastic Mohr-Coulomb soil model. Groundwater level was defined at the surface. The parameters of the relatively incompressible layer was set to high values, and various geotechnical parameters was assigned to the compressible layer until the surface load-settlement curve calculated from the finite element model matches with the field test data carried on untreated soil. The closest match, which is shown in Figure 5, was obtained with the parameters presented at Table 1.

Table 1. Calibrated soil parameters to be used in the finite element analyses.

Unit	γ (kN/m^3)	c (kPa)	ϕ(°)	E (kPa)	ν
Silty clay (0-8m)	18	22	0	4500	0.35
Clayey sand (8-12m)	20	0	40	50000	0.30

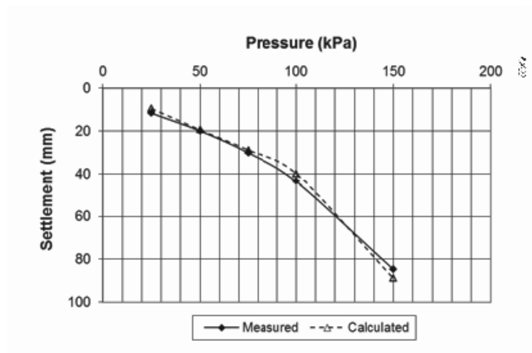

Figure 5. Comparison of surface load settlement curves for untreated soil

Once the geotechnical parameters of the native soil were determined, the next step was to model the field tests on three different rammed aggregate pier groups (i.e. Group A, Group B and Group C). In all three tests the rammed aggregate pier layout was similar (Figure 6) and the lengths of the aggregate piers were 3m, 5m and 8m for Group A, Group B and Group C, respectively. The size of the loading plate was 3.0mx3.5m, as it was the case at the field test on untreated soil.

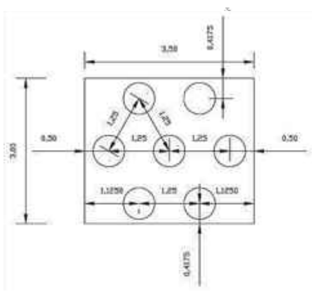

Figure 6. Field test rammed aggregate pier layout

The field load tests on rammed aggregate pier groups were again modeled by PLAXIS 3D Foundation. The size of the finite element mesh was kept the same as the model for the test on untreated soil for comparison purposes. Material model and geotechnical parameters derived from the calibration process were used for the native soil. Rammed aggregate piers were modeled with linear elastic material model and modulus of elasticity value was given as E = 39 MPa, as recommended by Özkeskin (2004), which is backcalculated from single pier load tests. Loading plate, which has dimensions of 3.0mx3.5m, was modeled as a rigid plate and the loading was applied as a uniformly distributed vertical load on this plate according to the loading scheme used during the actual field test. Calculated surface pressure-settlement curves for each aggregate pier groups are compared with the field measurements in Figure 7. (Surface pressure values are normalized with respect to the ultimate bearing capacity, q_{ult}, of the untreated soil.) The calculated surface settlements are larger than the measured ones for all cases.

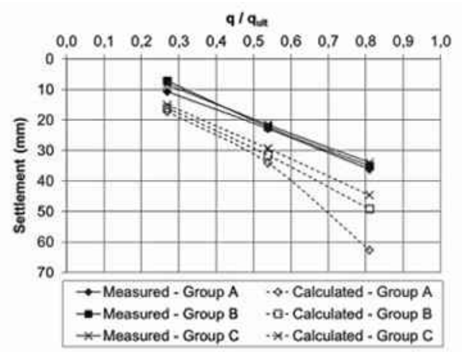

Figure 7. Comparison of surface load-settlement curves for loading on Group A rammed aggregate piers (Normal 3D FEM Model)

The observed stiffer and near-linear-elastic behaviour of aggregate pier groups can be explained by the increase of lateral stress in the matrix soil around the rammed aggregate piers caused by the ramming action during the installation of the piers. This increase in lateral stress of matrix soil results in improved stiffness characteristics as explained by Handy (2001). In order to match the observed stiffer and near-linear-elastic behaviour of actual field test measurements, it is decided to define linear elastic improved zones around the rammed aggregate piers at the 3D finite element model. It is assumed that a circular zone with a radius equal to two times of the rammed aggregate pier radius is improved around the rammed aggregate piers. (Modified Ring Model) This circular zone is also divided into two zones. (Figure 8) It is assumed that the modulus of elasticity value of the improved soil around the rammed aggregate pier increases to 2/3 of the modulus of elasticity value of the rammed aggregate pier at the first improved zone - $r = 1.5r_{aggregate\ pier}$ -, and to 1/3 of the modulus of elasticity value of the rammed aggregate pier at the second improved zone - $r = 2.0r_{aggregate\ pier}$ -.

