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Research Article

Theoretical Study of a Design Method for Underexcavation in Building Rectification

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For buildings with shallow foundations embedded in natural soil sediments, the underexcavation method is often used to correct building inclination. Relying on engineering experience and close field monitoring, rectification has been conducted successfully. However, theoretical studies are relatively scarce, resulting in an inadequately informed rectification design and procedure. Assuming the soil is an ideal elastic-plastic body, a simplified analysis was adopted to study the issue theoretically. First, the redistribution of the base contact pressure after building inclination was deduced. Second, according to the force balance between the total contact pressure of the base and the total stress on the horizontal plane at the excavation hole, the limit hole spacing at the critical state of building back tilt was obtained, which was also the preferable hole spacing for soil strip collapse. Third, because the amount of anticipated forced settlement at a certain section of soil excavation is equal to the volume of soil hole collapse, an accurate formula for the hole diameter was obtained. Combined with engineering experience, suggestions for the design procedure were proposed. Finally, two case histories were introduced to verify the correctness and practicability of the theoretical formula for hole spacing and diameter. These two key parameters provide a strong theoretical basis for building rectification in future engineering practice.

1. Introduction

In engineering practice, building inclination often occurs due to design error, severe settlement, or surrounding underground construction. For buildings with shallow foundations based on natural sediment layers or reinforced soil layers, underexcavation is the least intrusive and most economical method for building rectification [1–3]. The success of rectification and building safety heavily depend on close monitoring and dynamic construction. Theoretical guidance is urgently needed in construction design and correction. Based on the small hole expansion theory and Tresca yield criterion, a formula was reported to determine the radius of the plastic zone [4]. By submitting the Mohr–Coulomb failure criterion to an elastic solution of the stress around the hole for the plane strain problem, an analytical plastic zone around the excavation hole was obtained [5]. The finite element method was also introduced to further study the mechanism of building rectification [6, 7].

To directly observe soil deformations and obtain detailed data, several scale model tests were performed [8], and the test results indicated that the vertical stress decreased above the holes while increasing between the adjacent holes, showing the stress transfer law. Using the finite element method, Xiao et al. further described the continuous stress redistribution and displacement field [9] and the rectification mechanism was revealed.

Previous research has focused on the plastic zone and hole spacing. The consensus is that when the plastic zone bridges the soil strip between neighbouring holes, the strips yield and produce plastic flow. At this moment, the building starts to tilt reversely. Although the finite element method can be used for inclination correction analysis, calculating a preferable hole spacing with a numerical simulation is excessively demanding for an engineer. Till to now, there is no applicable formula for the rectification design. Furthermore, there is a lack of research on the relations between the contact pressure and the redistributed stress between soil strips in the critical state of back tilt. The forced settlement of building rectification by underexcavation derives from the hole closure [3, 9], but few studies have focused on the quantitative relationship between the parameters of soil excavation and the expected base settlement.

A practical rectification design, given the expected correction target (forced settlement), is to determine the hole spacing, hole diameter, and plane layout of excavation holes under certain building load and subsoil conditions. By examining a number of rectification projects and studying case histories, the authors have comprehended the relationship between the design parameters and the rectification target. In this study, the subsoil is assumed to be an ideal elastic-plastic body. By using the simplified theoretical analysis, the two formulas for ultimate hole spacing and hole diameter are derived, which are the key parameters for a rectification design. The settlement can also be predicted by the underexcavation configuration.

In the next section, the redistribution of contact pressure is determined after the inclination of buildings. The third section presents the derivation of the preferable hole spacing and hole diameter. The fourth section describes the rectification design procedure. In the fifth section, two case histories are introduced to verify the design parameters. Finally, conclusions are offered in the last section.

2. Redistribution of Contact Pressure

When the building is inclined, the contact pressure is redistributed. For a building with a raft foundation, it is assumed that the total height of the building is H, the length of raft is L, and the width is B. The building tilt is often along the direction of width. The horizontal displacement of the building roof is ΔB, and the inclination of the building is i. When the building has a regular shape and uniform weight, it can be considered that the total structure load P of the building acts on the centroid. The horizontal eccentricity caused by inclination is e, as shown in Figure 1. The building inclination can be expressed as follows:

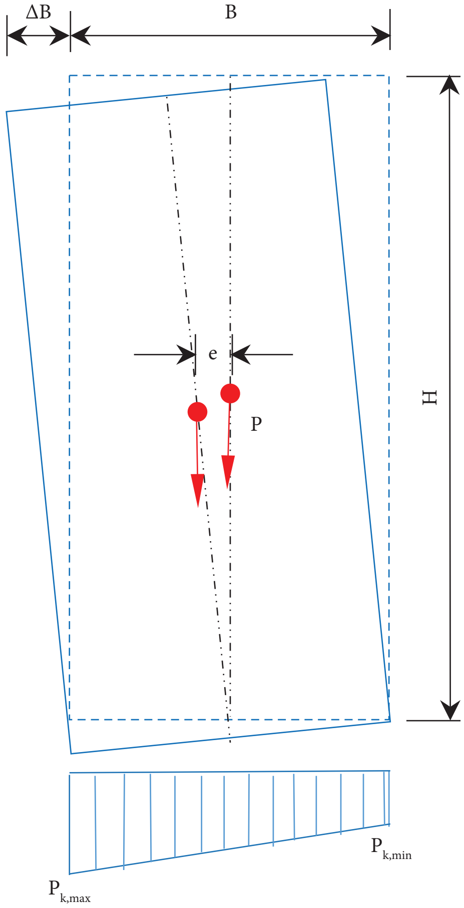

FIGURE 1: Analysis sketch for redistribution of contact pressure.

