Procds. of the 16th Asian Regional Conference on Soil Mechanics and Geotechnical Engineering,
October 14-18, 2019, Taipei, Taiwan

Modeling and analysis of the pile cluster foundation in SCAD and SMath Studio

L. Nuzhdin [1,2], V. Mikhailov [1], V. Rezyapkin [1]

[1] Novosibirsk State University of Architecture and Civil Engineering (Sibstrin), 113, Leningradskaya, Novosibirsk 630008, Russia.
[2] Perm National Research Polytechnic University, 29, Komsomolsky prospekt, Perm 614990, Russia.

ABSTRACT

The article presents a brief review of the main methods for analytical and numerical modeling of cluster-pile foundations in the FEM structural analysis software SCAD Office 21.1. Two analytic methods are considered in accordance with design codes SNiP 2.02.03-85 and SP 24.13330.2011. A part of the analysis is performed with the use of the mathematical software SMath Studio. The detailed description of the calculation technology is presented, indicating the limits of applicability of both methods and recommendations for their use in static conditions.

Keywords: pile cluster foundation; linearly elastic ground base FEM model; SCAD Office software.

1 INTRODUCTION

The latest updated version of Russian design code SP 24.13330.2011 «Pile foundations» presents a more precise analysis method for settlement of pile cluster in comparison with the previous version of the design code SNiP 2.02.03-85. To implement this method authors developed the technology for pile cluster calculation in accordance with Russian design codes. It is based on the integrated application of the FEM structural analysis software SCAD Office and the freely distributed mathematical software SMath Studio. Calculation of extra loads (ΔNh) in FEM model makes it possible to simulate ground base deformations in the form of the conical depression of a pile field consequently to vertical mutual influence of neighboring piles [1, 2].

2 ANALYZED PILE FOUNDATION

The object of the numerical study is a model of a cluster pile foundation with a pile raft of 2.3 × 2.3 m size and of 2.5 m depth from the earth surface. The calculation takes into account the stiffness of the pile raft of 500 mm thickness of concrete class B25. The slab is modeled by four- and three-node plate-type finite elements. The piles of concrete B25 are modeled by universal rod finite elements of rigid frame type.

Figure 1 shows a general view of the pile foundation model, consisting of nine bored piles, of 8.5 m long and 300 mm in diameter. The clear distance between the piles is 0.6 m, with average between-centers distance equal 0.9 m. The horizontal earth backpressure along the lateral surface of the piles is simulated by Winkler coefficients along the length of the pile rod elements. The settlement of the pile cluster is modeled with the use one-node springs and additional nodal loads ΔNh, which form the conical depression of linearly deformable ground base. Two loadings applied to the pile foundation model are a vertical one of 2403 kN (Fig. 2) and a horizontal one of 25 kN in the same node.

The upper soil layer of 5 m thick is composed of light loamy hard silt (I_L=0.49, e=0.86); the second layer of 1.5 m thick is heavy sandy stiff clay (I_L=0, e=0.74); the rest of the soil column is composed of pebble soil with sand-clay (I_L=0, e=0.56). External effects are reduced to two loadings - permanent vertical loading and temporary horizontal loading. In the calculation results, the stress-strain state of the foundation is also analyzed the combined action of the loadings.

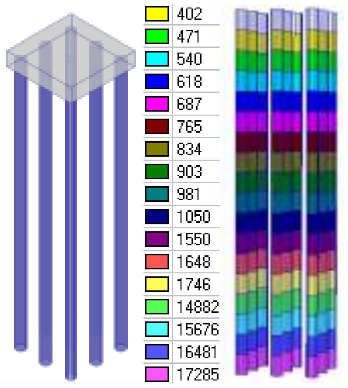

Fig. 1 View of a pile cluster and the coefficients of soil reaction along the lateral surface of the pile, kN/m^3;