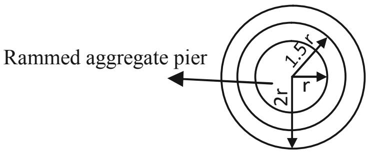

Figure 8. Geometry of the assumed improved zones around the rammed aggregate piers

Calculated surface pressure-settlement curves for each aggregate pier groups are compared with the field measurements in Figure 9. Calculated load-settlement curves fit to the expected near-linear-elastic behavior much better than before. The agreement with the measured surface settlement values are quite satisfactory for Group B and Group C loadings.

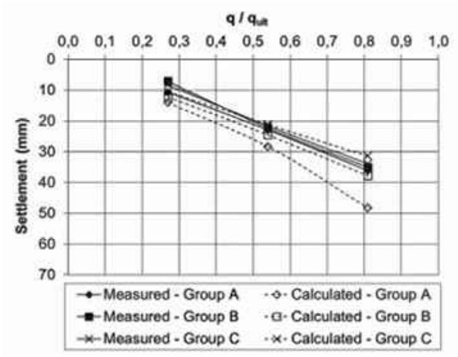

Figure 9. Comparison of surface load-settlement curves for loading on Group A rammed aggregate piers (Modified Ring Model)

The next step is to try to simplify this improved near-linear-elastic zone assumption (Modified Ring Model) so that it can be easily used for practical analyses. For this purpose, the area under the loading plate with the rammed aggregate piers is modeled as a composite soil block (Composite Soil Model). Linear elastic material model is used for the composite soil block and the modulus of elasticity of this composite zone is calculated as the weighted average of the rammed aggregate pier, improved zones around the rammed aggregate pier, and native soil, according to their respective areas. The improved modulus of elasticity values were selected as 2/3 of the modulus of elasticity value of the rammed aggregates pier at the first improved zone - $r = 1.5r_{aggregate\ pier}$ - , and to 1/3 of the modulus of elasticity value of the rammed aggregates pier at the second improved zone - $r = 2.0r_{aggregate\ pier}$ - , as concluded before. Calculated surface pressure-settlement curves for this case are compared with the field measurements in Figure 10. Calculated load-settlement curves with the Composite Soil Model yield more close results to the measured values than the Modified Ring Model, especially for floating pier groups. (i.e. Group A and Group B)

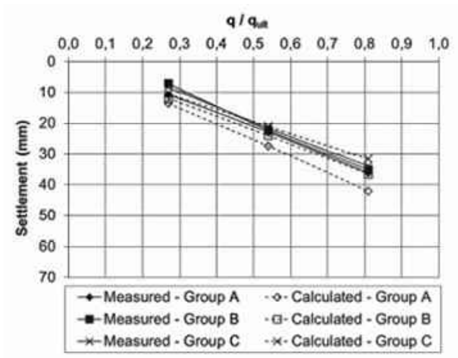

Figure 10. Comparison of surface load-settlement curves for loading on Group A rammed aggregate piers (Composite Soil Model)

As a result of the calibration process detailed in this chapter, it is concluded that the 3D finite element model, i.e. the Composite Soil Model, in which the area under the loading plate with the rammed aggregate piers is modeled as a composite soil block with equivalent linear elastic soil properties taking the stiffness increase around the piers during the installation process into account, satisfactorily models the surface pressure-settlement curves of uniformly loaded footings supported by rammed aggregate piers. It is to be mentioned that the model should be used cautiously for floating pier groups with pier lengths less than 1.5B (B = width of the footing), especially at high surface pressure levels , i.e. $q / q_{ult} > 0.5$, where q_{ult} = ultimate bearing capacity of the native soil.

3 DETAILS OF THE PARAMETRIC STUDY

Once the 3D finite element model (Composite Soil Model) to be used for the analysis of rigid footings resting on rammed aggregate piers was calibrated using the results of full-scale load tests as presented in the previous chapter, the next step is to carry out a parametric study using this finite element model to investigate the effect of both geometric parameters (area ratio of rammed aggregate piers, foundation load, width of foundation, rammed aggregate pier length) and material parameters (strength of foundation material, modulus of elasticity value of rammed aggregate piers) on the settlement improvement factor.