$$\mathrm{i} = \frac{\Delta \mathrm{B}}{\mathrm{H}} = \frac{\mathrm{e}}{(\mathrm{H}/2)}. \tag{1}$$

Solving for e, it can be expressed as

$$\mathrm{e} = \frac{\mathrm{Hi}}{2}. \tag{2}$$

Assuming that the subsoil is uniform, the redistributed contact pressure caused by building inclination can be calculated by

$$\left.\begin{array}{l} \mathrm{p_{k,\,max}} \\ \mathrm{p_{k,\,min}} \end{array}\right\} = \frac{\mathrm{P}}{\mathrm{BL}}\left(1 \pm \frac{6\mathrm{e}}{\mathrm{B}}\right) = \frac{\mathrm{P}}{\mathrm{BL}}\left(1 \pm \frac{3\mathrm{Hi}}{\mathrm{B}}\right). \tag{3}$$

Taking $(H/B) = \beta$, the formula can be written as

$$\begin{array}{l} \mathrm{p_{k,\,max}} \\ \mathrm{p_{k,\,min}} \end{array} = \frac{\mathrm{P}}{\mathrm{BL}}(1 \pm 3\beta \mathrm{i}). \tag{4}$$

Such a redistribution formula provides a basis for the rectification design in a more concise way. According to the "Code for Design of Building Foundation (GB50007-2011)" [10], the maximum inclination of buildings is controlled within 5%. Therefore, when the ratio of height to width $\beta \leq 10$ and the building inclination $i \leq 5‰$, the contact pressure changes within the range of ±15%.

3. Ultimate Hole Spacing and Hole Diameter

3.1. Ultimate Hole Spacing. When rectifying the inclined building, as the excavation proceeds, more holes are cut, the bearing area of the soil strips between the holes decreases gradually, and vertical stress is more transferred to the soil strips. Taking the subsoil as an ideal elastic-plastic body, when the vertical stress on the minimum section of the soil strips increases to the ultimate soil bearing capacity, the soil strips will yield and collapse [3, 4]. The researchers simulated the plastic zone evolution. Under the conditions of a contact pressure of 90 kPa and an excavation hole spacing of 2.15 d, the maps of effective plastic strain are shown in Figure 2. For analysis details, we refer to document [9].

Marking contact pressure as p, it is close to or equal to the allowable bearing capacity of the subsoil when the raft area of a building foundation is determined. Therefore,

$$\mathrm{p} \approx \mathrm{f}_{ak} = \frac{p_u}{K}, \tag{5}$$

where p_u is the ultimate bearing capacity of the foundation that can be determined by property parameters or by unconfined compressive strength of the subsoil and K is the safety factor of the foundation bearing capacity.

Underexcavation is conducted from the less subsidence side of the building. Taking the cutting length as 1.0 m, when the hole spacing is l, hole diameter is d, and the total number of holes at the cutting section is n, the effective area for transferring vertical stress to deep is $n(l-d)$ at the cutting section. If the horizontal plane for small holes is to reach the crushing state, the vertical stress loading on the soil strip between the holes must reach the ultimate bearing capacity p_u of the subsoil, as shown in Figure 3. The excavation hole is generally within 1.0 m underneath the raft; therefore, the diffusion of contact pressure to the depth of the excavation hole can be ignored. According to the total vertical stress at the horizontal plane in the middle of the hole being equal to the total contact pressure under the raft, the following equilibrium formula is obtained:

$$nlp = n(l-d)p_u, \tag{6}$$

i.e., $nl(p_u/K) = n(l-d)p_u$

The ultimate hole spacing is

$$l = \frac{K}{K-1}d = \lambda d, \tag{7}$$

$$\lambda = \frac{K}{K-1}, \tag{8}$$

where λ is the multiple of hole spacing to diameter, depending on the safety reserve of the building foundation.

For an inclined building, its foundation bearing reserve is somewhat lower with a safety factor of 1.5~2.0, so the corresponding hole spacing is (2.0~3.0)d, which is consistent with the previous engineering experience.

3.2. Applicable Hole Diameter. The finite element method has been introduced to predict the building settlement [11–13]. However, the simulated settlement caused by underexcavation is often far less than the observed settlement in the engineering practice. Taking the soil elastic modulus as 15 MPa, when a pressure of 90 kPa is applied to the ground, the soil is excavated at a spacing of 4.3 d and the diameter of the excavation hole is 110 mm. The maximum ground settlement caused by underexcavation is approximately 1.5 mm according to the finite element calculation, as shown in Figure 4, whereas under the same excavation hole configuration, the excavation settlement in the project is approximately 20 mm. The reason is that the finite element method is applicable to continuous bodies, and the calculated deformation only represents those caused by stress redistribution. After the soil strips between the holes yield and collapse, the finite element method is no longer applicable for a broken discontinuous body. Nevertheless, hole collapse is the main source of forced foundation settlement for building rectification. This conclusion was also supported by Ovando–Shelley and Santoyo [3] and Xiao et al. [9]. Therefore, a simplified method is used to derive the hole diameter given the target settlement.

