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Research Article

Analysis of Foundation Pit Support Selection and Design Problems in Deep Soft Soil Area

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The aim of this study is to address challenges encountered in the design of foundation pit support systems for soft soil areas, which include vague calculation methodologies, insufficiently representative parameters, and limited design engineer experience. To address these issues, we conducted a comprehensive review of successful and failed case studies and observed that actual working conditions significantly impact the calculation method of soil and water pressures as well as the selection of representative strength values. Furthermore, we found discrepancies between the current calculation methods for factors such as antiuplift and overall stability and practical applications. When calculating forces like sliding torque and antisliding moment, the choice between using saturated or buoyant gravity can have significant implications. Additionally, we observed that under high pit edge loads, such as 20 kPa, the maximum bending moment in cantilever piles can significantly increase, necessitating stringent limits on these loads. Therefore, in designing foundation pit support systems for soft soil areas, it is essential to consider practical site conditions and lessons learned from previous projects. By selecting appropriate calculation methods and parameters, we can ensure the accuracy and safety of these critical structures.

1. Introduction

Soft soil is distributed in the coastal areas in the east of China, as well as in the areas where inland rivers, rivers, and lakes are widely distributed. The design and construction of foundation pit in soft soil area is difficult and costly, especially for shallow foundation pit (basement on the first floor) with the excavation depth of 3–6 m, which is easy to be ignored by the design, construction, and management units due to the shallow excavation, resulting in the instability of foundation pit, local sliding, engineering pile displacement, and other accidents, which often occur. The internal environment is more serious and more difficult to deal with the environmental impact caused by foundation pit instability than the external environment.

Many scholars have carried out a lot of research on the calculation method of foundation pit support in soft soil areas, foundation pit stability, construction environment impact, optimization design, and other topics. D. Z. Gao, Y. C. Zhang et al. [1–4] briefly described the engineering characteristics of soft soil and discussed some problems in the support of soft soil foundation pit; Y.K. Geng, W. Lu, L. Y. Zhao et al. [4–14] analyzed the mechanism of large deformation of foundation pit in deep soft soil area and studied the influencing factors and control measures of deformation according to the characteristics of "space-time effect" of foundation pit engineering in soft soil area; X. C. Wu, Y. Q. Xu, et al. [15–29] studied the design and construction of deep foundation pit support in deep soft soil and analyzed the reinforcement effect of passive zone and the stability of foundation pit.

However, due to improper design, accidents occur frequently in foundation pit support in soft soil areas. There are three elements of geotechnical design calculations: mode, parameters, and safety [30]. The calculation model requires the concept to be correct; the calculation parameters are required to be well representative and operable to the test; safety is inseparable from engineering experience. Patterns refer to methods for modeling and describing the mechanical behavior of soils and structures. Parameters refer to the characteristics and properties of the soil and structure that need

Table 1: Stability coefficient k when the excavation depth is 4 and 6 m.

Excavation depth	4 m	6 m	4 m	6 m
Grade Depth of slope toe	1 : 1.5	1 : 1.5	1 : 0.3 (spray anchor)	1 : 0.3 (spray anchor)
0	1.086	0.793	0.785	0.550
1 m	1.053	0.994	0.970	0.695
2 m	1.043	0.926	0.991	0.721
3 m	1.038	0.886	1.006	0.775
4 m	1.037	0.871	1.020	0.782
6 m	1.051	0.879	1.042	0.827
8 m	1.063	0.898	1.058	0.849
10 m	1.074	0.919	1.071	0.864
12 m	1.083	0.937	1.080	0.895
14 m	1.090	0.958	1.088	0.922

to be considered in the design calculation, such as the shear strength of the soil and shear modulus. The degree of safety refers to the safety indicators that need to be considered in the design calculation, such as reliability index and safety factor. In geotechnical design, the shear strength of fine-grained soil is mainly expressed by the shear angle, not by the cohesion. In addition, the parameters in the partial coefficient method design are obtained by statistical analysis according to the probability distribution pattern of the variables. The partial coefficient method further improves the safety of the design by using a partial coefficient of less than 1 to consider the uncertainty of resistance and load [31]. If the calculation parameters are replaced by the same calculation mode (e.g., UU undrained shear strength is replaced by cross plate strength, compressive modulus is replaced by deformation modulus), the safety degree needs to be adjusted appropriately. The selection of parameters, the applicable conditions of the formula, the special properties of different soils, the role of groundwater, the interaction between rock and soil and supporting structures, etc., the analysis, judgment, value, and experience of engineers are particularly important in the design of foundation pit support.

This paper collects more than 10 successful cases of foundation pit engineering in soft soil areas, summarizes the selection of foundation pit support in soft soil areas, takes the analysis of the causes of foundation pit accidents in Hangzhou Metro Line 1 as an example, collects and analyzes more than 10 failure cases, and discusses the theory, methods, and improvement measures of foundation pit design in soft soil areas.

2. Analysis of Foundation Pit Support Selection in Deep Soft Soil Area

The main problems of deep soft soil foundation pit engineering are large active earth pressure, small passive zone resistance, and large deformation of support structure; with low shear strength, it is easy to cause overall instability and pit bottom uplift. The following ways can be adopted: The retaining structure is passed through the soft soil layer to the soil layer with high resistance, and the pile top is provided with support. When the bottom buried depth of soft soil layer is large, the supporting structure bears large stress, and the feasibility and economy should be determined through calculation.

Reinforce the passive zone, improve the shear strength of soft soil, reduce deformation, and solve the problems of overall stability and pit bottom uplift.

The common types of foundation pit support for the basement on the first floor in soft soil areas include sloping excavation, cantilever structure, soil nailing wall, cement–soil gravity retaining wall, cast-in-place pile row wall, profiled steel cement–soil mixing wall, steel sheet pile, reinforced concrete sheet pile, etc.; due to the space limitation, this paper only analyzes slope excavation and row pile support.

2.1. Slope Excavation and Shotcrete and Anchor Support. In this chapter, a foundation pit in the Houhu area of Wuhan City is selected, the thickness of the soft soil layer is 20 m, $c = 10\,\mathrm{kPa}$, $\varphi = 4°$, $\gamma = 17\,\mathrm{kN \cdot m^3}$, and the excavation depth of the foundation pit is 4–6 m, and the slope is 1 : 1.5–1 : 0.3. The stability calculation results of the sliding arc of the garden arc method through the stability coefficient k at different depths at the foot of the slope are listed in Table 1.

