



Research paper

Ground settlement and estimation of maximum settlement value in adjacent foundation pit excavation

Yan Wu¹

Abstract: The excavation of adjacent pits following the initial foundation pit excavation can significantly influence ground settlement. Using a foundation pit excavation project in Changzhou as a prototype, this study employed the numerical simulation method in conjunction with the HSS model to analyze the settlement deformation characteristics of the original excavation and compare them with the recorded monitoring values. In this study, the analysis focused on the ground settlement between two pits by varying the spacing between them at different excavation depths. The findings revealed that the ground settlement does not exhibit a significant increase when the new pit is excavated at a shallow depth. However, it rapidly increases when the excavation depth of the new pit surpasses that of the existing pit. Furthermore, an increase in the distance between the two pits causes the maximum settlement position to shift towards the edge of the new pit. The maximum ground settlement is found to have a linear relationship with both the maximum horizontal displacement of the two pits and the spacing between them.

Keywords: double foundation pit, numerical simulation, maximum settlement position, maximum settlement

¹M.SC., Eng., Changzhou University Huaide College, Architecture and Environmental Engineering Department, Tiaozhou, Jiangsu, China, e-mail: 90001714@cczu.edu.cn, ORCID: 0000-0003-3830-4272

1. Introduction

After excavation, foundation pits can induce ground settlement in the surrounding area. Severe ground settlement can result in road collapse, posing a significant threat to human lives and property [1]. Scholars have extensively researched the excavation of individual foundation pits using theoretical analysis [2], model experiments [3], numerical simulations [4–7], and field monitoring [8–11], yielding fruitful outcomes [12–16]. These studies indicate that during foundation pit excavation, the movement of the inner soil mass alters the active and passive earth pressures on the inner and outer sides of the retaining structure. The retaining structure of the foundation pit undergoes horizontal displacement towards the inner side of the pit due to the active earth pressure exerted by the outer soil mass. Simultaneously, as the outer soil mass shifts towards the inner side of the pit, voids develop in the outer soil layers, leading to ground settlement. Various support structures generate diverse settlement patterns. Triangular, parabolic, and exponential settlements are the most prevalent types, supported by ample engineering field monitoring experience [17, 18]. Conversely, the combination of self-weight unloading of the upper soil during excavation and the compression of the outer soil mass into the pit creates a discrepancy in soil pressure between the inside and outside of the pit bottom, potentially resulting in uplift of the pit bottom.

Nevertheless, the construction process frequently encounters a challenge of adjacent foundation pits due to the scarcity of available land in urban areas [19]. Xinhai Zhang [20] et al. considered factors such as deformation of the foundation pit support structure, distance between the tunnel and the foundation pit, and excavation depth of the foundation pit. They analyzed the confining pressure of the adjacent shield tunnel, the values of bending moment and shear force, and the axial force at the top and bottom of the tunnel's segment ring. The results indicated that when the distance between the foundation pit and the tunnel is close, the interaction between them is more significant. Chen et al. [21] conducted a monitoring study on a group of foundation pits located in coastal soft soil areas. They observed that the excavation of nearby pits resulted in reduced lateral deformation of the original pit, whereas the excavation of the original pit had minimal impact on the columns of the new pit. In a similar vein, Zeng et al. [22] investigated the performance of two adjacent soft soil foundation pits in Shanghai. They discovered a close correlation between the maximum ground settlement between the pits and the deformation of the foundation pit, which was attributed to the interaction between excavations. Hou et al. [23] analyzed the influence of dual foundation pit excavation on their respective deformation characteristics and proposed the utilization of sectional excavation. Ye et al. [24] examined the deformation characteristics of adjacent foundation pit excavations, taking into account factors such as excavation sequence, distance between the pits, and support methods. They identified the primary factors influencing foundation pit deformation. Chen [25] explored the coupling effect of dual foundation pit excavations through a case study involving deep foundation pit support in Kunming, establishing the lower limit of the coupling effect. These studies have provided insights into the mechanical performance and stress of adjacent foundation pits. However, they have not presented a calculation method for determining the maximum settlement between adjacent foundation pits. Moreover, when there are roads between two foundation pits, the monitoring of ground settlement can be impeded by vehicular

