Influence of the enclosing structure of a trench-type wall in the ground on the heeling of a high-rise building on a raft foundation

V V Znamenskii¹ and A Ganbold²,³

¹ Department of Soil and Geotechnical Engineering, Moscow State University of Civil Engineering, Moscow, 129337, Russia
² Mongolian University of Science and Technology, Ulaanbaatar, 14191, Mongolia
³ Adiyajav1020@gmail.com

Abstract: This article presents the results of studying the influence of the enclosing structure of the pit, made according to the technology of the reinforced concrete wall in the ground of the trench type, on the heeling of a high-rise building on a raft foundation. The study was performed using the numerical method with the PLAXIS 2D software package. The influence of the wall in the ground on the building roll was determined depending on the distance from the wall in the ground to the edge of the raft foundation of the building, the embedding depth of the wall in the ground below the bottom of the excavation and the characteristics of the contact element. The degree of influence of each of these factors on the heeling of the raft foundation was determined by the factor analysis based on the theory of experimental planning. The mosaics of deformations of the soil massif at the base of the raft foundation are given, as well as graphs of the dependence of the change in heeling for the considered factors of influence. According to the study results, the boundaries of the significant influence of each of the factors considered, as well as the walls in the ground as a whole on the heel of the building are determined. The issues are discussed on applications of the study results to reduce the heeling of high-rise buildings at the design stage.

1. Introduction
The stress-strain state (SSS) of the base soils of raft foundations of high-rise buildings with a developed underground part depends on a number of factors, one of which is the use of pit fences with the technology of a wall in the ground trench. Many foreign and domestic scientists and specialists have studied this topic – Shulyatiev et al (2012), Galyamichev (2015), Vlasov et al (2018), Leung et al (2004), Korchak and Moroz (2010), Sirozhiddinov (1992), Lemmen et al (2017), Paramonov and Slivets (2008), Xiangfu (2011), Viggani (2011), Van Impe (1991), Lv et al (2017), Mirsayapov and Safin (2011), Trushko and Kutyavin (2018) [1 to 20]. Experimental and theoretical studies have shown that the presence of an enclosing structure of this type can cause a redistribution of the foundation plate sediment and an additional heeling of a high-rise building. The reason for this is an increase in horizontal stresses acting in the soil mass next to the wall in the ground and leading to an increase in the vertical modulus of the soil deformation in this zone, and the friction force of the soil on the side surface of the wall in the ground. According to the available scattered information, the effect of the enclosing structure on the stress-strain state of the soil base of the raft foundation may depend on its...
depth, the distance from the edge of the raft foundation, the method of construction, dimensions and loads from the structure, the construction method of the underground part, etc. This effect, as shown by the analysis of a number of numerical and experimental studies, can be significant, but this issue has not been specially investigated. This was the reason for carrying out further more detailed studies of the influence of the wall in the ground on the heeling of high-rise buildings in a fairly wide range of changes in the factors influencing it.

2. Materials and methods
The study of the influence of the pit fence on the deformation of the raft foundation base depending on various factors was carried out using the Plaxis 2D software package (Plaxis, Users Manual). The design scheme of the problem being solved is shown in figure 1, the breakdown of the finite element mesh and the boundary conditions are in figure 2. Fixed supports are installed on the sides and bottom of the calculation area. Sandy soil was modeled by the Hardening soil model. The raft foundation and the wall in the ground were modeled as a linear elastic material, the contact element was installed between the wall in the ground and the ground to simulate the friction forces in accordance with the Hardening soil model. The calculated parameters of the soil and reinforced concrete are shown in table 1.

| Properties                              | Raft foundation | Slurry wall | Sand     |
|-----------------------------------------|-----------------|-------------|----------|
| Saturated unit weight, $\gamma_{sat}$ (kN/m$^3$) | 25              | 20          | 17       |
| Modulus of elasticity $E$, (kPa)       | $3\times10^7$   | $3\times10^7$ | 20.6     |
| Poisson’s ratio of soil, $\nu$         | 0.2             | 0.2         | 0.3      |
| Friction angle at the critical state, $\phi'$ | -               | -           | 28°      |
| $K_o = \nu/(1-\nu)$                    | -               | -           | 0.53     |
| The initial void ratio, $e_o$          | -               | -           | 0.54     |

Table 1. Summary of material properties used in the numerical analysis.
The influence of the wall in the ground on the heeling of the building was determined depending on the following factors:

- factor $m = b / B_{raft} \in [0.1; 0.3; 0.5]$ is the relative distance from the fence to the nearest edge of the raft foundation;
- factor $t = h_{emb} / B_{raft} \in [0.53; 0.66; 0.8]$ is the relative depth of the embedment of the fence below the bottom of the pit;
- factor $R_{int} \in [0.2; 0.5; 1.0]$ is the coefficient of friction concrete and soil.

Where:

- $B_{raft}$ is width of the raft foundation
- $h_{emb}$ is the depth of embedment of the wall in the ground below the bottom of the pit
- $R_{int}$ is the coefficient of friction concrete and soil
- $b_i$ is the distance between the wall in the ground and high-rise building.