It can be seen from Table 1 that the stability coefficient $k > 1$ can be met in most cases when the excavation is 4 m, but the value k specified in the design cannot be reached. When excavating 6 m, the value of k is less than 1.0. When shotcrete and anchor support is adopted, the stability coefficient of deep sliding has not been substantially improved, indicating that it is difficult to solve the problem by adding anchor bolts. Therefore, in the deep soft soil area, it is not feasible to use shotcrete and anchor support when excavating a basement foundation pit, and slope excavation is not necessarily reliable.

2.2. Row Pile Support

2.2.1. Cantilever Row Pile. Assume that the excavation depth is 4, 5, 6, and 7 m, respectively, and the diameter of the retaining pile is Φ 900 mm, and the thickness of soft soil is 10, 12, and 16 m, respectively. The soil layer indicators are divided into the following three categories: Class I: $\gamma = 17\,\mathrm{kN \cdot m^{-3}}$, $c = 10\,\mathrm{kPa}$, $\varphi = 0°$, $m = 500\,\mathrm{kPa/m^2}$($m$ is the proportional coefficient of horizontal resistance coefficient of soil); Class II: $\gamma = 17\,\mathrm{kN \cdot m^{-3}}$,

Table 2: Minimum embedded depth of cantilever pile (m)/maximum displacement (mm)/maximum bending moment (kN · m).

Excavation depth (m)	Soil quality parameter	Soft soil thickness (m)		
		10	12	16
4	I	13.5/100/1209	15.6/150/1380	20.0/160/919
	II	12.6/95/914	14.5/110/966	18.3/110/578
	III	11.3/65/633	12.6/70/618	12.9/65/335
5	I	14.7/125/1658	16.8/175/2133	21.2/230/1885
	II	14.0/110/1346	15.9/140/1602	19.8/155/1247
	III	13.0/75/1014	14.6/100/1104	17.6/105/759
6	I	15.9/130/1940	18.0/220/2736	22.4/310/2645
	II	15.2/110/1640	17.2/170/2170	21.2/230/1793
	III	14.4/90/1302	16.0/125/1591	19.4/150/1112
7	I	17.2/135/2135	19.2/240/3217	23.5/410/3519
	II	16.6/120/1848	18.4/210/2662	22.4/320/2468
	III	15.8/100/1516	17.4/155/2,056	20.8/220/1583

Table 3: Minimum embedded depth (m)/maximum displacement (mm)/maximum bending moment (kN · m).

Excavation depth (m)	Soil quality parameter	Soft soil thickness (m)		
		10	12	16
4	I	10.5/18/598	12.4/30/975	16.4/43/1098
	II	10.2/16/494	12.1/24/751	14.5/32/723
	III	7.8/12/381	7.8/17/530	7.84/19/329
5	I	10.8/21/622	12.7/33/1044	16.7/55/1269
	II	10.6/18/527	12.4/27/831	16.2/37/867
	III	10.2/14/419	11.4/20/610	11.4/24/425
6	I	11.3/24/638	13.1/35/1099	16.9/59/1476
	II	11.0/20/552	12.8/30/903	16.5/44/1047
	III	10.6/17/451	12.3/23/692	14.9/29/541
7	I	11.8/28/645	13.5/27/1127	17.3/65/1703
	II	11.6/24/566	13.2/32/953	16.8/51/1253
	III	11.2/20/474	12.8/26/759	16.3/34/673

$c = 10\,\mathrm{kPa}$, $\varphi = 4°$, $m = 750\,\mathrm{kPa/m^2}$; Class III: $\gamma = 17\,\mathrm{kN \cdot m^{-3}}$, $c = 10\,\mathrm{kPa}$, $\varphi = 7°$, $m = 1{,}000\,\mathrm{kPa/m^2}$; below it is a silty fine sand layer, $\gamma = 19\,\mathrm{kN \cdot m^{-3}}$, $c = 0\mathrm{kPa}$, $\varphi = 30°$, $m = 15{,}000\,\mathrm{kPa/m^2}$; cantilever piles are used for support. The calculation results of the minimum embedded depth (m), maximum displacement (mm), and maximum bending moment (kN · m) of the supporting piles are shown in Table 2.

2.2.2. Pile Support. The calculation results of the minimum embedding depth (m), the maximum displacement (mm), and the maximum bending moment (kN · m) of the supporting pile are shown in Table 3, and the soil layer index is the same as that of the cantilever row of piles. Neither the calculations in Table 2 nor Table 3 take into account the ground overload, nor do they take into account the thrust that may occur when soft soils slide deeply. This is because the characteristics of soft soil determine that it has a low bearing capacity and is prone to settlement and deformation. However, foundation overload and deep sliding will further increase the deformation and instability of the foundation, so these factors are usually ignored in the design calculation to ensure the safety and reliability of the structure [32]. However, in practical engineering, the instability and deformation of soft soil foundation must be paid attention to. In order to strengthen the soft soil foundation, some measures can be adopted, such as heavy hammer tamping or strong compaction. In addition, in the reinforcement construction of soft soil foundation, hydrostatic grouting method can also be used for reinforcement. The hydrostatic grouting method can effectively improve the stability and bearing capacity of soft soil foundation. In the construction, it is necessary to pay attention to the investigation and evaluation of the soft soil foundation and select the appropriate reinforcement method and construction technology to ensure the quality of construction.

In conclusion, the purpose of not taking into account the overload of the foundation and the thrust that may occur when the soft soil slides at deep depths is not taken into account in the calculation to ensure the safety and reliability

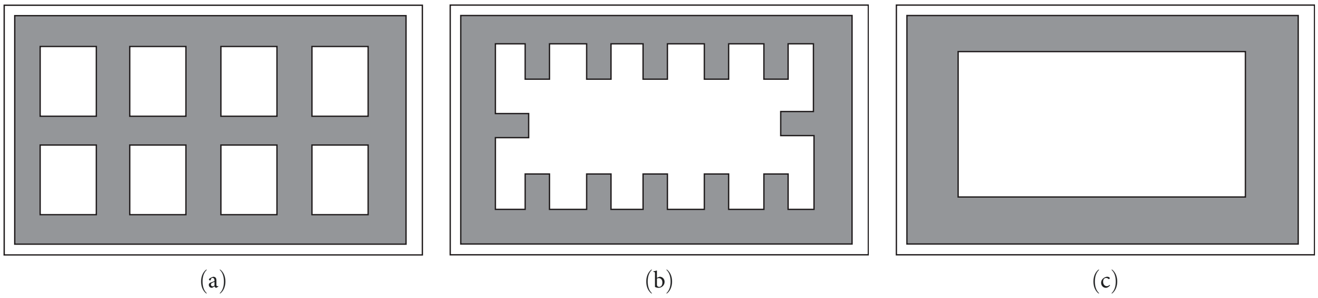

Figure 1: Reinforcement plan of passive area. (a) Lattice concealed bracing. (b) Pit bottom concealed buttress. (c) Pit surrounding concealed wall.