and pedestrian traffic, necessitating the development of a calculation method for ground settlement. The article centers on an excavation engineering project and the excavation model of a neighboring subway station in Changzhou City. It employed numerical simulation methods to investigate the settlement characteristics surrounding a single excavation and validated the precision of the model. Subsequently, a two-dimensional geometric model was constructed to assess the impact of varying excavation depths and pit spacing on ground settlement between adjacent pits. An empirical formula was derived for estimating the maximum ground settlement between the two pits. The findings of this analysis serve as a foundation for the design and monitoring of adjacent pit projects.

2. Generalization of foundation pit engineering

2.1. Brief introduction of the project and surrounding conditions

This project is located at the intersection of Longcheng Avenue and Jinling Middle Road in Changzhou City. It is bounded by Longcheng Avenue on the north, Huishan South Road on the west, Jinxiu Road on the south and Jinling Middle Road on the east. The pit area is about 134000 m² and the perimeter is about 1550 m. The excavation depth on the east side of the pit is 12.6 m. The excavation depth of the adjacent subway pit is 18 m. There are communication lines, water supply pipes, gas pipes and gas pipelines and residential areas around the pit. The ground condition of the pit is complicated. The specific location and surrounding environment of the twin foundation pit can be seen in Figure 1.

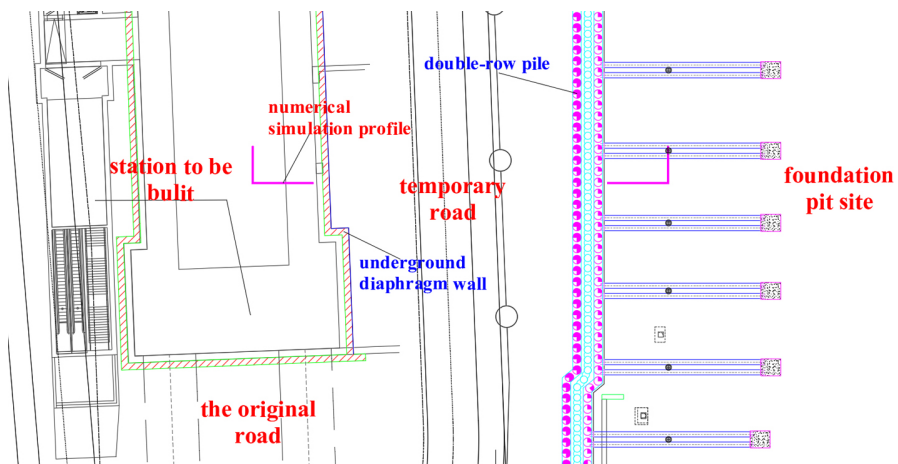


Fig. 1. Surrounding environment of foundation pit

2.2. Numerical simulation of foundation pit

The numerical simulation of the foundation pit used PLAXIS software, and the HSS model was adopted for the analyses. The upper part of the original foundation pit was excavated by 3 m of slope release and supported by soil nail wall. The slope surface layer was paved with a 60 mm thick fine stone concrete, and the soil nails were made of steel bars with a diameter of 14 mm. The lower part of the excavation is 9.6 m and is supported by a 1 m thick diaphragm wall. A diagonal brace and column were set at the top of the underground diaphragm wall. The diagonal bracing adopted double-hinged steel pipes with dimensions of 609×16 mm, and the columns were made of drilled and cast-in-place piles with a diameter of 700 mm. The soil was left in the pit and set to a certain slope. The double-row pile support system was employed in Figure 1. In the numerical model, it was equivalently represented as an underground continuous wall with a thickness of 1 m, based on the principle of equal stiffness. The adjacent subway pit was 38 m away from the original pit, with a depth of 18 m and a width of 13 m. The subway pit was supported by a 0.8 m thick diaphragm wall, and a support was set at 0 m, 5 m, 10 m and 15 m respectively. Different working conditions were as follows:

- Condition 1 – the original foundation pit is excavated with height of 3 m;
- Condition 2 – the original foundation pit is constructed with underground diaphragm wall. 9.6 m of retained soil is excavated, and internal supports and columns are set;
- Condition 3 – construction of new foundation pit diaphragm wall and setting the first internal support and excavation to 5 m;
- Condition 4 – new foundation pit with the second internal support and excavation to 10 m;
- Condition 5 – new foundation pit with the third internal support and excavation to 15 m;
- Condition 6 – new foundation pit with the fourth internal support and excavation to 18 m.