In this calculation, the heeling of high-rise buildings is determined by the formula (1)

$$i = \frac{S_1 - S_2}{B_{raft}} \leq 0.002$$  \hspace{1cm} (1)

where $S_1$, $S_2$ are the movement of extreme points 1, 2 of the raft foundation.

3. Results and Discussion

Mosaics of deformations of the ground mass caused by the loading of the foundation at different values of the factors $m$, $t$, and $R_{int}$ are shown in figure 3 to 5, indicating the heeling of the raft foundation. The values of the high-rise building heeling exceeding the maximum permissible values in accordance with the recommendations of SP 22.13330.2016 are highlighted with red.
Figure 3. Mosaics of soil mass deformations at t=0.53.

Figure 4. Mosaics of soil mass deformations at m=0.3.
Figure 5. Mosaics of soil mass deformations at Rint=0.5.

Figures 6 to 8 show graphs of the dependence of the foundation plate rolls on the factors considered.

Figure 6. Graphs of the dependence $i = f(m)$ for different values of the “$R_{int}$”: (a) factor $t=0.53$, (b) factor $t=0.8$. 
The results of assessing the degree of influence of each of the factors considered on the heeling of the raft foundation, performed by the factor analysis based on the theory of the experiment planning, are shown in the form of diagrams in figure 9.

According to the performed assessment, the greatest influence on the heeling of the raft foundation of a high-rise building is the relative distance from its corner to the pit fence. To a lesser extent, this
effect depends on the value of the coefficient of friction of the soil on concrete and the relative depth of embedment of the fence into the ground below the bottom of the excavation.

Summary data on the value of the raft foundation heeling depending on the factors considered are given in Table 2.

**Table 2.** The value of heeling of the raft foundation, depending on the factors considered.

| m=0.1 | m=0.3 | m=0.5 |
|-------|-------|-------|
| t=0.53 | t=0.66 | t=0.8 | t=0.53 | t=0.66 | t=0.8 | t=0.53 | t=0.66 | t=0.8 |
| Rint=0.2 | 0.00129 | 0.00131 | 0.00182 | 0.00017 | 0.00026 | 0.00088 | 0.00004 | 0.00011 | 0.00034 |
| Rint=0.5 | 0.00182 | 0.00194 | 0.00248 | 0.00044 | 0.00055 | 0.00126 | 0.00030 | 0.00031 | 0.00063 |
| Rint=1.0 | **0.00216** | **0.00221** | **0.00272** | 0.00048 | 0.00061 | 0.00131 | 0.00032 | 0.00039 | 0.00068 |

The results of the study showed that the pit fence made using the wall in the ground technology of the trench type, under appropriate conditions, can have a significant effect on the heeling of a high-rise building on a raft foundation. As shown by the factor analysis, the greatest influence of the raft foundation on the heeling belongs to its distance from the pit fence, characterized by factor m. According to the graphs in figure 9 and table 2, which contain the generalized results of the calculations, the influence of factor m increases with an increase in the depth of the fence in the ground below the bottom of the pit, characterized by factor t, and an increase in the coefficient of friction between the ground and the concrete of the fence, characterized by the Rint factor. In the calculations performed, the maximum value of the building heeling was obtained when the distance of the foundation from the fence was 1.0 m (m = 0.1), the coefficient of friction between the ground and concrete was equal to the coefficient of friction of the ground (Rint = 1.0) and the depth of the fence in the ground below the bottom of the pit is 8.0 m, i.e. 0.8 of the width of the foundation plate (t = 0.8). The heeling of the building in this case was i = 0.00272, which exceeded the limit value, according to the recommendations of the Norms. With a decrease in the friction forces between the concrete and soil to Rint = 0.2 with the values of factors m and t remaining unchanged, the heel decreased to i = 0.00182, i.e. decreased by 49.5%. With a decrease in the embedment depth of the fence into the ground to 5.3 m (t = 0.53), the roll decreased to i = 0.00216, i.e. decreased by 25.9%.

The influence of the friction coefficient between the soil and concrete on the heeling of the foundation, characterized by the coefficient Rint, is less than the influence of factor m. To the greatest extent, it is manifested at a small distance between the foundation and the fence of the pit, slightly increasing with the increase in the embedding of the fence in the ground (figure 7).

The depth of embedding of the fence in the ground, characterized by the factor, has a slightly smaller effect on the foundation heeling. This influence decreases with an increase in the distance between the fence and the edge of the foundation and increases with an increase in the coefficient of friction between the wall and soil (figure 8).