Three different footing sizes (2.4mx2.4m, 3.6mx3.6m and 4.8mx4.8m) were used for the parametric study. The thickness of the compressible clay layer under these footings was varied as Lclay = 5m, 10m and 15m for each different footing size. Four different area ratios (AR= 0.087, 0.136, 0.230 and 0.349) were used for the rammed aggregate pier groups under each different footing and compressible layer combination. Foundation pressures, q, were selected as q=25-50-75-100-125-150 kPa. Schematic representation of these parameters can be seen in Figure 11. The strength and deformation modulus values of the compressible clay layer were varied as shown at Table 2. The deformation modulus value of the rammed aggregate piers were selected as E_{column} = 36 MPa and 72MPa.

Table 2. Strength and deformation properties of the compressible clay layer used in the parametric study.

γ (kN/m^3)	c (kN/m^2)	ϕ (°)	ν	E_{clay} (kN/m^2)
18	20	0	0.35	4500
18	25	0	0.35	5625
18	30	0	0.35	6750
18	40	0	0.35	9000
18	60	0	0.35	13500

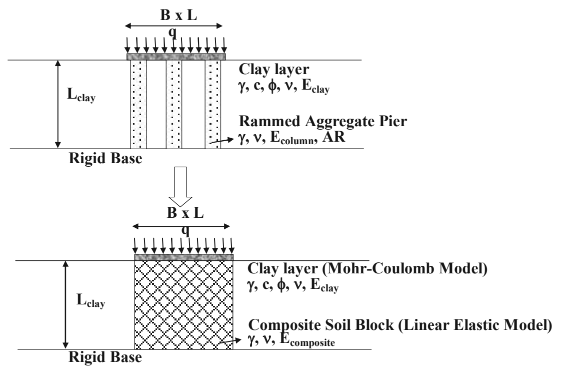

Figure 11 Schematic representation of composite soil model

For each case, first the untreated case is analyzed by modelling the uniformly loaded rigid footing on compressible clay using PLAXIS 3D Foundation. Untreated soil settlements were obtained by this way. Next, the rigid footings resting on rammed aggregate piers were modeled by PLAXIS 3D Foundation using the Composite Soil Block approach that was explained in detail in the previous section. Once the settlement values for the footings resting on rammed aggregate pier groups are calculated using this method, settlement improvement factors are calculated as:

$$IF = s_{untreated} / s_{treated} \quad (1)$$

where:

IF = settlement improvement factor

$s_{untreated}$ = settlement of rigid footing resting on untreated soil.

$s_{treated}$ = settlement of rigid footing resting on soil treated with rammed aggregate pier group.

The results of the parametric study detailed in this section are presented as design charts at Kuruoglu (2008). A sample design chart is shown in Figure 12. The design charts can be used to decide on the necessary area ratio of rammed aggregate piers for a target settlement improvement ratio for footings on compressible soils resting on rammed aggregate pier groups.

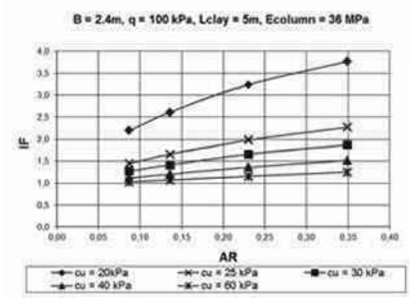

Figure 12. Settlement improvement factor (IF) vs. area ratio (AR) charts for a rigid square footing (B=2.4m) with a foundation pressure of q=100 kPa resting on end bearing rammed aggregate piers (L=5m, E=36 MPa)

As a result of the parametric study, it was found that, the settlement improvement factor increases as the area ratio, pier modulus and footing pressure increase. On the other hand, the settlement improvement factor is observed to decrease as the undrained shear strength and thickness of compressible clay and footing size increase.

4 CONCLUSIONS

A simplified 3D finite element model (Composite Soil Model) calibrated with the results of full scale load tests was developed, which shows that 3D models for estimating settlement improvement factor for foundations resting on rammed aggregate piers can be much simplified by modeling the area under the footing as a composite soil block with equivalent linear elastic soil properties, taking the stiffness increase around the piers during the installation process into account. It is to be mentioned that the model should be used cautiously for floating pier groups with pier lengths less than 1.5B (B = width of the footing), especially at high surface pressure levels , i.e. q / qult > 0.5, where qult = ultimate bearing capacity of the native soil.

Using this simplified model, design charts for settlement improvement factors of square footings of different sizes (B = 2.4m to 4.8m) resting on aggregate pier groups of different area ratios (AR = 0.087 to 0.349), pier moduli (Ecolumn = 36MPa to 72MPa), and with various compressible clay layer strengths (cu = 20kPa to 60kPa) and thicknesses (L = 5m to 15m) were prepared.

As a result of the parametric study, it was found that, the settlement improvement factor increases as the area ratio, pier modulus and footing pressure increase. On the other hand, the settlement improvement factor is observed to decrease as the undrained shear strength and thickness of compressible clay and footing size increase.

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