The soil parameters for the construction project were determined based on the findings of the geological survey report. Table 1 presents the parameter information of the soil layers, which corresponds to Figure 2.

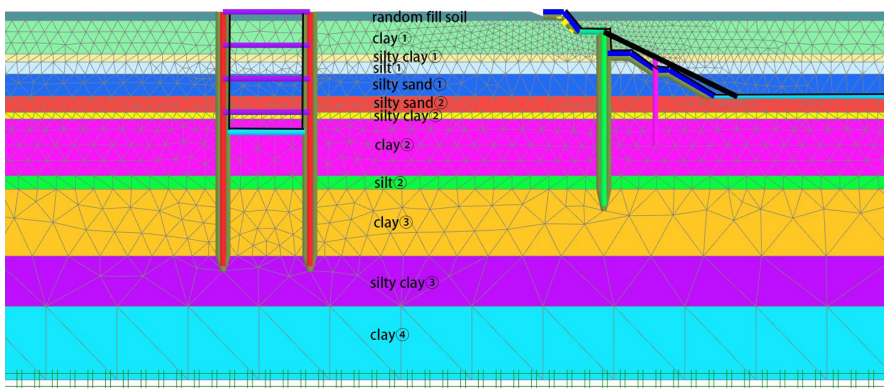


Fig. 2. Excavation model of adjacent double foundation pit

Table 1. Soil layer information

Soil layer	Depth (m)	bulk density (kN/m ³)	Cohesive force (kN/m ²)	internal friction angle (°)
random fill soil	1.3	17.50	20	10
clay?	6.2	19.5	60	12
silty clay?	7.5	19	31	18
silt?	9.3	18.7	15	25
silty sand?	12.6	18.9	10	30
silty sand?	15.0	19.4	10	33
silty clay?	16.0	19.5	50	15
clay?	24.5	19.7	57	16
silt?	26.5	18.7	16	23
clay?	36.5	18.8	67	15
silty clay?	44	19.5	52	13
clay?	55	19.8	69	16

3. Ground settlement law of existing foundation pit excavation

The foundation pit causes ground settlement in the surrounding soil after excavation. In Figure 3–5, d represents the distance from the settlement point to the edge of the excavation pit, while H represents the depth of the excavation pit. The symbol δ denotes the ground settlement value, and δ_{\max} represents the maximum ground settlement value. As can be seen in Figure 3, the settlement of the surrounding soil shows a parabolic distribution at both stages of the slope release excavation and the soil retained support. After the excavation of 12.6 m, the soil retaining support is carried out. The Figure 4 depicts the zoning map illustrating the impact of soil settlement. From the graph, it can be found that the main affected area of foundation pit settlement is within 6.3 times of the excavation depth. At 90 m from the pit there is still a relatively small amount of ground settlement.

According to the excavation monitoring report, this study specifically examines the road settlement monitoring point situated at a distance of 9.5 meters from the edge of the excavation support structure. The monitoring period encompasses the entire process from the excavation of the foundation pit to the retained soil and support stage, with a duration of 120 days. According to Figure 5, it is evident that the simulated values obtained using hardened parameters are higher than the monitored actual values. Specifically, during the slope excavation stage, the

disparity between the two is less than 1 mm. However, during the soil retained and support stage, this difference increases to 18.5 mm. This variation can be attributed to the execution of jacked pile construction in this area prior to the excavation of the foundation pit. Additionally, the monitoring process experienced a squeezing effect due to the construction of jacked pile in other areas, resulting in slightly smaller settlement values. In practical construction, the triaxial mixing piles, which serve as a cutoff wall, further minimize both horizontal and vertical displacements of the foundation pit. Despite the simulated values being larger than the monitored values, their influence on estimating equation parameters is not significant. Hence, it can be considered that this numerical model is accurate.

