Characteristics of the plastic zones of the large-scale buildings soil foundation

D Chunyuk and N Kurilin

Moscow State University of Civil Engineering, Yaroslavskoe shosse, 26, Moscow, 129337, Russia

E-mail: kurilin93@gmail.com

Abstract. The particular scientific article contains the research of the form and adjustment of the plastic deformation zones, arising in the reactor building’s foundation, with due account of the nearby large-scale NPP buildings influence. The main feature of this research is the consideration of the stages of the ground foundation loading, modeling the process of the buildings construction. Four different versions of the most common sequences of loads were simulated in the calculations. The research was performed using the finite element method in nonlinear statement with application of the Mohr – Coulomb model. Based on the results of the calculation, the most favorable variant of the large-sized NPP buildings foundation was selected, also, was analyzed the form of the plastic deformation zones.

1. Introduction

The precise evaluation of the ground foundation and the large-sized NPP buildings interaction type is an important task affecting the nuclear power plants safety. Currently, there is a large number of the Russian and foreign authors researches over this topic, among that we can note the researches of V. B. Glagovsky [1, 2], K.E. Egorov [3, 4, 5], Yu.K. Zaretsky [6, 7, 8, 9] and many other scientists. But, despite this diversity of scientific researches, the accuracy of the large-sized NPP buildings with the ground foundation interaction forecast is not always acceptable. This factor is due to the predicting complexity over the following factors:

- transferred to the foundation large load;
- large loading area;
- the complexity of the construction phasing in the different NPP buildings construction sites (due to the different construction materials accessibility for each site).

All the above factors and other distinctive features of large-sized NPP buildings encourage the emergence of the ground foundation plastic deformation zones, different from the plastic deformation zones arising in civil and industrial construction. The plastic deformation zones are considered to be the stress concentration area under the edges of the foundations, which are more than ¼ of the width of the base and lead to the bearing capacity of the base loss. Based on the fact that the occurrence of zones of plastic deformation significantly affects the security of nuclear power plants, in this work will
be executed the research of the shape of the plastic deformations zones and maximal values of stresses arising in the base of the most loaded building in accordance with the influence of adjacent buildings with consideration to different variants of the buildings construction sequence. Researches to assess the impact of the shape and size of the foundation bottom over the development of the plastic deformation zones in the soil foundation performed A. V. Glushkov in his scientific works [10, 11, 12, 13]. The results of this work proved that the shape of foundation significantly affects the volume of plastic deformation zones therefore the researches performed in this article are relevant.

The location of the concerned buildings on the plan is presented in Figure 1. The main buildings of the nuclear island (hereinafter – BNI) are considered as the studied buildings: reactor building (hereinafter – RB); auxiliary reactor building (hereinafter – ARB) and turbine building (hereinafter - TB). The characteristics of the buildings are presented in Table 1.

![Figure 1. The scheme of the BNI location](image)

**Table 1. The characteristics of the BNI**

| Buildings   | ARB       | RB        | TB         |
|-------------|-----------|-----------|------------|
| Sized, [m]  | 66 × 60   | 78 × 72   | 101.2 × 60 |
| Concrete raft area, [m²] | 3960     | 5616     | 6072       |
| Loads, [kPa] | 300       | 550       | 320        |
| The bottom of the foundation slab, [m] | 0        | 0        | -0.6       |

**2. Methods**

The research is carried out in three dimensional formulation using a software package based on FEM-Plaxis 3D. This software package is developed to solve complex geotechnical problems and allows calculate the soil foundation in a linear and nonlinear formulation. The estimated area has a plan size of 400 × 200 meters and a depth of 80 meters. The boundaries of the computational domain are sufficient and do not affect the results of calculations. A general view of the finite element model is presented in Figure 2.
As initial data for engineering surveys of the operating object, and also values of stresses on the soil basis determined by means of converters of stresses of the soil established in the basis of the considered buildings were used. The transfer of pressure to the soil foundation is carried out with the use of an absolutely rigid foundation slab (the rigidity of the structure is due to the large thickness of the foundation slab). The physical-mechanical properties of soils presented in Table 2.