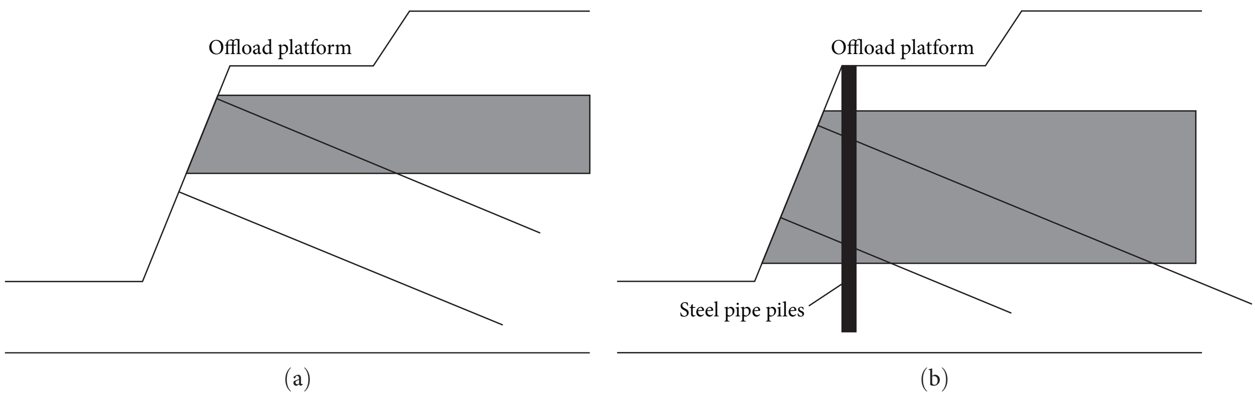

Figure 2: Sliding type support form of half slope and slope toe. (a) Half-slope landslide support form. (b) Slope foot sliding type support form.

of the structure. However, in actual engineering, the instability and deformation of soft soil foundation need to be solved by reasonable reinforcement measures.

It can be seen from Tables 2 and 3 that cantilever row pile support can be considered when the excavation depth is within 5 m and the soft soil is not too thick and the soil quality is not too poor. In deep soft soil, when cantilever row piles are used for support, the deformation is too large, the bending moment is too large, and the pile length is required to be large, so it is not economical and safe. The internal force and horizontal displacement will be reduced after adding a layer of internal support, but if the pile end is not embedded in hard soil layer (such as sand layer) after adding internal support, the phenomenon of "skirting" at the lower end of the pile will occur. The test results of Ye Yan of the Chinese Academy of Architecture and Research show that the displacement of retaining piles (walls) is doubled, the passive earth pressure is doubled, and the sand layer bears more than 60% of the load when the row piles embedded in the sand layer are embedded in the sand layer for $1/3h$ (h is the buried depth below the pit bottom of the retaining structure). However, when the thickness of the soft soil layer is more than 3 times of the excavation depth, the bending moment of the pile shaft is large, and the choice should be determined after calculation.

2.3. Reinforcement Design of Passive Area. The reinforcement of the passive area mainly includes pier reinforcement, skirt reinforcement, strip reinforcement, grid reinforcement, and full hall reinforcement according to the plane layout. Figure 1 shows the reinforcement plan of the passive area.

2.4. Summary of Foundation Pit Support Types in Soft Soil Areas. This paper collects more than 10 successful cases of foundation pit support in soft soil areas. The support types are summarized as follows.

(1) Load reduction—shotcrete-bolt support or composite shotcrete-bolt support. For the soft soil foundation pit of half-slope type and sliding type at the foot of slope, a relatively wide load reduction platform can be set to reduce the weight of the overlying soil to the point where no uplift or lateral extrusion will occur, and the shotcrete anchor or composite shotcrete anchor form (Figures 2(a) and 2(b)) can be adopted for support.

(2) Several support forms of deep soft soil foundation pit under different conditions: (a) The bottom of the pit is soft soil, but there is a relatively hard layer within a certain depth. When the site has conditions to set a load reduction platform, the support form of load reduction platform and cement–soil retaining wall can be used, and the wall bottom is deep into the hard soil layer (Figure 3(a)). (b) The bottom of the pit is soft soil, and there is a relatively hard layer within a certain depth, but the site is narrow and there is no conditions for slope and load reduction, rigid retaining piles (walls) plus internal support can