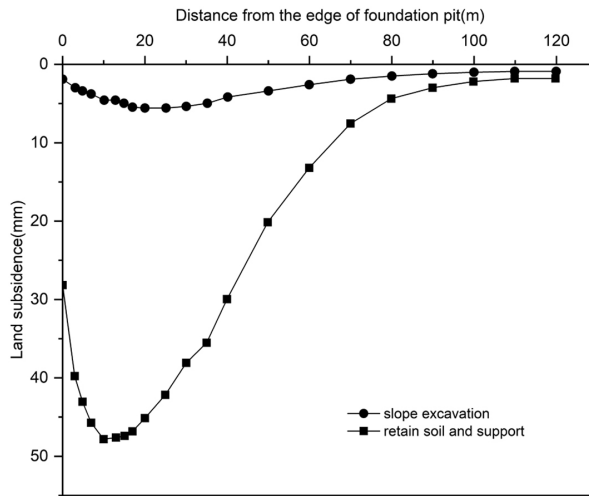


Fig. 3. Change of settlement around excavation of existing foundation pit

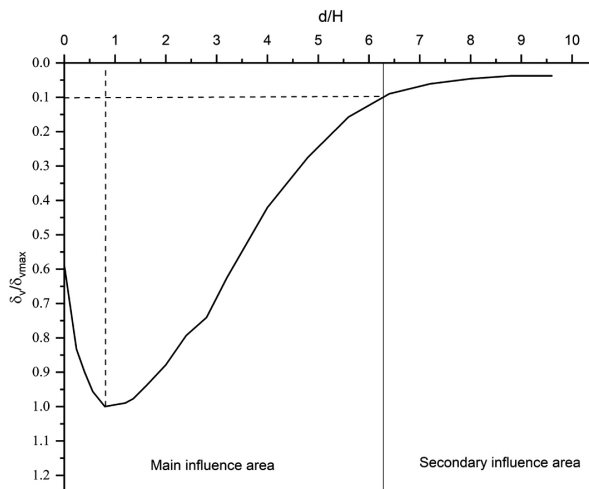


Fig. 4. Different settlement influence areas of existing foundation pit excavation

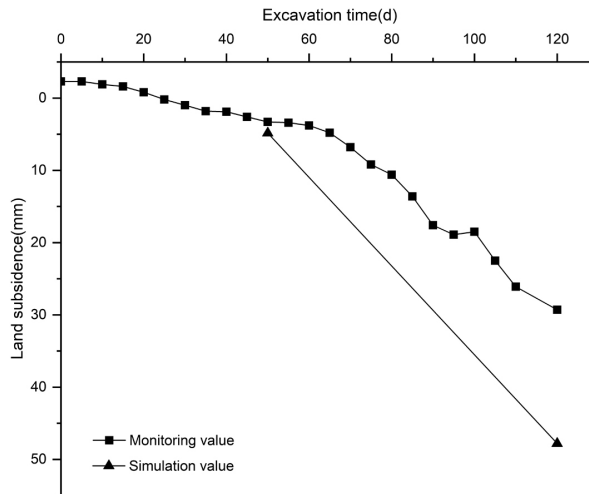


Fig. 5. Comparison of monitoring value and simulation value of road settlement around existing foundation pit

4. Variation law of ground settlement of two foundation pits with different distance

4.1. Settlement change between two foundation pits after existing foundation pit excavation

The ground settlement between the two foundation pits is depicted in Figures 6–8, illustrating the cumulative settlement resulting from the completed excavation in the existing foundation pit and the subsequent excavation in the new foundation pit. This settlement curve represents the cumulative settlement resulting from the excavation of both foundation pits. As can be seen in Figures 6, 7, and 8, the settlement of the pit shows a parabolic variation in relation to the distance from the edge of the pit, regardless of how deep the excavation is and how far the distance between the two pits changes. As the excavation depth of the pit increases, the settlement of the surrounding soil shows an increasing trend. It can be seen in these plots that in the period from 5 m to 10 m of excavation, although there is an increase in settlement, it is not significant. The maximum settlement increase from a depth of 10 m to 15 m exceeds the maximum settlement increase from a depth of 5 m to 10 m by more than 10 times. The spacing between the two excavations has been observed to have a diminishing effect on the maximum settlement increase, specifically between depths of 10 m and 15 m. However, even with this increased spacing, the maximum settlement remains greater than 10 mm. The settlement change graphs for the three different spacings all remain consistent in the magnitude of settlement change. After comparing the excavation depth with the original pit, which was 12.6 m, it can be assumed that the settlement of the adjacent pit will change abruptly and the settlement change rate will surge when the excavation reaches the same depth as the former pit. At the