Ignoring the elastic deformation caused by stress redistribution from soil excavation, a section perpendicular to the soil cutting is taken for analysis. Assuming that the amount of forced settlement at this section is s, the multiple, i.e., λ of the hole spacing to diameter is determined by the above formula (8), the number of rows of soil excavation holes is m, and the number of holes in each row is n, as shown in Figure 5. If the settlement volume is equal to the amount of extraction soil, the equation is obtained as follows:

$$\text{ie}, snl = mn\frac{\pi d^2}{4}, \tag{9}$$

$$\text{ie}, sn\lambda d = mn\frac{\pi d^2}{4}. \tag{10}$$

The hole diameter is

$$d = \frac{4\lambda s}{m\pi}. \tag{11}$$

Forced settlement can also be predicted according to rectification design parameters as follows:

$$s = \frac{m\pi d}{4\lambda}. \tag{12}$$

It should be noted that the relationship between the diameter of the excavation hole and foundation settlement is derived under the condition of ignoring the raft stiffness. According to the theoretical calculation, the settlement along the cutting direction changes abruptly. Due to the stiffness of the raft and structure, the settlement along the cutting direction changes linearly with the maximum settlement at the cutting side. In engineering projects, when predicting the maximum settlement using the previous formula, a coefficient should be introduced to modify the difference between the theoretical value and site observations. According to the experience obtained from case histories, the coefficient is in the range of 1.0~3.0.

$$\mathrm{s}_{\max} = \eta\frac{\mathrm{m}\pi\mathrm{d}}{4\lambda}. \tag{13}$$

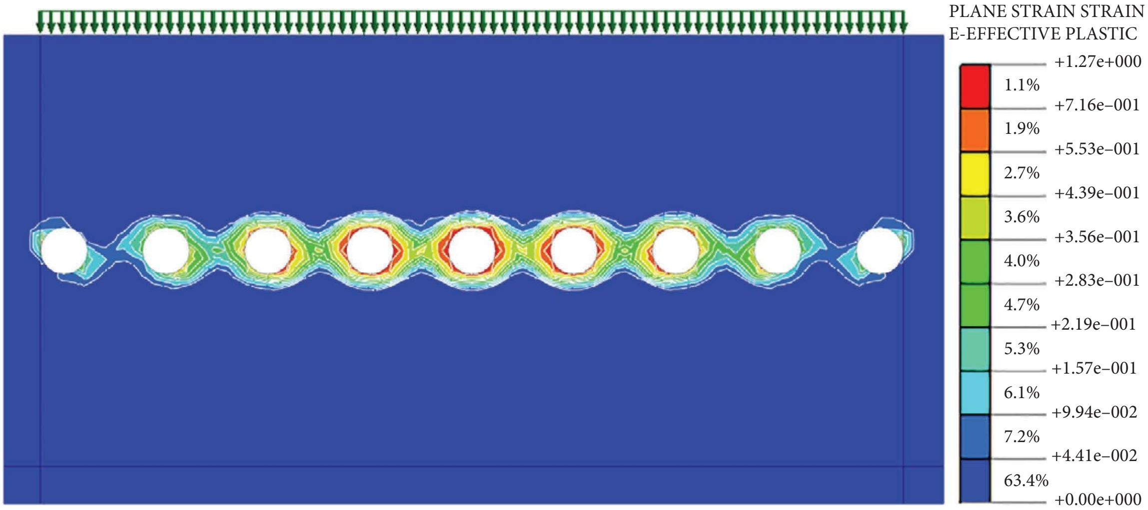

Figure 2: Maps of effective plastic strain of underexcavation.

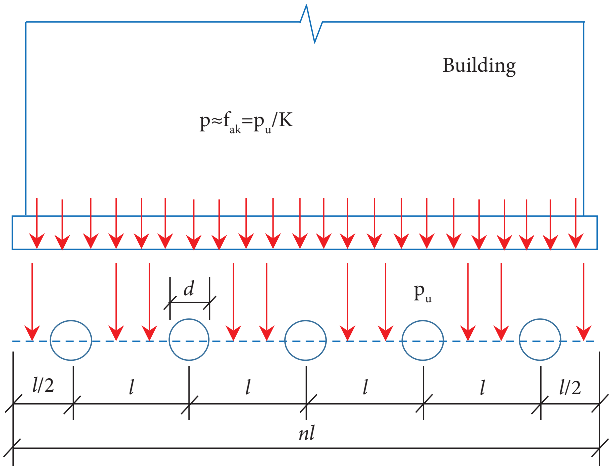

Figure 3: Analysis sketch for the ultimate spacing of holes.

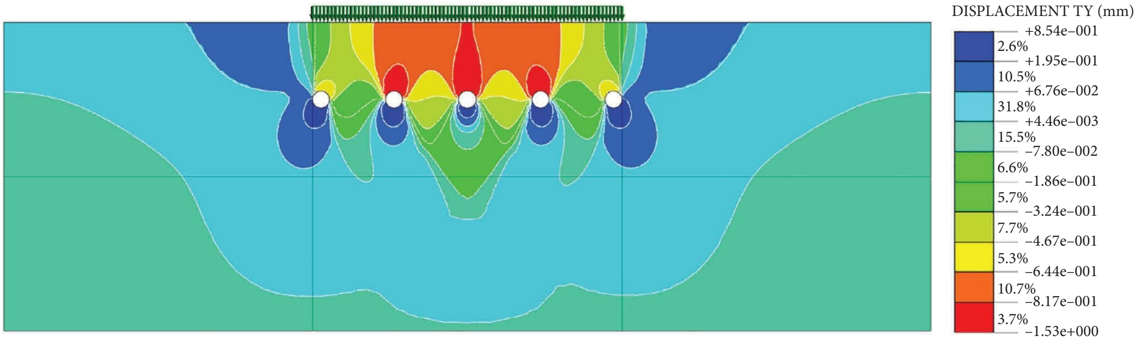

Figure 4: Simulated settlement after underexcavation.