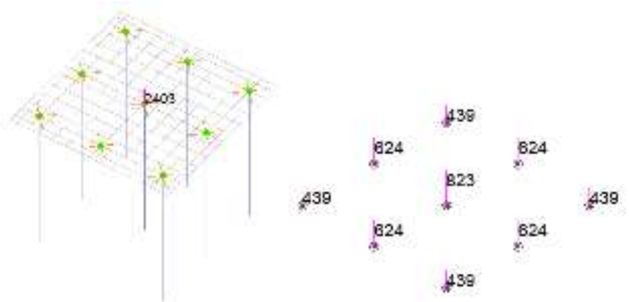

Fig. 2 Vertical loading of pile cluster, kN; vertical bracings of final stiffness and additional nodal loads *ΔNh*, kN;

3 PRELIMINARY ANALYSIS

The calculation of a single drill pile load capacity according to SP 24.13330.2011 was carried out in the program ZAPROS, included in the SCAD Office software. When entering the above parameters, the single pile settlement is s_1=4.46 mm, and the pile load capacity is F_d=393.87 kN. The maximum design load allowed to one pile with a safety factor γ_c=1.4 is

$$F_R = F_d / \gamma_c = 281.54 kN \,. \tag{1}$$

With the first limit state constant load on the foundation N_{0I}=2403.45 kN, the minimum amount of piles with a coefficient of 1.05, which takes into account piles and soil self-weight, must be, at least,

$$n = 1.05\, N_{0I} / F_R = 9 \,. \tag{2}$$

The width and length of the square base of the equivalent foundation according to the SNiP 2.02.03-85 p. 6.1. is 3.89 m. With the aim of preliminarily estimate the expected average settlement of a pile cluster, the depth of the compressible thickness is H_C = 6.05 m and the settlement S_C = 10,02 mm, as for a shallow foundation, can be determined in the ZAPROS program using the SNiP 2.02.03-85 method, knowing the dimensions of the base of the equivalent foundation. The width and length of the square base of the equivalent foundation according to the standard calculation method in SP 24.13330.2011 7.4.7 is 2.7 m.

4 FEM MODEL OF PILE CLUSTER

The first step to build a finite element model in SCAD, when the geometry is finished, is to set coefficients of soil reaction along the lateral surface of the piles in order to set their horizontal stiffness, which increases in depth. The horizontal influence of in-group piles is based on the works of V.G. Fedorovskiy, S.N. Levachev, S.V. Kurillo and Yu.M. Kolesnikov [3]. The horizontal earth backpressure along the lateral surface of piles within the framework of the study depends on the reduction coefficient α which is calculated with the empirical formula B.5 of SP 24.13330.2011. For the case under consideration, when neighboring piles are at the distance of 0.9 m from each other, the required coefficient of pile capacity reduction under horizontal loads along the X or Y directions is α = 0.05 due to essential mutual influence of piles in group.

Then, the coefficient values of soil reaction on the lateral sides C_z (Fig. 1) according to the Appendix B.2 of SP 24.13330.2011 are calculated according to the table of stiffness for different types of soils, which is borrowed from the work of KS. Zavriev, G.S. Shpiro, N.M. Glotov [4,5].

$$C_z = K \cdot z \frac{\alpha}{'\gamma_c} , \tag{3}$$

where K - the tabular value of the stiffness of the soil with horizontal back pressure on the lateral sides of the piles in the table. B.1 of SP 24.13330.2011; z - depth, from the surface of the earth, on which lateral reduction is calculated; $'\gamma_c$ - the coefficient of working conditions which in all cases has the value 3.

Within the second step of the calculation in SCAD the starting boundary conditions in vertical direction are assigned without taking into account the mutual influence of the pile group. The calculation of the preliminary vertical stiffness of the piles is made in accordance with clause 7.4.2. of SP 24.13330.2011.

