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Parameter Sensitivity Analysis of Soft Soil based on Orthogonal Test

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Abstract

To study the effect of excavation of subway station pit on the lateral displacement of enclosure structure and surface settlement, and to explore the influence degree of soft soil on the lateral displacement of retaining structure and surface settlement in the construction area, a small mileage section of a subway station pit in Shenzhen was simulated and analyzed by finite element numerical software, and the data of lateral displacement of enclosure structure and surface settlement outside the pit were obtained, and the orthogonal test method was used to compare and analyze the deformation of the soft soil with different burial depth under different parameters. The results show that soil at the lower position is more sensitive to the deformation of the pit. Among the nine parameters of the three soft soil layers, the top four parameters with the greatest influence on the horizontal displacement of the enclosure structure are φ_3, c_3, φ_2, c_2 and the greatest influence on the surface settlement outside the foundation pit are c_3, φ_3, c_2, φ_2 respectively.

Keywords

Soft Soil; Lateral Displacement of Enclosure Structure; Surface Settlement; Sensitivity Analysis.

1. Project Overview

The project is based on the small mileage section of the foundation pit of a subway station in Shenzhen. The length of the foundation pit area is 70 m, the width is 12.2 ~ 20.8 m, the excavation depth is 17 ~ 18 m, the site of the foundation pit construction area is relatively flat, and the surface elevation is 2.72 m ~ 3.16 m. According to the geological borehole survey report, the site is covered by the Quaternary Holocene Artificial Fill Layer (Q4ml), Holocene Sea-Land Interaction Layer (Q4mc), Upper Pleistocene Alluvium Layer (Q3al+pl) , and Residual Layer (Qel). The enclosure structure adopts an 800mm thick diaphragm wall with C35 (P8) submerged concrete, and the downward embedded depth is about 6m. A concrete support and two steel supports are used in the foundation pit, the concrete strength grade of the support and crown beam is C30, the steel support is Φ=800mm, t=20mm steel pipe, and the waist beam adopts a double-spliced I-beam combined steel structure.

2. Numerical Simulation

2.1 Introduction to the Model

The geotechnical general finite element software MIDAS GTS NX was used to establish the three-dimensional numerical model of the foundation pit. According to the maximum excavation impact range of the foundation pit in 3-5 times the excavation depth[1], considering the boundary response, mesh quantity and model calculation accuracy, combined with the excavation size of the foundation pit, the model was determined to be 124m in the length direction, 128.8m in the width direction, 54m

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in the height direction, with a total number of 49698 elements and 31934 nodes, with normal constraints applied to the sides and fixed boundaries applied to the bottom surface. The model and the internal support structure of the foundation pit are shown in Figure 1.

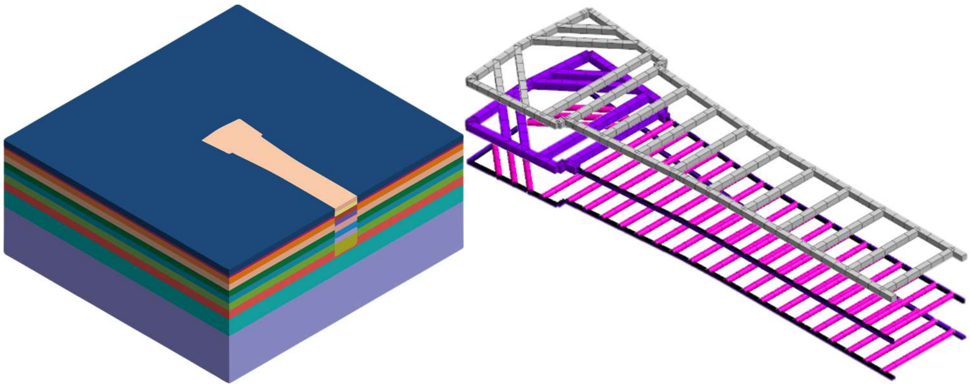

Figure 1. Schematic diagram of model and support structure

2.2 Model Parameters

The correctness of the numerical simulation results depends on the selection of the principal structure model and the reasonable setting of the parameters. Considering the foundation excavation as the unloading project, several scholars have verified the applicability of the modified Mohr-Coulomb principal model (MMC model for short) in the foundation pit excavation simulation project through numerical simulation and field monitoring[2,3]. The MMC model considers different moduli for loading and unloading, and is more consistent with the surface settlement around the foundation pit and lateral displacement of the enclosure structure. Therefore, the soil is selected from the modified Mohr-Coulomb principal model, and the solid element is used for simulation. The enclosure structure is simulated by the plate element, and the support, crown beam, waist beam, and other 1-D structures in the pit are simulated by the beam element, and both the plate element and beam element are used in the linear elastic principal structure. The mechanical parameters of the soil layer are selected regarding the geological survey report combined with the empirical values of the region, and the thickness distribution of the soil layer is simplified according to the geological drilling results.