Table 2. Physical-mechanical properties of soils used in the calculation

| EGU | Type of soils                      | Specific gravity, $\gamma$ [kN/m$^3$] | Cohesion, $c$ [kPa] | Angle of internal friction, $\varphi$ [$^\circ$] | Young modulus, $E$ (MC) [MPa] | Young modulus with scale factor, $E$ (MC SF) [MPa] |
|-----|-----------------------------------|---------------------------------------|--------------------|-------------------------------------------------|-----------------------------|-----------------------------------------------|
| -   | Backfill soil                     | 16.5                                  | 0                  | 30                                              | 30                          | 30                                            |
| 7a  | Fine sands                        | 17.7                                  | 0                  | 32                                              | 37                          | 109.1                                         |
| 7b  | Medium sands                      | 17.7                                  | 0                  | 33                                              | 36                          | 106.2                                         |
| 9a  | Fine sands and medium sands       | 18.5                                  | 0                  | 22                                              | 60                          | 177                                           |
| 9b  | Coarse sands and gravelly sands   | 18.5                                  | 0                  | 29                                              | 30                          | 88.5                                          |
| 12  | Sandy loams                       | 19.7                                  | 100                | 12                                              | 40                          | 76.8                                          |
| 14  | Loams                             | 21                                    | 85                 | 6                                               | 20                          | 38.4                                          |
| 15  | Limestones                        | 25.3                                  | -                  | -                                               | 1300                        | 1300                                          |
| 16  | Mudstones                         | 19.1                                  | 64                 | 11                                              | 27                          | 51.84                                         |
The research is performed using an ideal elastic-plastic Mohr-Coulomb model taking into account the scale factor proposed by Yu.K. Zaretsky in the book [6], which corrects the soil deformation modulus at a loading area of more than 1000 m$^2$. The main feature of the Mohr – Coulomb model (more details about this model [14]) in comparison with the linear-elastic model is the possibility of transition of the soil to the plastic state, which is determined by the formula:

$$f = (\sigma_1 - \sigma_3) - (\sigma_1 + \sigma_3)\sin\varphi - 2\cos\varphi$$

The diagram of the dependence between stresses and strains used in the calculations according to the Mohr – Coulomb model is present in Figure 3.

**Figure 3.** Soil loading behavior in the Mohr-Coulomb model (black graph) versus natural soil behavior (gray graph)

The deformations obtained from the calculations carried out in this research correspond to the observed deformations of existing buildings, which confirms the possibility of using the Mohr – Coulomb model to determine the stresses in the soil mass. Also the correct use of the model Mohr – Coulomb confirmed by the analysis of the calculated settlements NPP reactor building received by various methods in comparison with the results of field observations of rainfall in article [15].

The ground water level (GWL) is located 23 meters below the bottom foundation slab, so this research will not take into account the influence of excessive pore pressure in the stress concentration areas under the edges of the NPP large-sized buildings. The ultimate stress of the soil mass (design strength of the base soil), as a result of which the plastic deformation zones arise, is determined by the formula I, PiNAE-5.10-87:

$$R = \frac{\sin\varphi}{M} \cdot \gamma_{II} \cdot Z_{max} + \left(1 + \frac{\sin\varphi_{II}}{M}\right) \cdot \gamma'_{II} \cdot d_1 + \frac{\cos\varphi_{II}}{M} \cdot c_{II}$$

(1)

Based on the results of the calculation according to the above formula defined the soil design strength value, arising in the RB’s foundations above which appear the plastic deformation zones, posing a danger of the foundation bearing capacity loss (if $R_{max} \geq 1400$ kPa) at a depth less than six meters from the bottom of the foundation slab. The research of the NPP large-sized buildings construction phasing effect on the plastic deformation zones behavior will be carried out in four variants. These variants correspond the main sequence of base loading.