The shear modulus G_1 of the soil layers cut by the pile is calculated on the basis of the averaged modulus of deformation E_1 and the averaged dimensionless Poisson ratio ν_1 for the layers cut by the pile:

$$E_1 = \frac{\sum_{i=1}^{rows(E)-1} E_i \cdot L_i}{\sum_{i=1}^{rows(E)-1} L_i} ; \quad \nu_1 = \frac{\sum_{i=1}^{rows(E)-1} \nu_i \cdot L_i}{\sum_{i=1}^{rows(E)-1} L_i} ; \tag{4;5}$$

$$G_1 = \frac{E_1}{2(1+\nu_1)} ; \quad G_2 = \frac{E_2}{2(1+\nu_2)} , \tag{6;7}$$

where E_i - the modulus of deformation of soil separate layers cut by the pile, MPa; L_i - the thickness of the soil layers cut by the pile, m; ν_i - Poisson's ratio of soil layers cut by the pile.

The modulus of deformation of the soil layers located under the pile, E_2, is taken as an averaged one within a depth equal to half the pile length 0.5L or equal to 10d of the equivalent pile diameters of the lower ends of the pile. Poisson's ratio v_2 is set according to the layer, which is located below the base of the equivalent foundation. Similarly, the shear modulus G_2 is calculated for the soil layers, which are located under the lower ends of the piles.

Finally, determining the average value of the Poisson’s ratio, it will be possible to calculate the initial vertical stiffness k_z (kN/m) of one-node elastic springs:

$$v = \frac{v_1 + v_2}{2}; \quad k_z = \frac{G_1 \cdot L}{\beta'}. \tag{8;9}$$

This one-node springs of final stiffness is assigned to all nodes of the lower ends of single piles cluster to simulate the interaction of foundation structures with the surrounding soil within the finite element method without taking into account the vertical mutual influence of the pile group, and is determined with already known variables. Additional settlement coefficient of the rigid pile $\beta=0.17ln[(k_vG_1L)/G_2d]=0.483$ is calculated with the use of the intermediate empiric coefficient $k_v=2.82\text{-}3.78v+2.18v^2$.

The significant excess of the launching value of the vertical stiffness k_z compared to the values C_1 in the SNiP method according to the Winkler model is explained by the fact that the final stiffness k_z decreases due to iterative improvement during the next stage. In the next stage, the vertical mutual influence of in-group piles calculated considering joint deformations in sediment conic funnel.

To start the iterative refinement calculation, the values of the coordinates of the lower nodes of the piles in the cluster and the values of the actual loads are necessary. This information can be displayed in the SCAD analysis postprocessor. In the postprocessor, where reactions in special elements could be visualized, the design model should be fragmented in the horizontal plane of the lower pile cluster. Thus, the vertical reactions R_z from loading combinations for the color scale of the visible fragment should be analyzed (Fig. 6, *d-f*).

5 ANALYTICAL MODEL

The first step, based on the coordinates of the lower nodes of the piles, is to form a matrix *a2* of the relative position of the piles in luster in the form of calculated distances between them. The size of the square matrix corresponds to the number of piles in the foundation [6]. Figures 3-5 show fragments of the calculation in SMath Studio of the mutual influence of piles in cluster.

A significant parameter is the limited radius of influence, beyond which there will be no mutual vertical influence between piles. This parameter is determined by the formula:

$$R_v = \frac{k_v G_1 L}{2G_2}. \tag{10}$$

The matrix *δ2* of the vertical mutual influence of the piles cluster, based on the matrix of the relative position of the piles *a2*, is calculated according to the theory of elastic half-space [7]. This is ensured by performing multiple calculations of each part of the matrix in accordance with the formulas of the SP 24.13330.20111 clause 7.4.4, where the coefficient of mutual influence of one pile on the other is set when a certain distance between them is exceeded.