Table 1. Mechanical parameters of soil materials

Name of soil	Density γ(kN/m^3)	Secant stiffness E_{50} (Mpa)	Unloading-reloading stiffness E_{ur} (Mpa)	Poisson ratio μ (/)	Internal friction angle φ(°)	Cohesion c (kPa)
Plain fill	17.80	6.0	18.0	0.32	13	15
Silt clay	16.10	2.0	10.0	0.43	4	10
Silty powdery clay	16.50	3.5	17.5	0.4	5.5	12.5
Powdery clay	18.80	6.5	19.5	0.3	12.5	25
Coarse sand	19.50	8.5	25.5	0.29	35	0
Sandy clay	18.50	9.0	27.0	0.28	22.5	25
Fully weathered rock	18.80	15.0	45.0	0.26	25	30
Strongly weathered rock	19.30	20.0	60.0	0.25	27	35
Weathered rock	24.50	40.0	120.0	0.22	40	500

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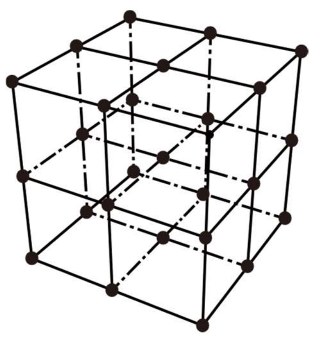
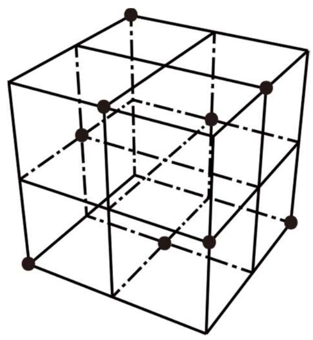
3. Orthogonal Test

3.1 Principle of Orthogonal Test

The orthogonal test method is a scientific, effective and economical experimental design method[4], when studying the degree of influence of multiple factors and multiple levels for a certain result, according to the conventional, only one parameter is changed in each test, and a single control variable is adopted, which will often require a large number of tests, and a 9-factor, 3-level test, for example, will be conducted 3^9 times, which will consume a lot of financial resources. The core idea of the orthogonal test is to use orthogonality to select representative points for testing in a comprehensive test, and use the test situation of this representative part of the points to express the overall test results. Using the cube and the points on the upper side to represent the distribution of the test, as shown in Figure 2, it can be seen that the full-scale test considers all cases, the test points are distributed in each vertex of each cube, while the distribution of the orthogonal test points is only part of the distribution of the full-scale test points, but each side of the cube is arranged with test points, by comparison, it is clear that the orthogonal test method can significantly reduce the number of tests and reduce the workload of the test.



Full-scale test point distribution



Orthogonal test point distribution

Figure 2. Distribution of test points

The orthogonal test table is a table formed by selecting the combination of the levels of each influencing factor from all the tests, which needs to satisfy two conditions, one is that the number of times each level appears in any column should be equal; the second condition is that for any level in any column, the number of times each level in other columns meets with it in the same row is equal; based on this, the combination of each factor in the orthogonal table is evenly distributed. The results obtained from the orthogonal test are still credible, although the combination of the levels of all the influencing factors is not tested. In addition, the orthogonal table is not uniquely fixed, it can be modified according to the actual test needs to choose the appropriate orthogonal table for the combination, to meet the two conditions of neat comparability, which is generally expressed as $L_n(x^y)$, where n indicates the number of orthogonal tests, x indicates the number of levels of influencing factors, y indicates the number of influencing factors, such as the common four factors and three levels can be expressed as $L_9(3^4)$, the orthogonal table is shown in Table 2.