In the first variant, the loading of all NPP large-sized buildings is carried out jointly, the order of loading used in the other variants is presented in Table 3.
Table 3. Variants of phasing loading of the base of large-sized buildings of NPP

| Variant | 1/1   | 1/2   | 1/3   | 1/4   | 1/5   |
|---------|-------|-------|-------|-------|-------|
|         | ARB   | RB    | TB    | ARB   | RB    |
|         | Percentage of full load, % (load [kPa]) | Percentage of full load, % (load [kPa]) | Percentage of full load, % (load [kPa]) | Percentage of full load, % (load [kPa]) | Percentage of full load, % (load [kPa]) |
| 2/1     | 0 (0) | 20 (110) | 0 (0) | 20 (64) |
| 2/2     | 20 (60) | 40 (220) | 20 (128) |
| 2/3     | 40 (120) | 60 (330) | 40 (128) |
| 2/4     | 80 (240) | 80 (440) | 60 (192) |
| 2/5     | 100 (300) | 100 (550) | 100 (320) |
| 3/1     | 0 (0) | 20 (110) | 0 (0) | 20 (64) |
| 3/2     | 20 (60) | 40 (220) | 0 (0) |
| 3/3     | 80 (240) | 60 (330) | 0 (0) |
| 3/4     | 100 (300) | 80 (440) | 40 (128) |
| 3/5     | 100 (300) | 100 (550) | 100 (320) |
| 4/1     | 0 (0) | 20 (110) | 20 (64) |
| 4/2     | 0 (0) | 40 (220) | 60 (192) |
| 4/3     | 0 (0) | 60 (330) | 60 (192) |
| 4/4     | 40 (120) | 80 (440) | 60 (192) |
| 4/5     | 100 (300) | 100 (550) | 100 (320) |

3. Results

According to the results of calculations, stress values in the RB building base were obtained, taking into account the influence of ARB and TB buildings in different loading variants. Stresses exceeding the soil design strength ($R_{\text{max}} \geq 1400$ MPa) on a depth less than 6 meters below the slab bottom form the plastic deformation zone, which general form is shown in Figure 4 (on the example of the loading variant № 1).

![Figure 4](image-url)

**Figure 4.** Type of plastic deformations zones of at the 1 variant of loading (joint loading of the soil foundation)
When determining the maximum values of stresses in the plastic deformations zones of the RB buildings foundation was revealed the restriction of the stress values and the loading variant (watch Table 4).

| Variant 1 | Variant 2 |
|-----------|-----------|
| 1          | 2          |
| 2.6        | 4.3        |
| 2          | 3          |
| 4          | 2          |

*Information over the numbering of the RB building corners is presented in Figure 1.*

Apart from the above data, important information is the order of the plastic deformations zones change arising in the place of the RB building foundation slab bottom and the soil foundation contact. The area and percentage of plastic deformations zones arising of the RB building foundation slab bottom are presented in Table 5.

| Variant 1 | Variant 2 | Variant 3 | Variant 4 |
|-----------|-----------|-----------|-----------|
| 1          | 2          | 3          | 4          |
| 1560       | 1496       | 1458       | 1492       |
| 27.8 %     | 26.6 %     | 26.0 %     | 26.6 %     |

The information presented in Table 5 allows us to conclude that the smallest area of plastic deformation zones arising from the building pressure and allowing for the order of the base loading by nearby large-sized buildings is obtained in the loading variant № 3, as well as the lowest values of maximum stresses. In addition, it is necessary to pay attention to the location of plastic deformation zones in the plan of the RB building foundation slab bottom (watch Figure 5). These zones, located on the RB building perimeter occupy more than 25% of the bottom slab and soil foundation contact. These areas should be considered mandatory when performing the calculations of the building over the soil foundation shear.
Figure 5. Type of zones of plastic deformations arising in the plan of the base slab bottom

4. Discussion

In this work, as in the previously published [15], the correctness of the Mohr – Coulomb model use was confirmed, taking into account the scale factor when performing calculations of the NPP buildings with the ground base interaction (calculated precipitation of NPP buildings have good convergence with the observed ones). Thanks to the correct modeling of this problem using Mohr – Coulomb model have been obtained parameters of the plastic deformations zones in the reactor building base, applying different order of concerned and nearby buildings construction. The total volume and shape of these zones allows us to make a conclusion about the complex nature of the large-sized NPP buildings with the soil foundation interaction.