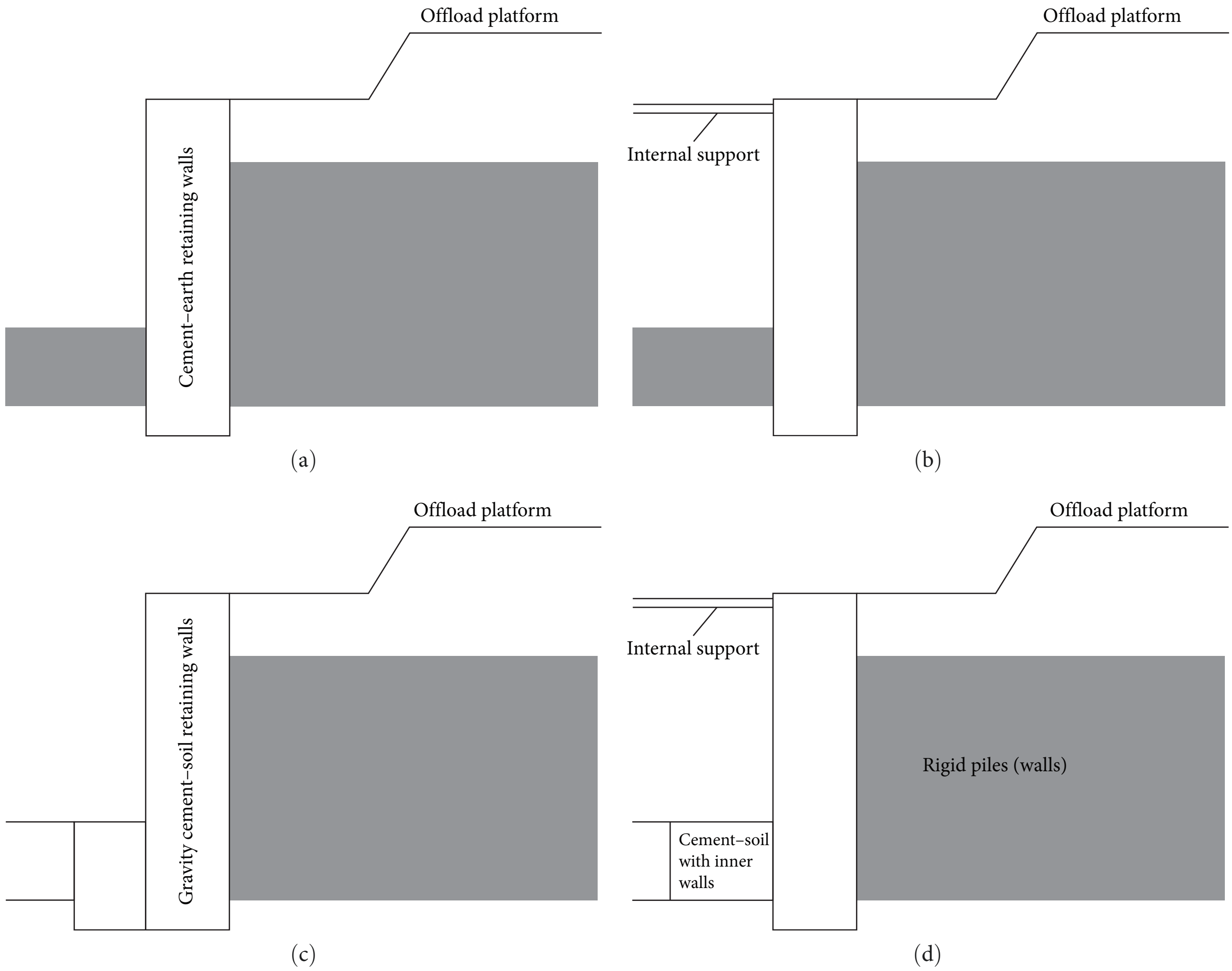

FIGURE 3: Deep sliding support form of deep soft soil base uplift.

be used, and the pile bottom is deep into the hard soil layer (Figure 3(b)); gravity cement–soil retaining wall can also be used, and the bottom of the wall is deep into the hard soil layer (Figure 3(c)). (c) The bottom of the pit is deep soft soil, there is no relatively hard soil layer within a certain depth, and there is no large amount of load reduction conditions on the site. When rigid piles (walls) are used with internal support, the passive area is reinforced within a certain depth under the pit inside the pile to control the "skirting" deformation of the lower part of the pile toward the pit (Figure 3(d)).

(3) Composite shotcrete and anchor support. When the thickness of the soft soil is not large and the excavation depth is small, the cement soil pile or micro steel pipe (plate) pile and spray anchor joint support form can be used (Figure 4). Sometimes, there are silt or silt interlayers or interbeds in the soft soil of river and lake facies, and the impermeability curtain must be separated at this time. The composite spray anchor support adopts a combination of grouting materials and anchors, which can fully strengthen the formation and improve the stability and bearing capacity of the slope. This can reduce the size and cost of reinforcement works.

The construction process of composite spray anchor support is relatively simple and does not require a large amount of equipment and materials. The preparation and grouting operation of the grouting material are relatively easy to master, and the installation and tensioning of the anchor rod are also relatively simple. This can reduce the construction period and the consumption of human resources. Composite spray anchor support can provide reliable support effect under complex geological conditions, high slope engineering and temporary support needs, and the construction is simple and the cost is relatively low, so the use of "composite support" is more economical and reasonable.

(4) When the excavation depth is large (such as two floors of basement), or the depth is small, but the surrounding environment is severe, rigid pile anchor or internal bracing support system shall be adopted.

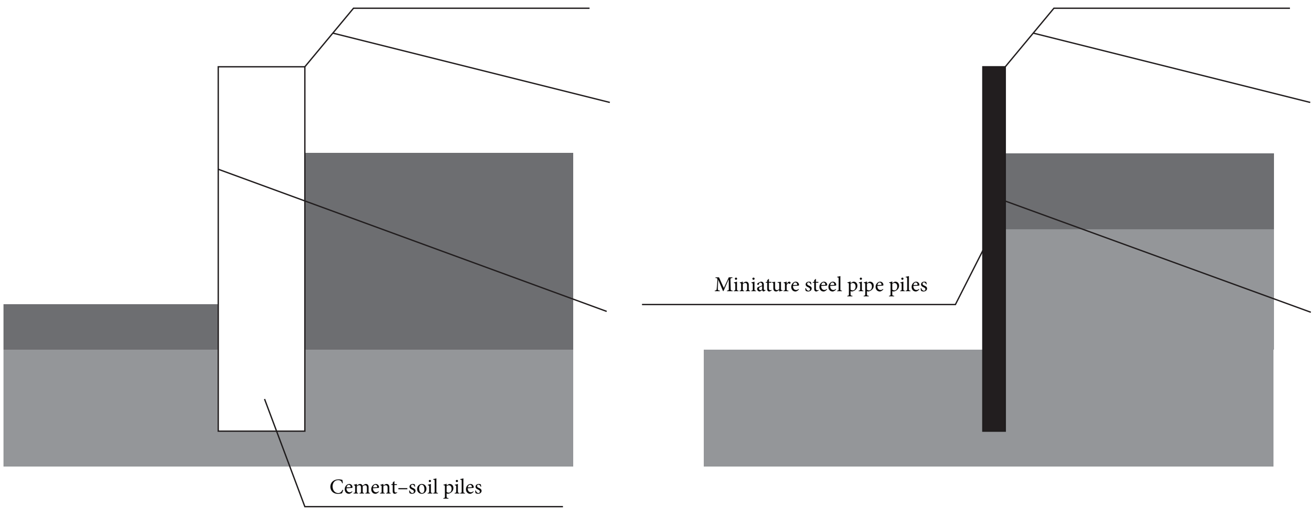

Figure 4: Composite shotcrete and anchor support.