Table 2. $L_9(3^4)$ orthogonal test table

Parameters \ Test number	1	2	3	4	5	6	7	8	9
1	1	1	1	2	2	2	3	3	3
2	1	2	3	1	2	3	1	2	3
3	1	2	3	2	3	1	3	1	2
4	1	2	3	3	1	2	2	3	1

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3.2 Orthogonal Test Design

The purpose of this test is to determine the degree of influence of different parameters of the weak soil layer in the area of the foundation pit project on the horizontal displacement of the enclosure structure and surface settlement outside the pit, based on engineering monitoring, and later to determine the value of the soil layer parameters within a reasonable interval through the inverse analysis of the weak soil layer parameters. According to the actual engineering situation on site, the soil layer is complex and multi-layered, if the influence of all parameters is considered, the results obtained are often more reliable, and the fit with the actual monitoring results is also higher, but the calculation volume will be very large, and it is not very realistic and cost-effective to conduct a comprehensive test, so it is crucial to select the appropriate parameters for analysis to ensure the accuracy of the test on the one hand and greatly reduce the time and workload invested on the other. According to the relevant literature, the main influencing factors of soil layer parameters are unloading modulus, cohesive, and friction angle. In order to simplify the test, the influencing factors of this orthogonal test mainly select the above three parameters in three layers of soft soil layers of silt clay, silty powdery clay and powdery clay for sensitivity analysis, i.e., a total of 9 parameters, each parameter is set at 3 levels. The specific parameters and their values are shown in Table 3. Eur_i , c_i and φ_i indicate the unloading modulus, cohesion and friction angle of the i-th layer of soft soil respectively.

Table 3. The values of each level of orthogonal test of soil parameters

Levels	Eur_1	φ_1	c_1	Eur_2	φ_2	c_2	Eur_3	φ_3	c_3
1	8000	3.2	8	14000	4.4	10	15600	10	20
2	10000	4.0	10	17500	5.5	12.5	19500	12.5	25
3	12000	4.8	12	21000	6.6	15	23400	15	30

According to the determined number of influencing factors and levels, a suitable orthogonal table was selected to ensure that all influencing factors of this experiment could be covered on the one hand and to minimize the number of trials on the other hand. This testing scheme is 9 factors and 3 levels, choose $L27(3^{13})$ orthogonal test table, which can carry out up to 13 factors and 3 levels of test, the total number of tests 27 times, much less than the number of control variable test scheme, according to the actual number of factors considered in this test is 9, the redundant factors will be deleted, still meet the neat and comparable nature, and does not affect the orthogonality of the orthogonal table.

4. Numerical Simulation Results Analysis

4.1 Deformation Law of Foundation Pit

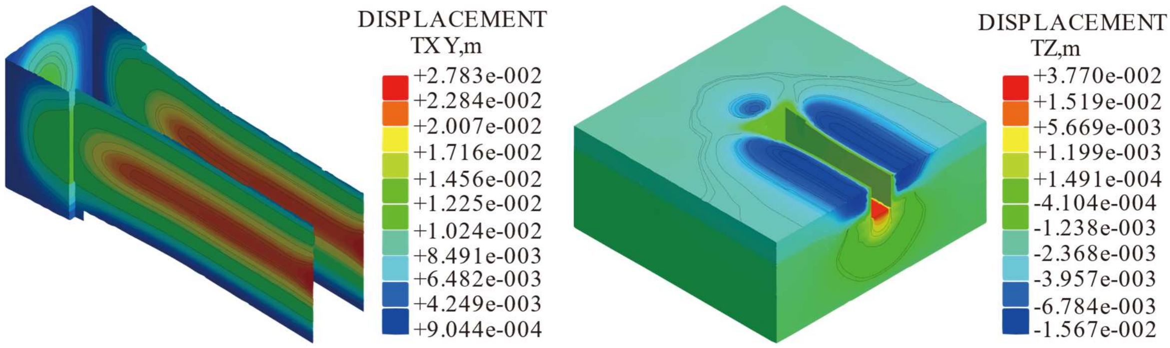

Figure 3. Foundation pit deformation cloud map

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Figure 3 shows the cloud diagram of the horizontal displacement of the enclosure structure and the surface settlement outside the pit after the excavation is completed. It can be seen from the figure that the retaining structure presents a parabolic deformation law. The maximum horizontal displacement value is located in the middle position, and the surface outside the pit presents a groove-type settlement. As the distance from the foundation pit increases, the settlement value gradually increases and then decreases. In addition, according to the cloud diagram, it can be seen that the lateral displacement of the enclosure structure and the settlement deformation of the ground surface outside the pit are larger at the long side of the pit, and the deformation at the short side is smaller, which has a strong spatial effect.