5. Conclusions

As the results of the calculations was determined are form of plastic deformation zones arise of the reactor building foundation and the character of zones changing in different variants of the RB and the ARB and the large-sized NPP building construction order.

According to the results of the analysis, the smallest dimensions and maximum stresses occur in the plastic deformation zones in variant № 3, which concludes the initial loading of the soil foundation with loads from the ARB and RB buildings and the subsequent construction of the TB building.

In addition, during the research of plastic deformation zones area over the contract: foundation slab-RB building soil foundation, it was concluded that it is necessary to exclude these zones when calculating the building shear load.

Acknowledgments
This study was performed with the financial support of the RF Ministry of Education and Science, President Grant #NSh-3492.2018.8.
References

[1] Glagovsky V B, Evnevich A A and Shifrin G M 1991 About calculation of foundation slab on the heterogeneous soil base taking into account creep of soil (Saint – Peterburg: J. Izvestiya VNIIG im. B V Vedeneeva Vol. 223) pp 81-84
[2] Glagovsky V B, Zalizsky A G, Kagan A A, Krivonogova N F and Finagenov O M 2005 Analysis of settlements and tilts of the foundation reactor building Balakovo NPP (Moscow: J. The bases, foundations and soil mechanics Vol. 4) pp 17-22
[3] Egorov K E and Sokolov N S 1985 Characteristic of deformations of the foundation reactor building NPP (Moscow: J. The bases, foundations and soil mechanics Vol. 4) pp 14-17
[4] Egorov K E 1979 Experience of observation deformation bases of the buildings and constructions (Moscow: J. Foundation engineering Vol. 5), pp 9-11
[5] Egorov K E 1958 About deformation of finite thickness (Moscow: J. Collections of works NIIOSP) pp 5-33
[6] Zaratskii Yu K and Garitselov M Yu 1989 Deep Soil Consolidation by Impact Loadings (Moscow: Energoatomizdat) p 193
[7] Zaratskii Yu K and Lombardo V N 1983 Static and dynamic of the ground dams (Moscow: Energoatomizdat) p 135
[8] Zaratskii Yu K and Hakimov R H 1973 Dependence of settlement wet soil in time on the stamp area (Moscow: J. The bases, foundations and underground structure № 62) pp 21-27
[9] Zaratskii Yu K and Orekhov V V 1983 Stress-strain state of the soil base under the action of a rigid strip foundation (Moscow: J. The bases, foundations and soil mechanics Vol. 5) pp 21-24
[10] Glushkov A V, Glushkov V E and Bartlomiej L A 2013 Analysis of stress-strain state of foundations complex shape (Voronezh: Mat. of scien. and tec. Conf. with int. parti. Innovative designs and technologies in Foundation construction and geotechnics - Paleotip) pp 146-151
[11] Glushkov A V and Glushkov V E 2014 Influence of strength and deformation characteristics of soil on the stress-strain state of the bases foundations complex shape bottom (Cheboksary: Proc. of the VIII all-Russian (II Int.) conf. NASCR-2014 ChSU) pp 346-351
[12] Glushkov A V, Glushkov V E and Bartlomiej L A 2013 Influence of the h foundations on the stress-strain state of the base (Yoshkar-Ola: Mat. of the int. scien. and prac. conf. "Actual problems of construction and road complex" PSTU) pp 112-116
[13] Glushkov A V and Glushkov V E 2015 Stress-strain state of the bottom bases foundations complex shape (Penza: J. Modern problems of science and education № 2) pp 122 - 128
[14] Atkinson J H and Bransby P L 1978 The Mechanics of Soil (London: McGraw-Hill Book Company) p 375
[15] Kurilin N and Chunyuk D 2018 Comparative evaluation of the use of various codes when performing the calculation total settlement of the reactor building nuclear power plants in cohesive soils (SGEM 2018 Conference proceedings Volume 18) pp 145-152