4. Recommended Practical Design Steps

With two key parameters of hole spacing and diameter, combined with engineering experience, the design steps are recommended as follows:

Step 1. we calculate λ, the multiple of ultimate hole spacing to hole diameter. According to the ultimate bearing capacity of the foundation and contact pressure, the safety factor, K, is determined by formula (8). For a concise rectification design, the redistribution of contact pressure can be taken

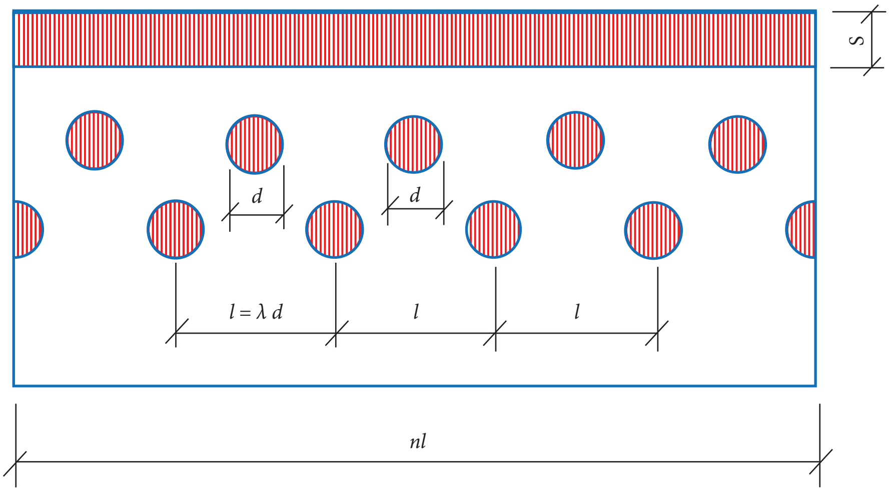

Figure 5: Analysis sketch for diameter of the digging hole.

into account. For the convenience of subsequent instructions, we take $\lambda = 3$.

Step 2. we determine the lengths of the excavation holes. For ordinary residential buildings within 16 m in building width, two drilling lengths can be appropriate for rectification. According to many years of experience in rectifying projects, the optimal maximum drilling length extends to the 3/4 of the dimensions in tilt direction [14], which not only facilitates the building back tilt but also avoids unnecessary settlement on the less subsidence side. The recommended hole lengths are 0.75 B and 0.5 B, as shown in Figure 6.

Step 3. we determine the hole diameter and the hole configuration. The target maximum forced settlement at the cutting side is $s_{\max}$; when the foundation is completely rigid, the settlement at the centerline is $s_{\max}/2$. Using formula (11), the corresponding diameter of the excavation hole is

$$\begin{aligned} d &= \frac{4\lambda}{m\pi} \bullet \frac{s_{\max}}{2}. \\ &= \frac{6s_{\max}}{m\pi}. \end{aligned} \tag{14}$$

When taking m = 1, we obtain

$$d = \frac{6s_{\max}}{\pi}. \tag{15}$$

Assuming the expected maximum settlement $s_{\max} = 60\,\text{mm}$, we obtain $d \approx 115\,\text{mm}$. According to the available bit type in the present market, a hole diameter of 110 mm is applicable. For the convenience of construction, the drilling diameters of the two types of holes with different lengths are taken as the same. It is recommended to take 2/3 of the total number of excavation holes with a length of 0.75 B and 1/3 of the total number with a length of 0.5 B to ensure that the theoretically calculated settlement area on the inclination correction profile is equal to the settlement area of the raft. The layout of the soil extraction holes is shown in Figure 6.

Step 4. we dynamically modify the rectification scheme. For each specific correction project, the building structure, foundation, subsoil, construction technology, and accompanying measures are different and the design scheme should be modified according to the site circumstances. For example, if the basement is surcharge loaded on site, the contact pressure increased. Correspondingly, the safety factor K of the soil strips is decreased. Based on $\lambda = K/(K-1)$, the critical hole spacing should be modified to be larger. For another example, water injection into an excavation hole helps decrease the shear parameters of cohesive subsoil, especially for those with a naturally low water content; as a result, the ultimate bearing capacity of the soil strip decreases. Therefore, when the measure of flushing water is adopted in the field, a larger hole spacing can crush the soil strip.