Fig. 3. Calculation of the matrix a2 of the relative position of the piles and calculated values

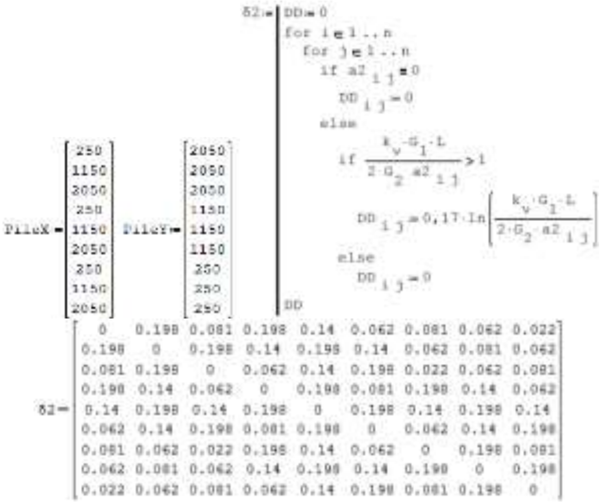

Fig. 4. Pile lower nodes coordinates in the XY plane; matrix of mutual influence between piles and the calculation algorithm.

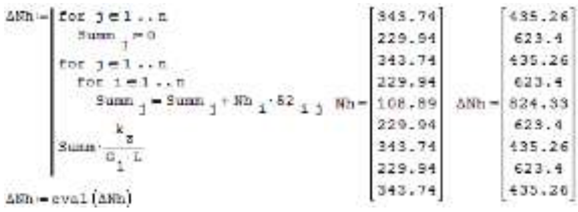

Fig. 5. Algorithm for calculating the additional loads of *ΔNh* to the preliminary loads on the lower nodes *Nh*.

The last step is to calculate the additional loads *ΔNh*, which is the sum of the vertical loads *Nh* and the additional settlements of the closely located piles, taking into account the coefficient of mutual influence

$\delta 2$. The resulting loads ΔNh should be transferred into each corresponding lower pile node in the SCAD design model. These additional loads are necessary for simulating ground base deformations in the form of a conical depression of a pile field consequently to the vertical mutual influence of neighboring piles. In the area where the largest number of piles is located, the additional settlements forming the deformation of the foundation will be greater. In the marginal areas of the cluster and, especially, in its corners, the concentration of piles will be less and the depth of the conical depression will be smaller.

6 CONCLUSION

Changes in the stress-strain state of the pile cluster foundation are shown in Figure 6 (*a-c*). The pile bending moments from constant impacts on the foundation and the effect of the margin pile could be seen (Fig.6, *d-f*), which was described by V.P. Petrukhin, S.G. Bezvolev, O.A. Shulyatev and A.I. Kharichkin [8].