Table 4: Physical indexes of soil and average cone resistance of static cone penetration test.

Layer no.	Name of soil layer	General thickness (m)	State	Water content (%)	Void ratio	Liquidity index	Cone tip resistance (MPa)
②$_2$	Clayey silt	4	Plastic	31	0.87	—	2.49
④$_2$	Mucky clay	16	Flow plastic	50	1.42	1.34	0.54
⑥$_1$	Argillaceous powder Silty clay	17	Flow plastic	46	1.33	1.49	0.77
⑥$_2$	Silty clay	9	Soft plastic	35	0.98	0.97	1.20

The main soft soil layer is ④$_2$ muddy clay and ⑥$_1$ muddy silty clay. See Table 5 for the recommended soil strength parameters in the survey report.

In summary, the reasons for choosing the support form mainly depend on the specific requirements of the underground structure and the conditions of the engineering environment [33]. It is necessary to comprehensively consider the factors such as underground horizontal load, vertical load, soil conditions, and groundwater level and select the most suitable support form. For example, in the case of large horizontal loads in the underground, rigid support piles (walls) can be selected with internal supports to increase the stability of the underground structure. In the case of small horizontal load underground, load reduction—spray anchor support can be selected to reduce the load of the underground structure. The composite spray anchor support can be comprehensively used according to the specific situation of different support forms to achieve better results.

3. Case Analysis of Foundation Pit Accident in Soft Soil Layer

3.1. Case Analysis of Hangzhou Metro Line 1

(1) Project overview. The foundation pit of Hangzhou Metro Line 1 is 107.8 m long, 21 m wide, and 16 m deep. It is supported by underground continuous wall + 4 steel supports; the thickness of the diaphragm wall is 800 mm, the depth of the wall is about 33 m, embedded 17.3 m below the bottom of the foundation pit, and the horizontal spacing of the support is 3 m. The design requires excavation in layers and sections, and the length of each section is 15–20 m. When the excavation reaches 0.5 m below the elevation of the support surface, the excavation must be stopped, the support must be erected, and overexcavation is not allowed.

(2) Engineering geological conditions. Table 4 is the physical property index and static penetration test data of the stratum and soil provided in the survey report of the project.

(3) Accident and cause analysis. On November 15, 2008, when the design elevation of the foundation pit was reached and the bottom plate and lining wall were being operated, the west side of the Fengqing Avenue collapsed suddenly, with a depth of 5–6 m, and dozens of vehicles were trapped.

(a) Construction overbreak. The construction overbreak is the direct cause of the accident in this case. According to the calculation, the absence of

Table 5: Strength index of soil.

Layer no.	Layer name	Direct shear and quick shear		Direct shear and fast fastening		Unconfined strength	Three-axis UU		Three-axis CU		Triaxial	
		c_q (kPa)	φ_q (°)	c_{cq} (kPa)	φ_{cq} (°)	*qu (kPa)*	c_{cq} (kPa)	φ_{cq} (°)	c_{cu} (kPa)	φ_{cu} (°)	c'(kPa)	φ' (°)
②$_1$	Clayey silt	11.6	16.8	16.2	18.1	—	—	—	—	—	—	—
②$_2$	Clayey silt	7.6	26.9	10.2	31.8	—	—	—	—	—	—	—
④$_2$	Mucky clay	8.5	6.7	15.3	13.0	20.3	8.3	0.2	18.3	4.7	16.0	4.5
⑥$_1$	Argillaceous powder Silty clay	7.2	8.5	13.5	13.6	24.1	10.1	0.3	17.3	12.6	20.3	16.7
⑧$_2$	Silty clay	7.3	8.1	14.4	16.5	—	8.6	0.6	19.0	15.1	24.0	19.9

The effective stress index of the consolidated undrained (CU) test results of layer ④$_2$ in Table 5 is abnormal. See Table 6 for the relevant data provided by Zhejiang Institute of Geology and Mineral Exploration.

Table 6: Mechanical parameter table for foundation pit support design.

Layer no.	Layer name	Direct shear and quick shear	Straight shear Solid fast	Direct shear and quick shear	Straight shear Solid fast	No side limiting strength	Three-axis UU		Three-axis CU		Triaxial	
		φ_q (^{0})	c_{cq} (kPa)	φ_q (°)	c_{cq} (kPa)	q_u (kPa)	c_{cq} (kPa)	φ_{cq} (°)	c_{cu} (kPa)	φ_{cu} (°)	c' (kPa)	φ' (°)
②$_1$	Clayey silt	11.6	16.8	16.2	18.1	—	—	—	—	—	—	—
②$_2$	Clayey silt	7.6	26.9	10.2	31.8	—	—	—	—	—	—	—
④$_2$	Mucky clay	8.1	6.1	15.8	11.9	25.34	11.0	0.2	17.1	9.7	19.0	12.6
⑥$_1$	Argillaceous powder Silty clay	7.1	8.3	13.8	13.6	24.06	9.0	0.4	17.8	13.2	21.3	17.5
⑧$_2$	Silty clay	7.3	8.1	14.0	18.2	—	8.0	0.6	19.0	15.1	24.0	19.9

Table 7: Shear strength of undisturbed soil and remolded soil (kPa).

Layer no.	Name of soil layer	Shear strength of undisturbed soil	Shear strength of remolded soil	Sensitivity
②$_2$	Clayey silt	60.6	23.0	2.63
④$_2$	Mucky clay	28.6	13.8	2.07
⑥$_1$	Muddy silty clay	34.1	18.4	1.85

Table 8: Unconfined strength and sensitivity of soils at different locations.

Layer no.	Unconfined strength of surrounding soil (kPa)/sensitivity	Unconfined strength of disturbance area outside the pit (kPa)/sensitivity	Unconfined strength in pit (kPa)/sensitivity
④$_2$	47.9/6.6	37.5/4.8	—
④$_3$	58.2/3.8	38.4/2.4	—
⑥$_1$	51.9/9.1	40.3/6.4	45.0/7.5
⑥$_2$	60.5/11.5	47.5/8.0	54.2/8.0
⑧$_2$	76.0/8.0	61.2/6.8	28.5/3.7

the fourth support increases the axial force of the third support, the shear force, and bending moment of the diaphragm wall to 1.5–1.6 times of the original design.