5. Verification by Case Histories

5.1. Case 1: An 11-Storey Building with a Frame Structure. A residential building in Jiangsu Province in China has a frame structure of 11 floors above ground and one floor underground [15]. The building is based on a beam-embedded raft of 450 mm in thickness. According to the geotechnical survey report, the bearing stratum underneath the raft is silt and silty clay, which have a characteristic bearing capacity (allowable bearing capacity in design) of 100 kPa. After completing the structure, it was found that the uneven settlement had occurred. Until building rectification, the inclination had reached 6%. The building is 52.8 m in east-west length and approximately 14.0 m in south-north width. A total of 76 excavation holes with three lengths were set at the building's north side, with a spacing of 600 to 800 mm; during onsite construction, 20 additional excavation holes were drilled due to difficulties in back tilting the building. The construction process was divided into three stages as follows:

Stage 1: preparation of underexcavation, including excavation of the working trench and dewatering to

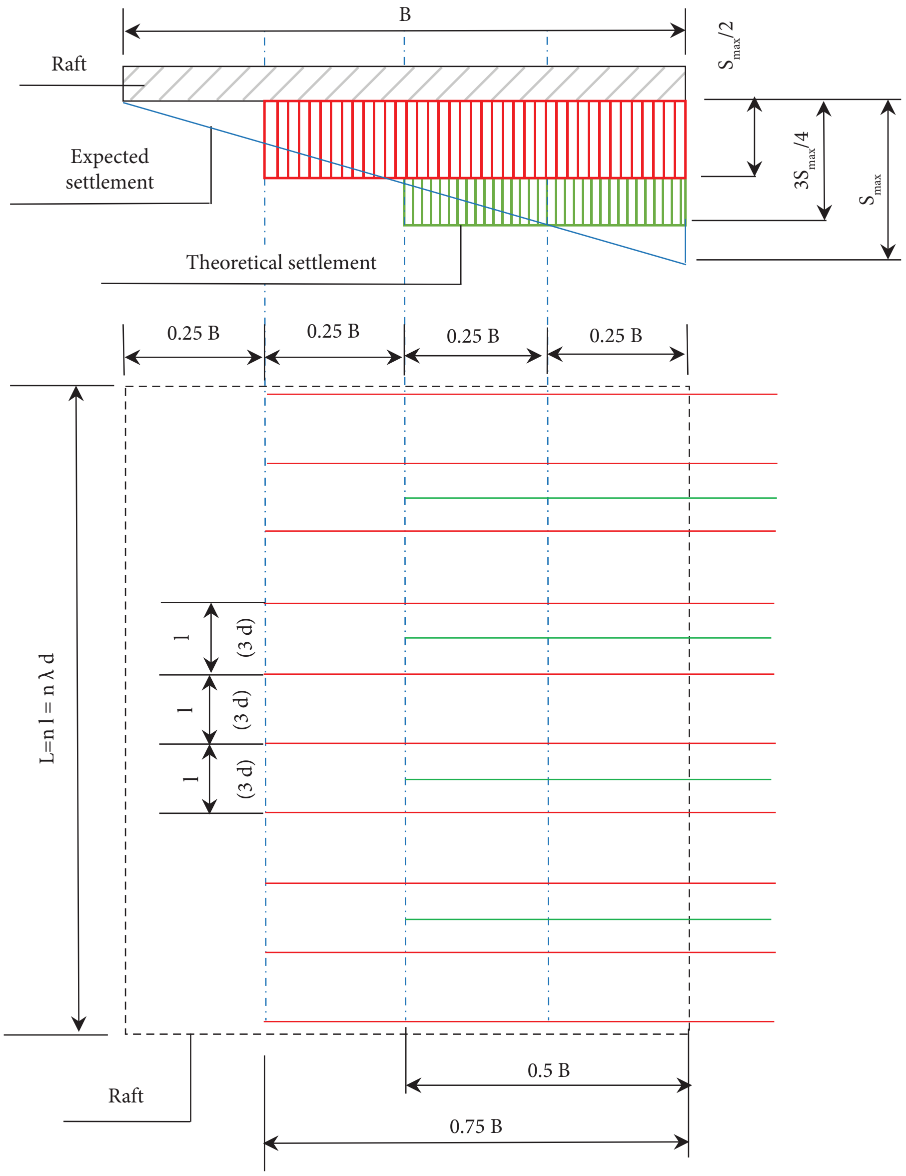

Figure 6: Sketch for rectification design.

lower the groundwater level below the working trench bottom

Stage 2: underexcavation for building rectification, during which the holes were cut uniformly and *symmetrically* along the building north side, with short holes first, then long holes, and finally supplementary holes

Stage 3: foundation reinforcement, including grouting to fill the not completely closed holes and *collapsed* loose soils upon accomplishment of correction and then driving 188 micropiles as settlement reducers

The construction photos are shown in Figure 7. The building exhibited relatively high rigidity during the back tilting process. The curves of settlement versus time of typical monitoring points are shown in Figure 8. To verify the theoretical formulas, only the settlement data in the excavation stage are investigated. Taking the monitoring data of 4 points in the building middle, the induced average settlement of M5 and M6 was 58 mm during the underexcavation stage, while the south monitoring of M15 and M16 presented slight uplift at the same time. The observations indicate that the building tilts back by rotating around a certain axis, showing relatively high rigidity.

5.1.1. Verification of the Hole Spacing. According to the allowable bearing capacity of the supporting subsoil given by the site investigation report, we take the ultimate bearing capacity p_u as two times the allowable value, 200 kPa. Considering the dead load and live load, the 12 floors of the building exert a contact pressure $p = 12 \times 15 = 180$ kPa. Because the building was not decorated and not occupied, the contact pressure was taken as 0.9 times the above


(a) (b)

Figure 7: Underexcavation of case 1. (a) The building. (b) Underexcavation field.