same time, the settlement at the edge of the adjacent pit does not increase in parallel with the increase in depth outside the pit opening. Rather, after 12.6 m of excavation, the increase in excavation depth causes the settlement to gradually decrease. This requires that the change in excavation depth be noted during settlement monitoring in the excavation of adjacent pits. In particular, when the excavation depth of the adjacent pit is close to the original pit, a steep increase in settlement rate can trigger uneven settlement, which can threaten the safety of the surrounding environment.

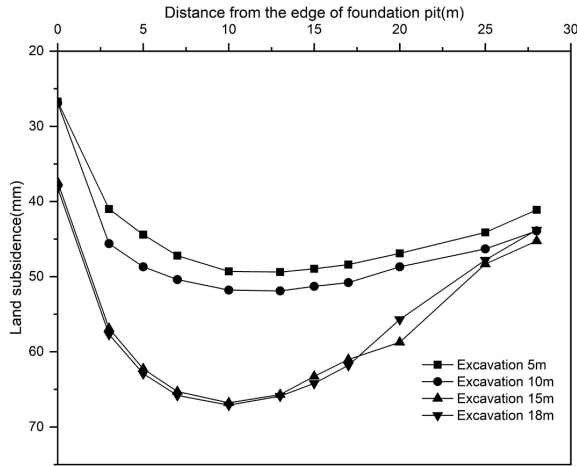


Fig. 6. Change of ground settlement after excavation of new foundation pit (the distance between two foundation pits is 28 m)

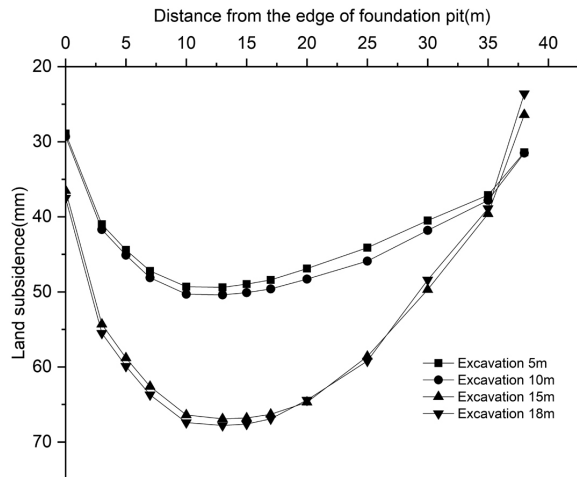


Fig. 7. Change of ground settlement after excavation of new foundation pit (the distance between two foundation pits is 38 m)

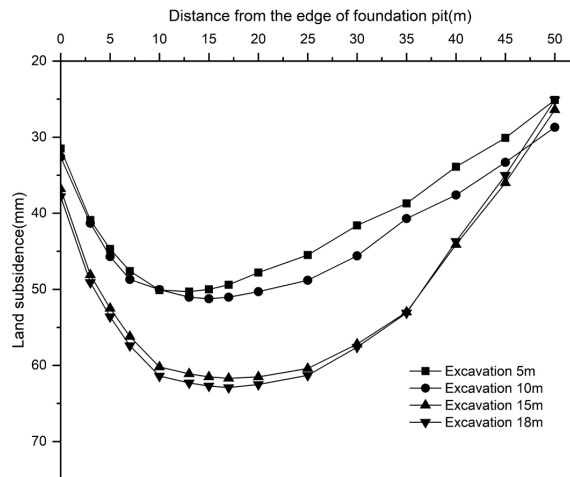


Fig. 8. Change of ground settlement after excavation of new foundation pit (the distance between two foundation pits is 50 m)