(b) Design calculation parameters. The mechanical parameters are too high, which reduces the safety reserve of the foundation pit system. For example, the standard value c of direct shear fast test for layer ④$_2$ is 14.8 kPa, φ is 10.8°, while the recommended value c in the survey report is 15.3 kPa, φ is 13.0°, which is higher than the standard value φ higher than the average value of 11.6°; the standard value c of layer⑥$_1$ test is 11.9 kPa, φ 11.7°, but the recommended value c in the report is 13.5 kPa, φ 13.6°. From the perspective of soil physical index and static cone resistance, the two layers of soil are very weak. The water content of layer ④$_2$ is 50%, layer ⑥$_1$ is 46%; the cone resistance of layer ④$_2$ is 0.54 MPa, and layer ⑥$_1$ is 0.77 MPa. According to the triaxial test results, the strength index is very low, and the consolidated undrained shear ④$_2$ layers φ is only 4.7°, and the value of layer ⑥$_1$ is 12.6°. The recommended value is not lower than the standard value but higher.

See Table 7 for the sensitivity of soil provided in the engineering survey report. The sensitivity of the main soil layers on the site is quite high (for example, the sensitivity of ④$_2$ is 2.07). After the accident, the soil inside and outside the pit is disturbed, and the sensitivity is reduced (for example, ④$_2$ is reduced from 6.6 to 4.8); see Table 8.

(c) Antiuplift and overall stability. According to the Code for Design of Building Foundation (GB 50007-2011) and other specifications, the uplift at the bottom of the pit was checked and calculated, and the safety factor could not meet the specification requirements. The overall stability is checked, and the safety factor is only 1.12, which does not meet the requirements of 1.3. As the underground diaphragm wall is suspended in the muddy soil, the wall will also have a large internal displacement, resulting in a large settlement (measured as 316 mm), thus making the internal support with poor integrity unstable.

(d) Stability of internal support. The overall rigidity of the internal support system is very weak, and the design document does not have the detailed drawing of the connection node of the support steel pipe and the underground diaphragm wall and the detailed drawing of the connection point of the steel pipe. When the diaphragm wall has a large displacement, the axial force of the support is too large and seriously eccentric, resulting in the rapid instability of the support system.

3.2. Commonality Analysis of Soft Soil Foundation Pit Cases. From the following aspects, the cases of Hangzhou Metro Line 1 and Wuhan Houhu are jointly analyzed.

(1) Stability analysis: excavation depth, slope ratio, and support mode all affect stability. For example, the stability requirement is met when the excavation is 4 m in the Houhu area of Wuhan City, but not when it is 6 m, indicating that the stability decreases with the increase of depth. Overexcavation of Hangzhou Metro Line 1 led to collapse, further emphasizing the importance of controlling the excavation depth.

(2) Selection of support mode: The support mode is crucial to stability. In the deep soft soil area, the spray anchor support is not feasible, while the cantilever row pile support is feasible, but the length, internal force and displacement of the pile need to be considered. Hangzhou Metro Line 1 uses underground diaphragm wall + 4 steel support support to meet the

design requirements, which illustrates the importance of choosing the appropriate support mode according to the engineering conditions and design requirements.

(3) Design parameter selection: Design parameters affect the safety and economy of the project. The physical properties, intensity index, and sensitivity of the soil should be considered when selecting. In the accident of Hangzhou Metro Line 1, the high parameter selection reduced the safety reserve.

(4) Engineering survey and actual conditions: Engineering survey provides a basis for design, but the actual construction conditions may not be consistent with the survey report and need to be monitored and adjusted.

(5) Accident analysis and prevention: The causes of accidents that have occurred should be analyzed in depth and preventive measures should be taken. The cause of the accident on Hangzhou Metro Line 1 was over-excavation and improper parameter selection, so the excavation depth should be controlled and appropriate parameters should be selected.

To sum up, stability analysis, support mode selection, design parameter selection, engineering investigation and actual conditions, accident analysis, and prevention are the key points. These factors should be fully considered in the actual project to ensure the stability and safety of the foundation pit project.

4. Discussion on the Causes of Soft Soil Foundation Pit Accidents and Support Design

This paper collects more than 10 domestic cases of foundation pit accidents in soft soil layer to analyze, summarize, and discuss the design of foundation pit in soft soil layer.

4.1. Selection of Soil Layer Calculation Parameters

4.1.1. Calculation Parameters. The shear strength of soil is the main parameter for foundation pit design calculation, but the reliability of the strength parameters provided in some survey reports is very poor, especially the triaxial test results, which are far from the empirical value [34]. One of the possible reasons for this is the uncertainty factor in the trial process. Triaxial testing requires consideration of several variables, such as the drainage conditions of the specimen, pore water pressure, and axial load. There may be some errors in the measurement and control of these variables, which can have an impact on the test results. In addition, some deviations may also be introduced in the preparation and handling of specimens. Another reason is the complexity of the soil itself during the experiment. Soil is a multiphase medium, and changes in its internal structure and properties can affect the test results. Factors such as the particle shape, particle size distribution, and friction between particles in the soil will affect the shear strength parameters. In addition, the consolidation and rheological properties of the soil may also have an impact on the test results. In order to improve the reliability of the triaxial test results, a number of measures can be taken. First of all, the test parameters are correctly selected, such as drainage conditions and pore water pressure, to ensure that the test process meets the requirements of practical engineering problems. Second, the preparation and handling process of the sample is strengthened to ensure the quality and consistency of the sample. Finally, multiple replicates of the trial are performed to obtain more reliable average results. However, it should be noted that the triaxial test is only an experimental method, and its results still need to be comprehensively analyzed and judged in combination with practical engineering problems. The difference between the test results and the empirical values may be due to the difference between the test conditions and the actual engineering conditions. Therefore, when applying the triaxial test results, it is necessary to make reasonable explanations and corrections based on the actual situation.

The direct shear test cannot control drainage and determine the effective strength of soil, but it is simple to operate and has more experience in China and can be used as an alternative method [34]. The direct shear test is a commonly used test method, as a simplified test method, the shear strength parameters of the soil can be obtained in a relatively short time. However, it should be noted that the results of the direct shear test may be different from the actual engineering situation because it does not fully simulate the mechanical behavior of the soil under triaxial conditions.