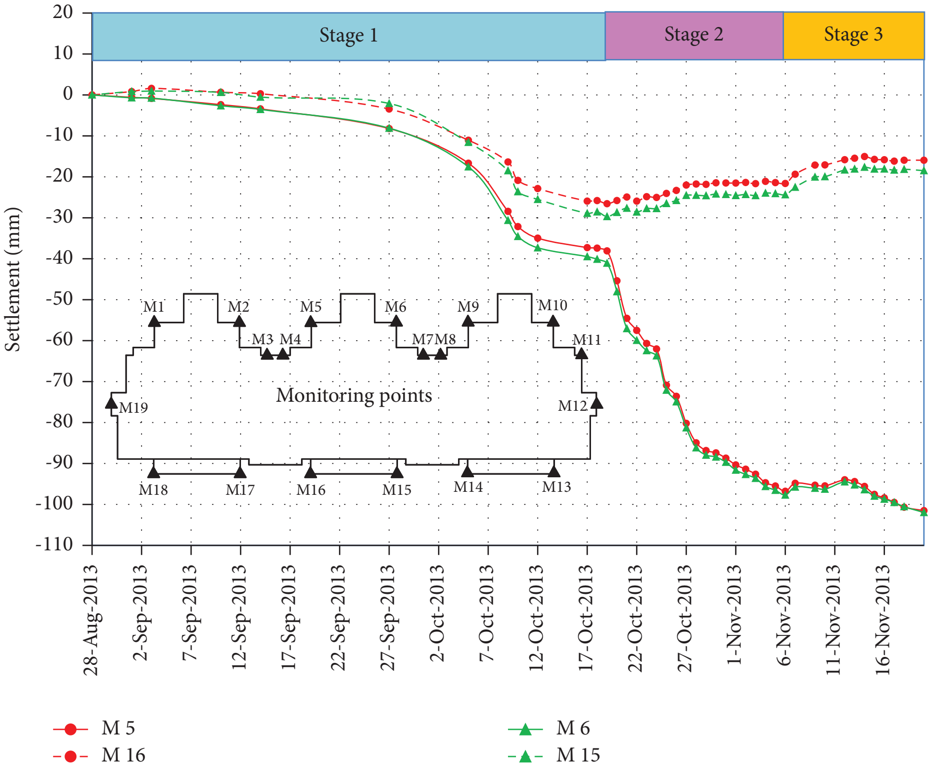

Figure 8: Settlement versus time of case 1.

estimated value, which is approximately 160 kPa. At the onset of rectification, the safety factor of the foundation soil is $K = (p_u/p) = (200/160) = 1.25$. Consequently, the ultimate hole spacing is $\lambda = (K/(k-1)) = 5$, i.e., hole spacing is $l = 5d$. The adopted hole diameter is 110 mm, and the theoretical spacing is 550 mm. Amazingly, the average hole spacing in the field is $l = (L/n) = (52800/(76+20)) = 550\text{mm}$, which agrees well with the theoretical calculation.

5.1.2. Verification of the Relationship between the Hole Diameter and Foundation Settlement. Using formula (12), the theoretical settlement is

$$s = \frac{m\pi d}{4\lambda} = \frac{1 \times 3.14 \times 110}{4 \times 5} = 17.27\text{mm}. \qquad (16)$$

During the whole operational process of the building rectification and foundation reinforcement, the back

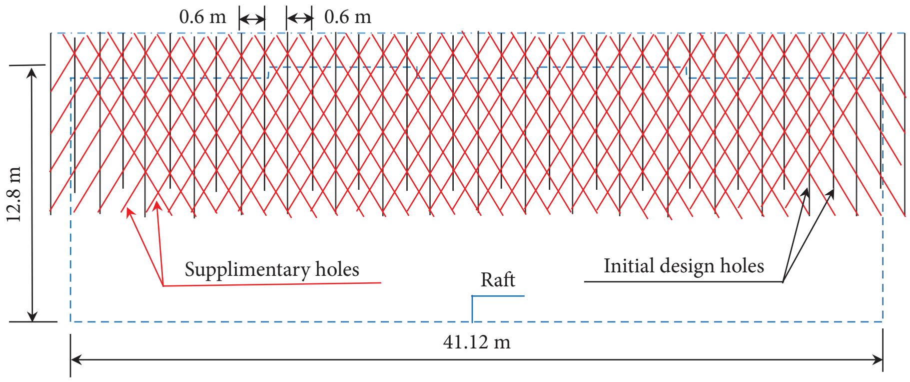

Figure 9: Hole configuration of case 2.

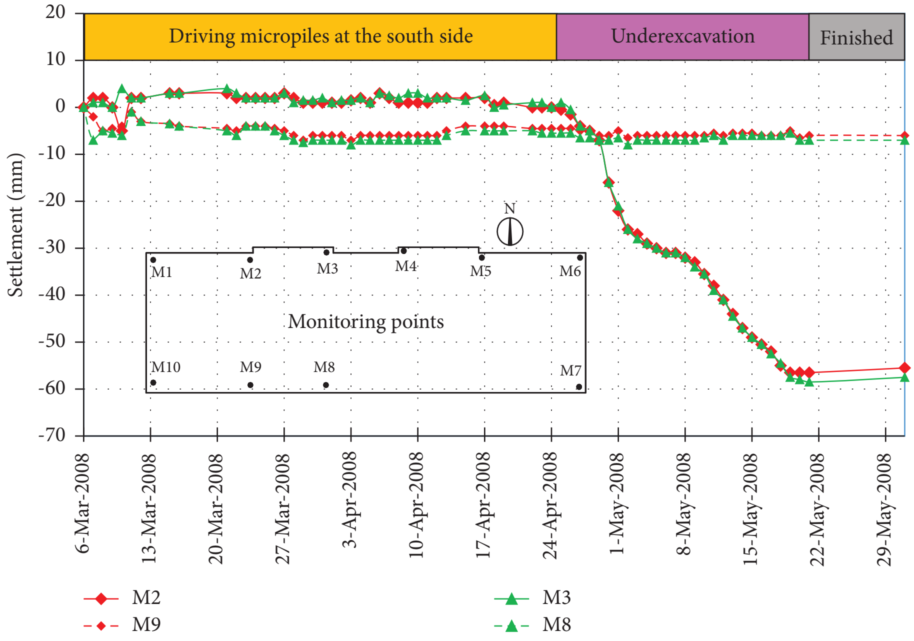

Figure 10: Settlement versus time of case 2.