4.2. Position change of maximum settlement of two foundation pits with different spacing

When building the model, the location of the adjacent pits was different, making the results after meshing different and thus leading to differences in the finite element calculation results. In Figure 9 to 11, D represents the distance from the location of the maximum settlement point to the edge of the original excavation pit, while H represents the depth of the new excavation pit. According to Figures 9, 10, and 11, it is evident that the maximum settlement point on the ground occurs during the excavation phase of the current foundation pit. After the excavation and installation of support, this settlement point is typically located at a distance approximately equal to the depth of the foundation pit. With the excavation of adjacent pits, the position of the maximum settlement point between pits varies significantly with different pit spacing.

In the new pit excavation of 5 m, the position of the maximum ground settlement at all three pit spacings does not change. With 10 m of new pit excavation, the location of the maximum ground settlement at 28 m pit spacing moves closer to the edge of the original pit. This trend becomes more apparent as the depth of excavation increased. The position of the maximum settlement point after 18 m of new pit excavation moves $0.306H$ from the original pit excavation during the soil retention phase, but after 10 m of new pit excavation when the two pits are 38 m and 50 m apart, the maximum settlement position moved towards the edge of the new pit. When the excavation depth exceeds 15 m, the position does not fluctuate much and remained more or less the same. The maximum settlement position is $0.310H$ and $0.316H$ away from the edge of the original pit for the two conditions of 38 m and 50 m between the two pits respectively, which also indicates that the maximum settlement position between the two pits moves closer to the edge of the new pit as the distance between the two pits increased.

This finding indirectly suggests that variations in the spacing among foundation pits constitute a significant factor that influences the maximum settlement of the ground.

Therefore, during the monitoring process, the extension of the settlement point arrangement should be considered after the excavation of adjacent pits. For composite supports, particular attention should be paid to the interval 2.2 to $3H$ to ensure that the maximum settlement point is within the monitoring range.

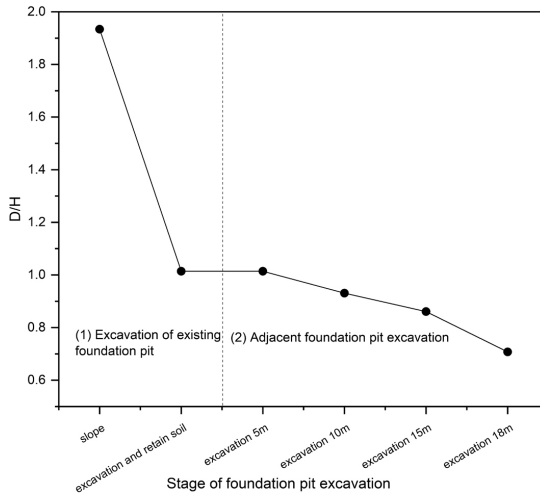


Fig. 9. Location change of maximum ground settlement (the distance between two foundation pits is 28 m)

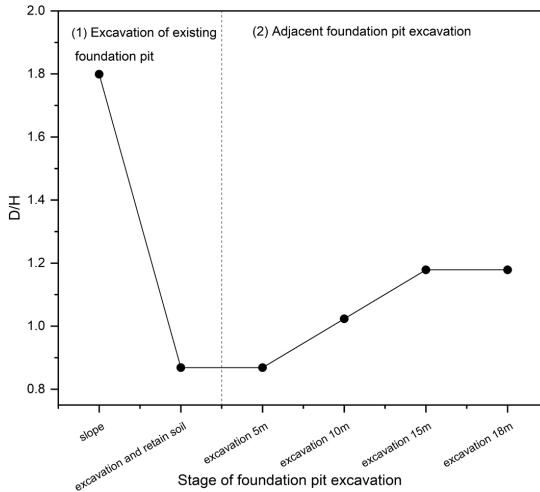


Fig. 10. Location change of maximum ground settlement (the distance between two foundation pits is 38 m)