4.2 Orthogonal Test Results

Table 4. Orthogonal test table

Test	Eur_1	φ_1	c_1	Eur_2	φ_2	c_2	Eur_3	φ_3	c_3	Maximum lateral displacement	Maximum surface settlement
1	8	3.2	8	14	4.4	10	15.6	10	20	30.61	17.35
2	8	3.2	8	14	5.5	12.5	19.5	12.5	25	27.08	15.22
3	8	3.2	8	14	6.6	15	23.4	15	30	26.25	14.76
4	8	4	10	17.5	4.4	10	15.6	12.5	25	28.91	16.25
5	8	4	10	17.5	5.5	12.5	19.5	15	30	26.67	14.90
6	8	4	10	17.5	6.6	15	23.4	10	20	28.63	16.25
7	8	4.8	12	21	4.4	10	15.6	15	30	27.36	15.23
8	8	4.8	12	21	5.5	12.5	19.5	10	20	29.06	16.41
9	8	4.8	12	21	6.6	15	23.4	12.5	25	26.81	15.01
10	10	3.2	8	21	4.4	12.5	23.4	10	25	28.77	16.54
11	10	3.2	10	21	5.5	15	15.6	12.5	30	27.40	14.94
12	10	3.2	12	21	6.6	10	19.5	15	20	27.28	15.49
13	10	4	8	14	4.4	12.5	23.4	12.5	30	27.61	15.62
14	10	4	10	14	5.5	15	15.6	15	20	27.59	15.21
15	10	4	12	14	6.6	10	19.5	10	25	28.72	15.98
16	10	4.8	8	17.5	4.4	12.5	23.4	15	20	27.39	15.91
17	10	4.8	10	17.5	5.5	15	15.6	10	25	28.45	15.53
18	10	4.8	12	17.5	6.6	10	19.5	12.5	30	27.12	15.10
19	12	3.2	12	17.5	4.4	15	19.5	10	30	27.92	15.00
20	12	3.2	12	17.5	5.5	10	23.4	12.5	20	28.37	16.23
21	12	3.2	12	17.5	6.6	12.5	15.6	15	25	26.89	14.66
22	12	4	8	21	4.4	15	19.5	12.5	20	28.22	16.14
23	12	4	8	21	5.5	10	23.4	15	25	26.96	15.87
24	12	4	8	21	6.6	12.5	15.6	10	30	28.01	15.59
25	12	4.8	10	14	4.4	15	19.5	15	25	26.83	14.80
26	12	4.8	10	14	5.5	10	23.4	10	30	28.06	15.77
27	12	4.8	10	14	6.6	12.5	15.6	12.5	20	28.25	15.71

According to the orthogonal combination of three physical parameters of the three soft soil layers and numerical simulation, 27 sets of test data were obtained, and monitoring points were arranged at the edge of the model to extract the horizontal displacement of the retaining structure and the surface settlement outside the pit, plotting the curve as shown in Figure 4, and extracting the maximum deformation value in each group of tests for summary, as shown in Table 4.