Generally, the survey report provides only one representative value (average value, standard value, or recommended value) of the strength index of the unconsolidated undrained shear (hereinafter referred to as the undrained shear) for each layer of soil. For the bearing capacity of the shallow foundation, the thickness of the soil involved is limited, and the problem is not serious; however, for the stability calculation of foundation pit, the thickness of soil involved is large, and one value is not representative enough. Because for thick soil, the undrained strength varies with the depth. The undrained strength of saturated cohesive soil is only cohesion, and the internal friction angle is 0, which represents the total strength of the soil. For normally consolidated soil, the total strength increases with the increase of depth. The vane test is the undrained strength, and the strength of the same layer of soil increases with the increase of the test depth. So is the indoor undrained shear test. Therefore, the undrained strength of normally consolidated soil in natural state is essentially the consolidated undrained strength under effective dead weight pressure at different depths, which can be expressed by Formula (1):

$$c_{\mathrm{uf}} = c_{\mathrm{cu}} + \sigma'_{\mathrm{zi}} \tan\varphi_{\mathrm{cu}} \tag{1}$$

where c_{cu} is the undrained strength at point i below the ground; σ_{Zi} 'is the effective dead weight stress at point i below the ground.

If only one representative value of undrained strength index is provided for a layer of soil, the shallow soil may be higher and the deep soil may be lower. When Formula (2) is used to calculate the foundation pit heave, an unreasonable result will be obtained that the deeper the embedment is, the smaller the safety factor is.

$$\frac{5.14c_u + \gamma t}{\gamma(H + t) + q} \tag{2}$$

where H is the excavation depth of the foundation pit; t is the embedding depth of the supporting structure; q is overloaded; K is the safety factor.

4.1.2. Calculation of Water and Soil Pressure. The calculation of water and soil pressure includes how to understand the pore water pressure, hydrostatic pressure and excess hydrostatic pressure of cohesive soil, whether cohesive soil with low permeability can transmit hydrostatic pressure, and the c φ. The soil water pressure should be calculated separately or jointly, the shear strength index of soil should be determined by triaxial test or direct shear test, and the test method should be consolidated undrained shear (CU) or undrained shear (UU), which should be selected according to the actual working conditions.

The cost of water and soil is shared. Based on the effective stress principle of soil, the water and soil separate calculation is reasonable, but the operation is difficult. In practical engineering, the effective stress method has not been used for the water and soil separate calculation of cohesive soil. The water and soil economy is not complete in theory, but it is easy to implement. With some experience correction, it is more reasonable to use the water and soil economy when there is experience.

According to the research progress of relevant data, the causes of soft soil foundation pit accidents mainly include the mechanical properties of soil mass, groundwater level changes, earthquakes, and other factors. The selection of soil layer calculation parameters in the support design is a key step. When designing the supporting structure system, it is necessary to consider factors such as the location of adjacent buildings, roads, and pipelines, as well as the mechanical properties and variability of the soil layer. In terms of the selection of soil calculation parameters, some scholars have proposed three methods to simplify the consideration of spatial variability, which are the parameter reduction method, the amplification coefficient method and the reliability partial coefficient calibration method. These methods are proposed on the basis of a large number of Monte Carlo calculations, which can provide a certain reference for practical engineering.

4.2. Stability Analysis. The surrounding environment of urban foundation pit is generally complex, and the design of foundation pit is mainly deformation control. The static balance method is used to determine the insertion depth of the pile wall, the limit load is used to check the uplift of the pit bottom, and the circular sliding method is used to check the overall stability of the foundation pit. At present, the calculation methods of uplift resistance and overall stability stipulated in the specifications, regardless of the calculation formula and parameters, are different from the actual situation. For example:

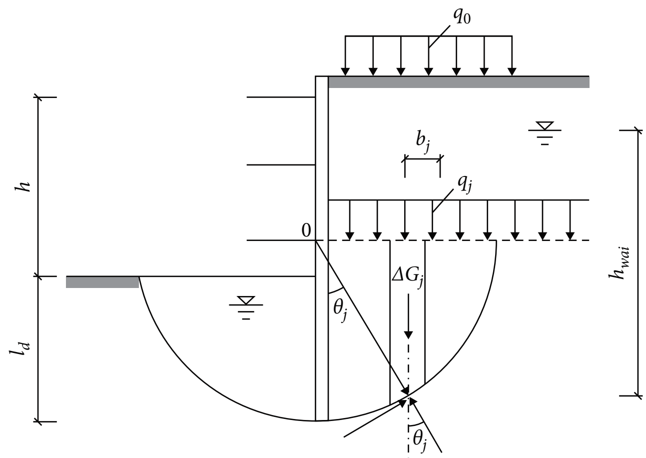

Figure 5: Schematic diagram for calculation of antiskirting.

(1) The consolidated undrained shear strength index is used for the underconsolidated soil, and the consolidated undrained shear strength index is used for the temporary overload of the ground. The actual consolidation state of the soil is inconsistent with the test method;
(2) Disturbance of vehicle, construction and other dynamic loads on highly sensitive soil;
(3) Rainfall and water leakage increase the dead weight of soil and reduce the strength of soil;
(4) The underground water at the back of the wall seeps downward and the underground water in front of the wall seeps upward, which has a negative impact on the effective pressure of the soil;
(5) Calculation and stability of water and soil. The above are all adverse factors, and there are also favorable factors, such as the structural strength of the soil, the matrix suction of the unsaturated soil, the three-dimensional effect of the plane of the foundation pit, the negative pore pressure caused by the swelling of the saturated soil during the excavation process, and the lowering of the groundwater level outside the pit. Since it is difficult to quantitatively analyze the favorable and unfavorable factors, the stability analysis specifies a certain safety factor.

For stability calculation, if the unconsolidated undrained strength index is used, since the internal friction angle of saturated cohesive soil is 0, the antisliding moment of this part is 0 regardless of the floating weight or saturated weight. However, if the consolidated undrained strength index is adopted, since the soil mass is consolidated under the floating weight rather than under the saturated weight, the sliding moment adopts the saturated weight, and the antisliding moment must adopt the floating weight. Figures 5 and 6 are the calculation schematic diagrams of antiskirting and antiuplift, respectively.