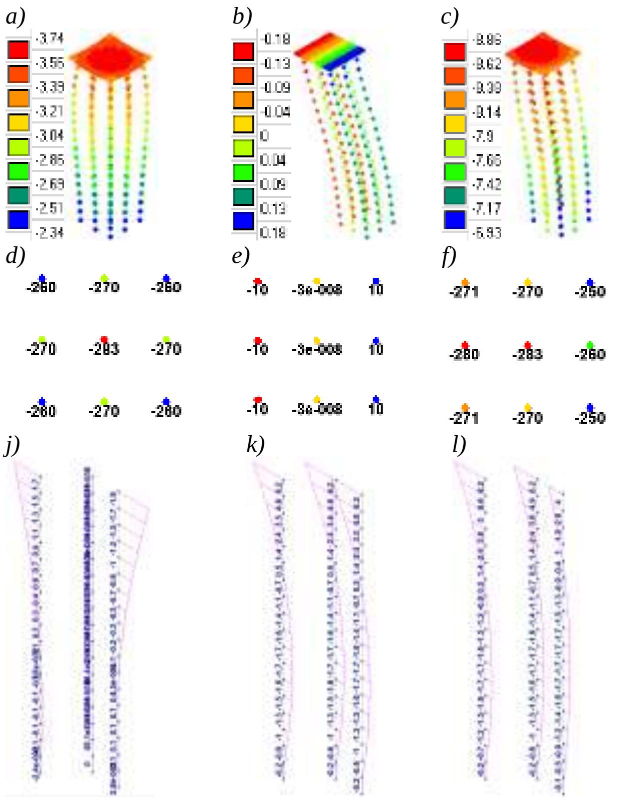

Fig. 6. The results of the calculation of the pile cluster in SCAD. *a* - vertical deformation of the nodes from the vertical impact, mm; *b* - vertical deformation of the nodes from the horizontal impact, mm; *c* - is the vertical deformation of the nodes from the total impact after the 3rd iteration, mm; *d-f* - efforts on the lower nodes of the piles from the vertical impact, only from the horizontal and total combination kN; *j-l* - projections of bending moments in piles from vertical impact, only from horizontal and total combination after 3 iteration, kNm.

When taking into account the horizontal temporary impact, the effect of margin pile does not disappear, but it decreases with the redistribution of stresses and the overlapping of projections from additional bending moments.

When accounting for the mutual vertical influence of piles in cluster, according to SP 24.13330.2011, the foundation sediment increases (Fig. 7). In the considered example, the increase was 29.27% from 2.54 mm to 8.37 mm. This settlement is comparable to a settlement of 10.02 mm according to SNiP 2.02.03-85, calculated during preliminary calculation in the ZAPROS as for the equivalent foundation settlement.

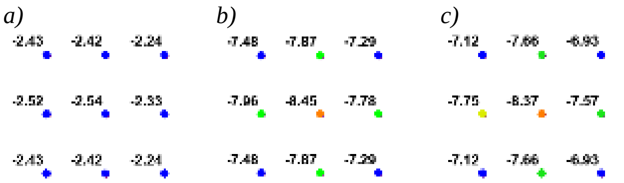

Fig. 7. The pile cluster calculation results in SCAD
a - the vertical displacements of the lower pile clusters from the group without taking into account the mutual influence of the piles, mm; b - vertical displacement of the lower pile clusters from the group taking into account the mutual influence of the piles, 1 iteration, mm; c - vertical displacement of the lower pile clusters from the group, taking into account the mutual influence of the piles, 3 iteration, mm.

REFERENCES

Perelmuter A.V., Slivker V.I. (2011) Design models of structures and the possibility of their analysis. 4th ed. SCAD SOFT Publishing House, Moscow, Russia, 418-445.

Nuzhdin, L. and Mikhaylov, V. (2018) Models and calculation methods of the pile foundation in SCAD Office. Geotechnical Hasards and Risks: Proc. of the XVI DECGE. European Conference on Geotechnical Engineering. V.2, Issue 2-3. Ernst & Sohn, ce/papers, 487-492.

Fedorovskiy V.G., Levachev S.N., Kurillo S.V., Kolesnikov Yu.M. (2003) Piles in hydraulic engineering. Publishing House DIA, Moscow, Russia, 198-207.

Zavriev K.S., Shpiro G.S., Glotov N.M. and other (1970) Recommendations for the calculation of the foundations of the deep foundations of bridge supports. Rotaprint ZNIIS, Moscow, USSR, 45-56.

Shapiro D.M. (2016) Theory and design models of bases and objects of geotechnics. Publishing House DIA, Moscow, Russia, 104-113.

Edigarov, G.E. (2015). Experience of using SCAD OFFICE in the calculation of the intermediate double-row pile bridge support, taking into account the mutual influence of piles in cluster. CADMASTER Journal, 88-97.

Tsudik E. (2013) Analysis of structures on elastic foundations. J. Ross Publishing, Florida, USA, 112-160.

Petrukhin V.P., Bezvolyev S.G., Shulyaev O.A., Kharichkin A.I. (2007) The effect of margin piles and its account when calculating the foundation. Urban development and geotechnical construction Journal (11), 90-97.