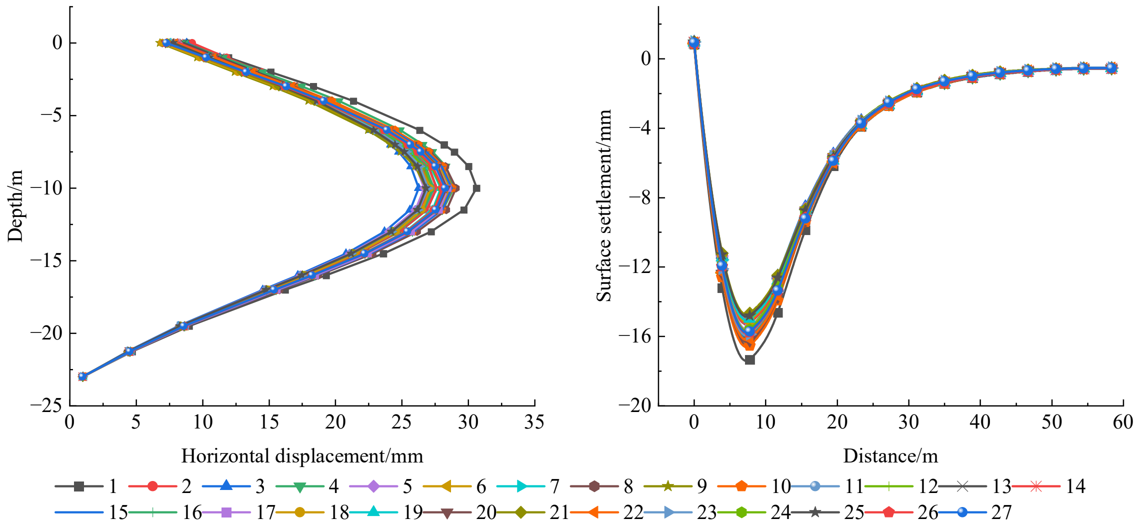

Figure 4. Orthogonal test displacement deformation curve

Combined with the figure and chart data, it can be seen that the displacement curve deformation law is basically the same in 27 groups of test results. Among the 27 groups of test results, the lateral displacement of the enclosure structure in the test group 3 has a minimum value, and the surface settlement outside the pit in the test group 21 has a minimum value. In the test group 1, the lateral displacement of the enclosure structure and the surface settlement outside the pit are the maximum values. By changing the parameter values, the maximum value of the lateral displacement of the diaphragm wall is 16.6% higher than the minimusm value, and the maximum value of the surface settlement is 18.35% higher than the minimum value.

4.3 Sensitivity Analysis of Orthogonal Test Parameters

Table 5-Table 6 shows the analysis of the results of different factors at different levels on the maximum value of horizontal displacement of the enclosure structure and the maximum value of surface settlement outside the pit. Ki corresponds to the accumulation of the dependent variable in multiple tests of a factor at a certain level, ki is the average value of the dependent variable in multiple tests of a factor at a certain level, and R is the extreme difference of the influencing factors at each level.

Table 5. Analysis of factors influencing horizontal displacement of enclosure structure

	Eur1	φ_1	c_1	Eur_2	φ_2	c_2	Eur_3	φ_3	c_3
K1	251.38	250.57	250.90	251.00	253.62	253.39	253.47	258.23	255.40
K2	250.33	251.32	250.79	250.35	249.64	249.73	248.90	249.77	249.42
K3	249.51	249.33	249.53	249.87	247.96	248.10	248.85	243.22	246.40
k1	27.93	27.84	27.88	27.89	28.18	28.15	28.16	28.69	28.38
k2	27.81	27.92	27.87	27.82	27.74	27.75	27.66	27.75	27.71
k3	27.72	27.70	27.73	27.76	27.55	27.57	27.65	27.02	27.38
R	0.21	0.22	0.15	0.13	0.63	0.59	0.51	1.67	1.00

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Table 6. Analysis of factors influencing surface settlement

	Eur_1	φ_1	c_1	Eur_2	φ_2	c_2	Eur_3	φ_3	c_3
K1	141.38	140.19	143.00	140.42	142.84	143.27	140.47	144.42	144.70
K2	140.32	141.81	139.36	139.83	140.08	140.56	139.04	140.22	139.86
K3	139.77	139.47	139.11	141.22	138.55	137.64	141.96	136.83	136.91
k1	15.71	15.58	15.89	15.60	15.87	15.92	15.61	16.05	16.08
k2	15.59	15.76	15.48	15.54	15.56	15.62	15.45	15.58	15.54
k3	15.53	15.50	15.46	15.69	15.39	15.29	15.77	15.20	15.21
R	0.18	0.26	0.43	0.15	0.48	0.63	0.32	0.84	0.87

In Table 5, the R-value represents the extreme difference value of the maximum value of horizontal displacement of the enclosure structure, and the relative magnitude of R-value under each factor indicates the degree of influence of the corresponding soil layer parameters on the maximum value of horizontal displacement of the enclosure structure; similarly, the relative magnitude of R-value in Table 6 indicates the degree of influence of the corresponding soil layer parameters on the maximum value of surface settlement outside the foundation pit. According to the extreme difference values in Table 5 and Table 6, it can be considered that the magnitude of the influence of the parameters of the three mentioned soft soil layers on the horizontal displacement of the enclosure structure and the surface settlement outside the foundation pit are: $\varphi_3>c_3>\varphi_2>c_2>Eur_3>\varphi_1>Eur_1>c_1>Eur_2$ and $c_3>\varphi_3>c_2>\varphi_2>c_1>Eur_3>\varphi_1>Eur_1>Eur_2$.

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