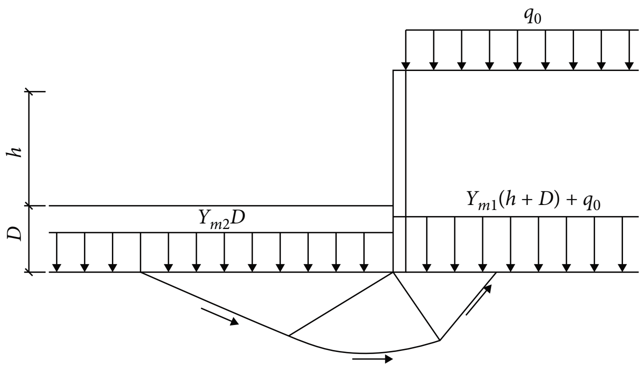

Figure 6: Schematic diagram for calculation of antiuplift.

Generally, Formula (3) is used to calculate the stability against uplift:

$$\frac{\gamma_{\mathrm{m2}}\mathrm{DN}_q + \mathrm{cN}_r}{\gamma_{\mathrm{m1}}(h + D) + q_0} \geq K_b, \tag{3}$$

where Nq is the bearing capacity coefficient related to depth, Nc is the bearing capacity coefficient related to cohesion, and other symbols are shown in Figure 6.

When the unconsolidated and undrained strength index is adopted, Nq = 1.0, Nc is 5.14 and Terzaghi is 5.7. If the consolidated undrained strength index is used for calculation, Nq is far greater than 1.0, thus expanding the bearing capacity, which is unsafe. Therefore, Li Guangxin suggested that Formula (4) should be used for calculation, that is, floating weight should be used for resistance and saturated weight should be used for load.

$$\frac{\gamma'_{m2}\mathrm{DN}_q + \mathrm{cN}_r}{\gamma_{\mathrm{m1}}h + \gamma'_{m1}D + q_0} \geq K_b \tag{4}$$

When analyzing the impact of earthquakes on the stability of foundation pits, it is crucial to consider the dynamic properties of earthquakes and their potential to compromise soil stability [35]. Earthquakes have the potential to cause liquefaction in sandy and silty soils, leading to a loss of support and subsequent sliding or collapse of the pit's sidewalls [36]. Furthermore, earthquakes can induce soil displacement and deformation, undermining the stability of foundation pits. There are three primary methods for designing and calculating both static and seismic loads. The static analysis method, which considers static and nondynamic loads like soil weight and construction load, aids in evaluating the stability of foundation pits in the absence of seismic activity. The dynamic analysis method, on the other hand, takes into account the dynamic characteristics of earthquakes to more accurately predict the dynamic response of soil and structures using tools like finite element or finite difference methods. A comprehensive analysis, which combines static and dynamic analysis, comprehensively considers the stability of foundation pits under both static and seismic loads [37]. Additionally, factors like soil physical properties, seismic characteristics, and the geometric shape and depth of the foundation pit can significantly influence the stability of the foundation pit [38]. In summary, to ensure engineering safety, economy, and rationality, a comprehensive evaluation of the impact of earthquakes on the stability of foundation pits should be conducted, and appropriate methods should be utilized for design calculations.

Based on the foundation pit of a soft soil layer in Wuhan City, the antiskid moment calculated by saturation gravity is 2.4 times higher than that calculated by floating weight.

Table 9: Maximum bending moment of cantilever piles with different overload and excavation depth (KN · m).

Overload (kPa)	Excavation depth (m)			
	4	5	6	7
0	452	1,549	3,781	7,546
5	670	2,038	4,655	8,919
10	953	2,624	5,657	10,451
15	1,309	3,313	6,794	12,149
20	1746	4,116	8,077	14,025

4.3. Pit Side Overload. Overload at the pit side has a great impact on the supporting structure. Table 9 shows the maximum bending moment of cantilever pile at different overload and excavation depth ($c = 10$ kPa for soil layer, $\varphi = 6°$).

As can be seen in Table 9, when the pit edge overload is 20 kPa, the maximum bending moment value of the cantilever pile is 2–4 times that of no overload. Therefore, the design should be calculated according to the possible overload intensity and distribution range at the pit edge rather than according to the infinite distribution mode outside the pit edge. When the impact of overload is too large, it is not advisable to blindly strengthen the supporting structure but should take measures to strictly limit the overload at the pit edge to reduce the burden of the supporting structure. The problem of pit edge overload in support design is a problem that needs to be focused on and solved in soft soil foundation pit engineering. In terms of research, some progress has been made in the research on the design of soft soil foundation pit support structure system.

To sum up, the causes of soft soil foundation pit accidents and the problem of pit edge overload in support design have attracted extensive attention from researchers. Through the in-depth discussion of related research, it can provide theoretical guidance and practical experience for the support design and construction of soft soil foundation pit engineering.

4.4. Monitoring and Early Warning. Foundation pit engineering is a complex system with dynamic changes in the interaction between soil and retaining structure. It is difficult to accurately predict the changes of the system in construction by mathematical and mechanical methods alone. Monitoring has become an extremely important measure. If the safety reserve is too large, the design can be modified in time. Through back analysis, the calculation model can be modified, the calculation parameters can be adjusted, the experience can be summarized, and the design and construction level can be improved.

5. Conclusion

(1) The analysis of foundation pit support type selection in deep soft soil area shows that it is not feasible to adopt shotcrete anchor support, and slope excavation is not necessarily reliable. When supporting cantilever row piles, the length of piles is required to be large, uneconomical and unsafe.

(2) For soft soil foundation pits of half-slope type and sliding type at the foot of slope, larger load reduction platform can be set. According to the distribution of soft soil layer, several support forms are summarized.

(3) Selection of soil layer calculation parameters for soft soil foundation pit support design:

   (a) At present, the reliability of shear strength parameters of triaxial test soil is poor;

   (b) The soil water pressure should be calculated separately or economically, the shear strength index of soil should be determined by triaxial test or direct shear test, consolidated undrained shear or undrained shear, etc., which should be selected according to the actual working conditions.

   (c) If only one representative value of undrained strength index is given for a layer of soil, the shallow soil may be higher and the deep soil may be lower. When calculating the heave of foundation pit, an unreasonable result will be obtained that the deeper the embedment is, the smaller the safety factor is.

(4) Stability analysis.

   (a) At present, the calculation methods of uplift resistance and overall stability stipulated in the specifications, regardless of the calculation formula and parameters, are different from the actual situation;

   (b) In the calculation of antikick and antiheave, the sliding moment should adopt the saturated weight, while the antisliding moment must adopt the floating weight;

(5) When the pit side overload is 20 kPa, the maximum bending moment of cantilever pile is 2–4 times of that without overload.

Data Availability

The [DATA TYPE] data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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