inclination is 5.6%, perfectly achieving the target level of building rectification. During the underexcavation stage, the observed settlement is 58 mm, which is approximately 3.35 times the value of the theoretical calculation. Even considering $\eta = 3.0$, the observed settlement at the soil cutting side is still slightly larger. It is speculated that the following factors existed:

1. Consolidation settlement continued to develop during underexcavation
2. The foundation soil was soft, and the excavation of working trench released the lateral earth pressure. As a result, the soil creep deformation occurred, contributing to the north side settlement
3. Dewatering caused additional stress in the subsoils, and additional settlement was induced
4. Approximately one-quarter of the holes were repeatedly excavated, which brought more soil out the hole

5.2. *Case 2: A 6-Storey Building with a Masonry Structure.*

A 6-storey masonry building in Shandong Province in China is 41.2 m in length and 12.8 m in width on plane [16]. The north side of the building is based on medium to stiff plastic silty clay, while the south side of the building is laid on a backfill and muddy soil layer. To solve this problem, a lime-soil cushion of 1.5 m in thickness was adopted above which a raft foundation was laid to strengthen the building stiffness. Nevertheless, half a year after the completion of the building, the measured inclination to the south reached 5.87‰. To correct the building, underexcavation beneath the lime-soil cushion was conducted.

5.2.1. Verification of the Hole Spacing. According to the geological survey report, the characteristic value f_{ak}, i.e., the allowable bearing capacity of silty clay is 150 kPa and the ultimate bearing capacity is 300 kPa. The building has 6 floors in total, and the estimated contact pressure, including lime-soil cushion weight, is $p = 15 \times 6 + 1.5 \times 18 = 117\,\text{kPa}$.

Table 1: Comparison between the practical value and the calculated value.

Project	Case 1	Case 2
Floor	11F + 1F	6F
Design bearing capacity f_{ak} (kPa)	100	150
Adopted hole spacing (mm)	550	200
Theoretical hole spacing (mm)	550	180
Observed settlement (mm)	58	50
*Calculated settlement (mm)	17.27	47.45

Note. $^{*}\eta = 1.0$.

Therefore, the safety reserve of the foundation soil is $K = p_u/p = 300/117 = 2.56$; then, the multiple value of hole spacing to diameter in the limit state is $\lambda = K/(K-1) = 1.64$. The ultimate hole spacing is $l = 1.64d$. With an applied hole diameter of 110 mm, the theoretical hole spacing should be 180 mm.

After the raft south edge was pinned by micropiles, soil extraction was conducted from the north side of the building. The excavation holes were spaced at 600 mm and extended to 7.0 m or 9.0 m in the tilt direction underneath the cushion. After the excavation was completed in accordance with the rectification design scheme, the back inclination of the building could not achieve the expected goal of less than an inclination of 2.0%. Therefore, supplementary holes with a length of 10.5 m were cut obliquely with the raft edge at a spacing of 600 mm. The conducted holes are shown in Figure 9. There are actually 3 excavation holes within each spacing of 600 mm, so the actual excavation hole spacing is 200 mm. This value is in good agreement with the theoretical calculation of 180 mm.

5.2.2. Verification of the Relationship between the Hole Diameter and Foundation Settlement. The actual multiple is

$$\lambda = \frac{200}{110} = 1.82. \tag{17}$$

Using formula (12), the theoretical settlement is

$$s = \frac{m\pi d}{4\lambda} = \frac{1 \times 3.14 \times 110}{4 \times 1.82} = 47.45\mathrm{mm}. \tag{18}$$

The rectified settlement of the monitoring points is approximately 50 mm, as shown in Figure 10, which is close to the theoretical formula. The coefficient of settlement η is 1.05.

Two case histories verify the correctness and practicability of the theoretical formulas of ultimate hole spacing and adoptable hole diameter. In addition, design modification and dynamic construction are necessary for each building with a specific foundation. The comparison of these two typical case histories is shown in Table 1.

6. Conclusions

In the previous correction projects, the engineers had to rely on experience to design and conduct rectification. The success was severely dependent on close monitoring and holding on underexcavating. Through simplified theoretical analysis, the key parameters for inclination correction are deduced and its validity and practicability are verified by two case histories. The main conclusions are as follows:

(1) After the building is tilted, the base contact pressure is redistributed. Under the condition of uniform distribution of structural loads, a formula is proposed to calculate the stress redistribution according to the building incline. For a concise rectification design by underexcavation, the redistribution of contact pressure should be considered.

(2) Through simplified theoretical analysis, based on the total contact pressure underneath the raft being equal to the total pressure at the soil strips between excavation holes, the ultimate hole spacing is obtained. It is also the preferable hole spacing that facilitates the hole crushing. According to the volume of induced settlement being equal to the volume of soil extraction, the applicable hole spacing is obtained. Meanwhile, the induced settlement could be predicted by the determined parameters for underexcavation.