4. Conclusions
The study confirmed the well-known fact of the influence of the pit fence in the form of a monolithic reinforced concrete wall in the ground of a trench type on the stress-strain state of the soil massif at the base of the raft foundation of a high-rise building, which, in particular, under certain conditions can lead to a significant change in its inclination. The fact of the influence of the pit fence on the building heel on the raft foundation and the dependence of this influence on the distance of the edge of the raft foundation to the fence, the depth of the fence in the ground below the bottom of the pit and the coefficient of friction of the soil on the concrete can be used to solve the following problems:
- leveling the uneven deformations of the soil at the base of the raft foundation
- leveling of the roll of the foundation plate caused by uneven or displaced (in terms of the load on it) or heterogeneous geological strata
- leveling the sediment and changing the foundation heeling can be achieved
- changing the distance of the slab foundation from the fence

Table 2. The value of heeling of the raft foundation, depending on the factors considered.
- changing the embedment of the fence into the ground below the bottom of the pit
- changing the frictional forces between of the foundation soil and the concrete of the fence, which depends on the material of the surface of the wall in the ground and its manufacturing technology (protected by a bentonites solution or with a polymer).

According to the data given in the work of O.A. Shulyat'va (2020) [3], in the case of a pit fence under the bentonite mortar, a decrease in the inclination is observed, and if the wall in the ground is performed under the protection of a polymer solution having an increased (by 30%) resistance by the contact concrete - soil increase. According to the same data, the reduction of the friction forces along the lateral surface of the wall in the soil can be achieved by covering it with a metal sheet.

For the conditions of the study (the non-cohesive soil with certain physical and mechanical characteristics, a given pit depth, dimensions of the raft foundation and the load acting on it), the maximum distance of the effective use of the wall in the ground to regulate its effect on the heeling of the raft foundation was about 6.0 m (0.6 B_{nfa}). And the greatest efficiency is achieved with a distance to the fence of the order of 2.0 m, which, however, is typical for most design cases.

References
[1] Shulyatiev O A, Pospelkov V S and Shulyatiev S O 2012 from the practice of design of an enveloping structure and a foundation plate of administrative complex of buildings with a four-level underground parking lot Housing construction 9 50–3
[2] Shulyatiev O A, Lesnitskiy V S and Shulyatiev S O 2015 Foundations for buildings and structures with load eccentricity Patent RU 152014
[3] Shulyatiev O A 2020 Soil and foundation of high-rise building (Moscow: ASV)
[4] Galyamichev A V 2015 The specifics of determining loads on the building envelope and its effect on the results of static analysis Naukovedenie 4
[5] Ganbold A and Znamenskii V V 2020 The influence of changes the stiffness of foundation slabs on the stress-strain state of the foundation soil Science prospects 7 (130) 69–75
[6] Znamenskii V V and Hegazy O M 2019 A comparative study of ordinary piles and superlong piles in consolidating soil IOP Journal of Physics: Conference Series 1425 12071
[7] Xiangfu C 2011 Settlement calculation on high-rise building (Science Press Beijing and Springer)
[8] Kewei Ding and Chen Li 2016 Elastic-plastic time history analysis on the super-high business-living building in hefei Advances in Engineering Research 72 178–8.
[9] Skorikov A V, Razvodovskiy E I, Kolybin V and Starshinov A A 2006 Behavior of plate foundation in deep excavation beneath 32-storey building in Moscow Geotechnicalaspects of underground construction in soft ground pp 907–13
[10] Mirsayapov I T and Safin D R 2011 Experimental surveys of deflected state of soil body consistent with rabbet in the process of graded excavation of ditch Izvestia KGASU 3 (17)
[11] Lemmen H E, Jacobsz S W and Kearsley E P 2017 The influence of foundation stiffness on the behaviour of surface strip foundations on sand Journal of the south African institution of civil engineering 59 19–27
[12] Korchak A V and Moroz A I 2010 Experimental studies of the influence of load on the stability of the boiler side fencing Mining information and analytical bulletin. MGGU 8 7–14
[13] Van Impe W F 1991 Deformation of deep foundation Proc. of the 10th European Conf. on Soil Mechanics and Geotechnical Engineering pp 1021–62
[14] Lv Y R et al 2017 Geometric effects on piles in consolidating ground: centrifuge and numerical modeling Geotechnical and Geoenvironmental Engineering 143,9: 04017040
[15] Sirozhiddinov Z 1992 Bearing capacity of driven piles in sandy soils by characteristics of resistances and their variability Ground, foundations and soil mechanics 5 14–7
[16] Vlasov A N, Korolev M V, Znamencik and V V Korolev P M 2018 The use of pressed piles when constructing the foundations of buildings and structures erected near potentially dangerous landslide slopes Science and Business: Development Paths 6 (84) 52–9
[17] Leung C F, Liao B K, Chow Y K, Shen R F and Kog Y C 2004 Behavior of pile subject to negative skin friction and axial load Soils and Foundations 44(6) 17–26
[18] Viggani C, Mandolini A and Russo G 2011 Pile and pile foundation (London: Spon Press)
[19] Paramonov V N and Slivets K V 2008 Experimental control of some non-liner soil models for calculation of retaining walls Vestnik TGASU 4 139–46
[20] Trushko O V and Kutyavin D V 2018 The construction of fore shaft in the conditions of highly deformable subsoils during the construction of a multi-storey business center, taking into account the stability of standing close the buildings and structures The Eurasian Scientific Journal 1(10) 118