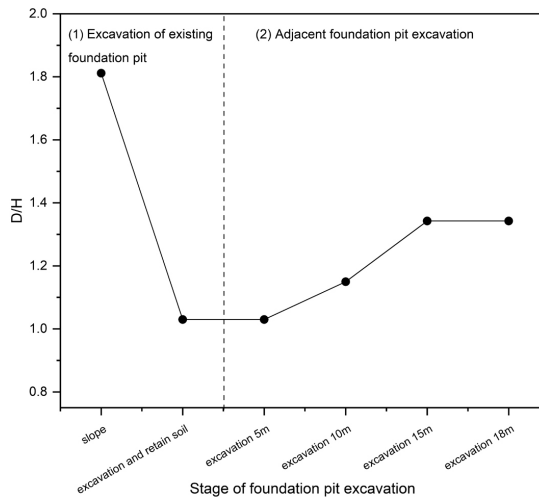


Fig. 11. Location change of maximum ground settlement (the distance between two foundation pits is 50 m)

5. Estimation of maximum ground settlement around double foundation pit excavation

In subway construction, foundation pits are often supported by underground continuous walls. When internal bracing is installed within these pits, the maximum settlement of the pit after excavation is directly related to the maximum horizontal deformation of the retaining structure. As a result, the maximum horizontal displacement of the new foundation pit becomes a significant factor influencing the overall settlement between the two pits [26].

Table 2 shows the values of ground settlement for different working conditions and pit spacing. Correlation analysis is carried out on the data in Table 1 and a heat map is drawn as shown in Figure 12. It can be seen from Figure 12 that the maximum settlement between pits correlates most strongly with the maximum horizontal displacement of the existing pits, followed by the working conditions of the pits, all of which have a correlation coefficient of 0.9 or more. The term “working condition” pertains to the various excavation depths of the newly foundation pit. The maximum horizontal displacement of the new pit and the spacing between the two pits do not have a very strong influence on the maximum settlement between the pits. Therefore, when double foundation pits are excavated, it is particularly important to control the horizontal displacement of the first excavated pit.

The increase in settlement after excavation of the original pit is correlated with the maximum horizontal displacement of the enclosure after excavation of the new pit, together with the spacing between the two pits, the data for which are shown in Table 1 below, and the

linear fitting equation for which is shown below:

$$(5.1) \quad y = -101.894 + 2.203x - 0.022b + 0.059z + 0.598m$$

$$R^2 = 0.94$$

where: y – maximum ground settlement between two foundation pits (mm); x – maximum horizontal displacement of existing foundation pit (mm); b – maximum horizontal displacement of adjacent foundation pit (mm); z – distance between two foundation pits (m); m – excavation depth of adjacent foundation pit (m).

The equation used for fitting effectively captures the correlation between the maximum settlement of the subsidence pit and various factors, thus demonstrating its significant practical significance. However, it is crucial to acknowledge that the data used is derived from numerical simulations and may contain certain deviations when compared to actual monitoring results. Therefore, the next research step will primarily concentrate on assessing the precision of the fitting parameters.

Table 2. Maximum ground settlement under different working conditions and foundation pit spacing

Working condition	Maximum ground settlement (mm)	Maximum horizontal displacement of existing foundation pit (mm)	Maximum horizontal displacement of adjacent foundation pit (mm)	Distance between two foundation pits (m)
Excavation 5 m	49.36	65.92	-34.40	38.00
Excavation 10 m	50.36	65.96	-34.68	38.00
Excavation 15 m	67.15	70.59	-38.06	38.00
Excavation 18 m	68.24	70.71	-38.09	38.00
Excavation 5 m	51.06	65.81	-46.11	28.00
Excavation 10 m	52.03	66.03	-46.53	28.00
Excavation 15 m	66.82	71.33	-51.88	28.00
Excavation 18 m	67.07	71.54	-51.88	28.00
Excavation 5 m	50.24	66.30	-25.37	50.00
Excavation 10 m	51.83	66.56	-25.86	50.00
Excavation 15 m	61.70	67.79	-28.24	50.00
Excavation 18 m	62.86	67.88	-28.34	50.00