(3) The verification of case histories shows that the formulas are effective and applicable. These two formulas provide a solid theoretical basis for the design of rectification by underexcavation, but the design scheme needs to be modified according to the structure type, geotechnical conditions, and other extra measures for promoting settlement. During the process of building correction, close monitoring and dynamic modification are still essential.

(4) With the formulas presented in this study as a guide, the critical safety state and desired settlement can be controlled and the excavation time can be reduced. In this research, the ultimate crushing bearing capacity of soil strips between holes is not exactly the same as the ultimate bearing capacity of the foundation, which requires further study. When the maximum settlement at the excavation side of a building is predicted according to the parameters for underexcavation, the coefficient requires further accumulating empirical data.

Symbols

B:	Raft width
L:	Raft length
H:	Total height of the building, including the underground part
ΔB:	Horizontal displacement of the roof caused by building inclination
i:	Inclination of building
e:	Horizontal eccentricity caused by building inclination
β:	Ratio of building height to width, $\beta = (H/B)$
P:	Nominal combination of building load
p:	Contact pressure of the shallow footing
$p_{k,\max}$:	Maximum contact pressure

$p_{k,\min}$: Minimum contact pressure
s: Building settlement caused by underexcavation
$s_{\max}$: Maximum settlement at the cutting side
p_u: Ultimate bearing capacity of the foundation
f_{ak}: Allowable bearing capacity in foundation design
K: Safety factor of the foundation
λ: Multiple of hole spacing to diameter
d: Hole diameter
l: Hole spacing
m: Number of rows of excavation holes
n: Number of holes in the excavation section
η: Coefficient of settlement.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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References

[1] J. B. Burland, M. Jamiolkowski, and C. Viggiani, "Underexcavating the tower of Pisa: back to the future," *Geotechnical Engineering Journal of the SEAGS & AGSSEA*, vol. 46, no. 4, pp. 126–135, 2015.

[2] S. F. Fu and X. Rong, "Theoretical and application research on shallow digging method in CFG pile composite foundation of high-rise building," *Building Structure*, vol. 49, no. 8, pp. 123–129, 2019.

[3] E. Ovando-Shelley and E. Santoyo, "Underexcavation for leveling buildings in Mexico city: case of the metropolitan cathedral and the sagrario church," *Journal of Architectural Engineering*, vol. 7, no. 3, pp. 61–70, 2001.

[4] X. D. Xu, L. D. Jia, J. P. Sun, K. Z. Zhao, X. Zhang, and S. M. Li, "Design and practice of rectifying leaning building by digging-out soil and filling-in with water method," *Journal of Building Structures*, vol. 20, no. 5, pp. 59–65, 1999.

[5] Z. D. Deng, X. B. Zhang, and L. Wang, "Mechanism analysis and calculation method of horizontal soil landing rectifying method," *Journal of Civil Engineering and Management*, vol. 33, no. 5, pp. 38–43, 2016.

[6] J. Bai, D. Chan, and N. Morgenstern, "Numerical analysis of time-dependent behaviour for the leaning tower of Pisa," *Soils and Foundations*, vol. 48, no. 2, pp. 207–220, 2008.

[7] S. F. Fu, X. Rong, and Y. R. Li, "Finite element analysis of excavation unloading ditch method for rectification on less inclined side of high-rise building foundation," *Building Structure*, vol. 49, no. 8, pp. 130–135, 2019.

[8] H. Sun, "Experimental study on failure mechanism of under excavation method for building rectification," ME Dissertation, Shandong Jianzhu University, Jinan, China, 2019.

[9] J. H. Xiao, J. P. Sun, X. Zhang, and Q. X. Yue, "Mechanism of underexcavation and practical design method for building rectification," *SN Applied Sciences*, vol. 4, no. 4, pp. 103–115, 2022.

[10] *Ministry of Housing and Urban- Rural Development of the People's Republic of China*, "GB50007-2011: Code for design of building foundation", China Architecture & Building Press, Beijing, China, 2011.

[11] W. Q. Niu, X. B. Zhang, F. R. Wang, Q. Sun, M. Z. Hu, and G. Z. Wu, "Analysis and research on the rectifying and strengthening example of a Xining high-rise commercial and residential building and numerical calculation," *Building Structure*, vol. 48, no. s2, pp. 721–725, 2018.

[12] X. D. Song and Y. G. Liang, "Application and finite element analysis of converting foundation form in rectification engineering," *Construction Technology*, vol. 48, no. 18, pp. 99–102, 2019.

[13] X. N. Zhang, S. Y. Shi, M. Lu, and B. Liu, "Analysis of forced settlement rectification method of available brick-concrete structures in soft soil area," *Building Structure*, vol. 46, no. 8, pp. 88–94, 2016.

[14] Z. L. Shen and Z. Wang, *Rectification and Reinforcement Technology of Ancient Pagoda*, China Railway Publishing House, Beijing, China, 2011.

[15] F. Yang, "Analysis and applied research of rectifying technology for building by drawing out soil," ME Dissertation, Shandong Jianzhu University, Jinan, China, 2015.

[16] J. P. Sun, H. W. Wei, G. B. Shao, and Z. B. Jinag, "Affect analysis of reinforcement correction design and construction," *Sichuan Building Science*, vol. 36, no. 1, pp. 97–99, 2010.