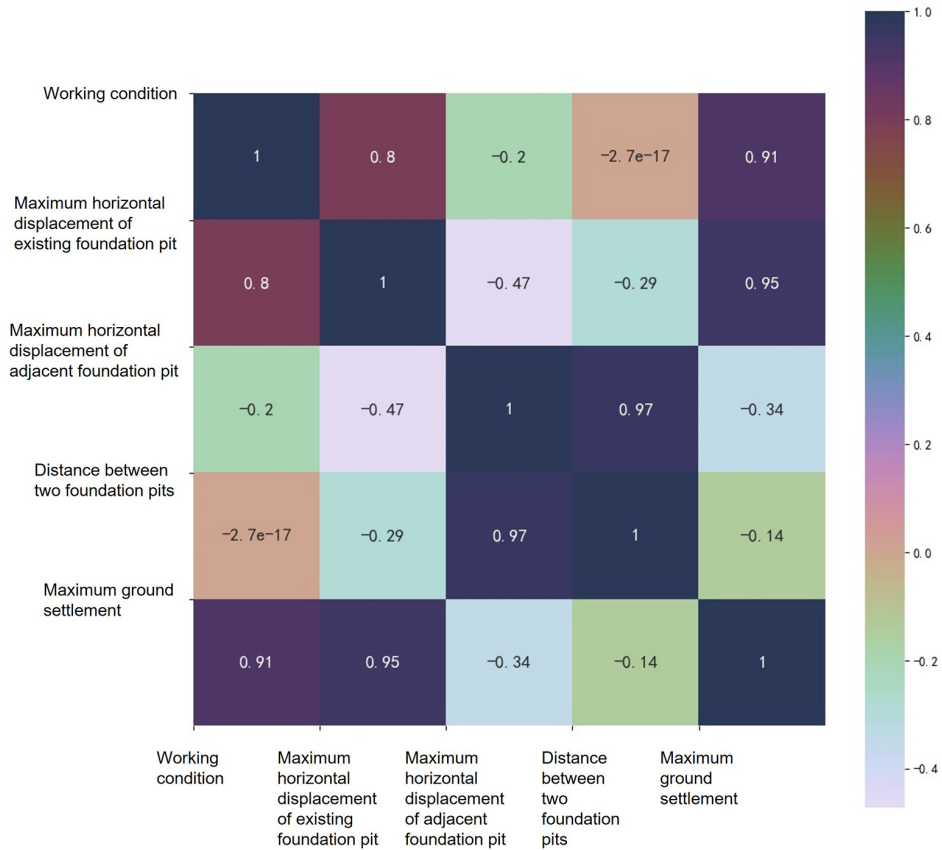


Fig. 12. Heat map of correlation between various factors and inter pit land subsidence

6. Conclusions

After the excavation of the original foundation pit, the excavation of the new foundation pit has a significant effect on the ground settlement between the two pits, and numerical simulations based on the actual project have led to the following conclusions:

1. The ground settlement between the two pits exhibits a decreasing trend from the sides towards the center during the excavation of a double foundation pit. Increasing the excavation depth of the new pit results in a higher amount of ground settlement between the two pits. The increase in ground settlement is not significant when the excavation depth of the new pit is shallow. However, the settlement amount increases sharply when the excavation depth of the new pit exceeds that of the existing pit.
2. The maximum settlement between the two pits is located closer to the edge of the newly excavated pit as the distance between the two pits increases. When the two pits are close together, the increase in excavation depth will cause the maximum settlement location

to move closer to the original pit. Where the two pits are farther apart, an increase in excavation depth will cause the maximum settlement to move closer to the new pit.

3. The maximum settlement between the two pits is linearly related to the maximum horizontal displacement of the existing pit envelope, the excavation depth of the new pit, the maximum horizontal displacement of the new pit envelope and the distance between the two pits, and the correlation decreases in descending order.

7. Recommendations for future studies

The model's simulated values may have some discrepancies compared to the actual monitoring data. Future research needs to consider additional environmental factors to improve its accuracy. The equation used for fitting effectively captures the correlation between the maximum settlement of the subsidence pit and various factors. However, the data used is derived from numerical simulations and may contain certain deviations when compared to actual monitoring results. The next step of the research will involve validating the accuracy of the equation parameters through more case studies.

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