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Numerical Simulation Study on Settlement of a Newly Built High-speed Railway Yard on a Marine Soft Soil Foundation

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Abstract

The settlement caused by engineering construction is the most important research topic in geotechnical engineering, and monitoring and numerical simulation are commonly used to study this type of settlement. This article takes the construction of a high-speed railway station yard on a soft soil foundation as the research object, and analyzes the modeling based on the construction steps of the project and external influencing factors. The conclusion indicates that soft soil has a low modulus, is prone to deformation, and exhibits hysteresis; Excavation of foundation pits and loading and unloading of construction around soft soil areas can cause further settlement of soft soil foundations; The settlement caused by the construction of two deep foundation pits near the parking lot is significant, accounting for 33% and 30% of the total additional settlement, respectively. The impact of dredging and unloading of two river channels on settlement accounts for 12% and 15%, respectively; The measured settlement after surface engineering is in good agreement with the numerical simulation results.

Keywords

Soft Soil; High-speed Rail; Settlement; Numerical Simulation.

1. Introduction

In recent years, the development of urban transportation has been rapid, but during the construction period, there is often a problem of excessive deformation of soft soil foundations. Soft soil foundations refer to soil layers with low bearing capacity and significant settlement deformation due to their large particle gaps, high water content, and loose soil particle structure.[1-2] The amount of deformation of the foundation pit is an important indicator to measure the stability and safety of the foundation pit, and the design of the foundation pit engineering should meet the requirements for the control of deformation in addition to the strength.[3-6] Deformation monitoring data directly affects the rationality and safety of the design scheme, and poor deformation monitoring can lead to difficulties in resolving sudden deformations in the later stage.[7] This paper takes a newly built high-speed railway yard on soft soil foundation as the background, establishes a three-dimensional geological body model according to the spatial composition and implementation sequence of different projects, and analyzes the causes of post-construction settlement of the yard.

2. Overview

2.1 Project Overview

The high-speed railway yard is located in a coastal plain area with flat terrain. Underneath the newly constructed yard, there is a thick layer of soft soil, primarily consisting of flow plastic silty clay. During the track fine-tuning process, significant post-construction settlement was observed around the newly built waiting room, with the maximum settlement point located at the edge of the large

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mileage side of the station's viaduct waiting room, reaching a maximum value of 33.8mm. To investigate the cause of the significant settlement along the line, it was found through investigation that during the construction period of the new yard, there were some large deep foundation pit projects being constructed simultaneously in the vicinity of the station area. Among them, a square is only 114 meters away from the viaduct station building of the new yard, and a bus center is only 99 meters away from the station building of the new yard. The foundation pits cover areas of 20,422 square meters and 5,742 square meters, respectively, with excavation depths of 10.5 meters and 5.7 meters, which are considered deep foundation pit projects. Additionally, the confluence of two tributaries of a certain river is located at the exit of the culvert of the existing high-speed railway line. The river compensation project involves shifting the river channel as a whole to the west. The first tributary is designed to dredge 46,000 cubic meters, and the second tributary is designed to dredge 60,000 cubic meters. The river compensation project's tributaries are adjacent to the right side of the newly built yard.

According to the plan of the high-speed railway station and surrounding buildings, as shown in Figure 1 below.

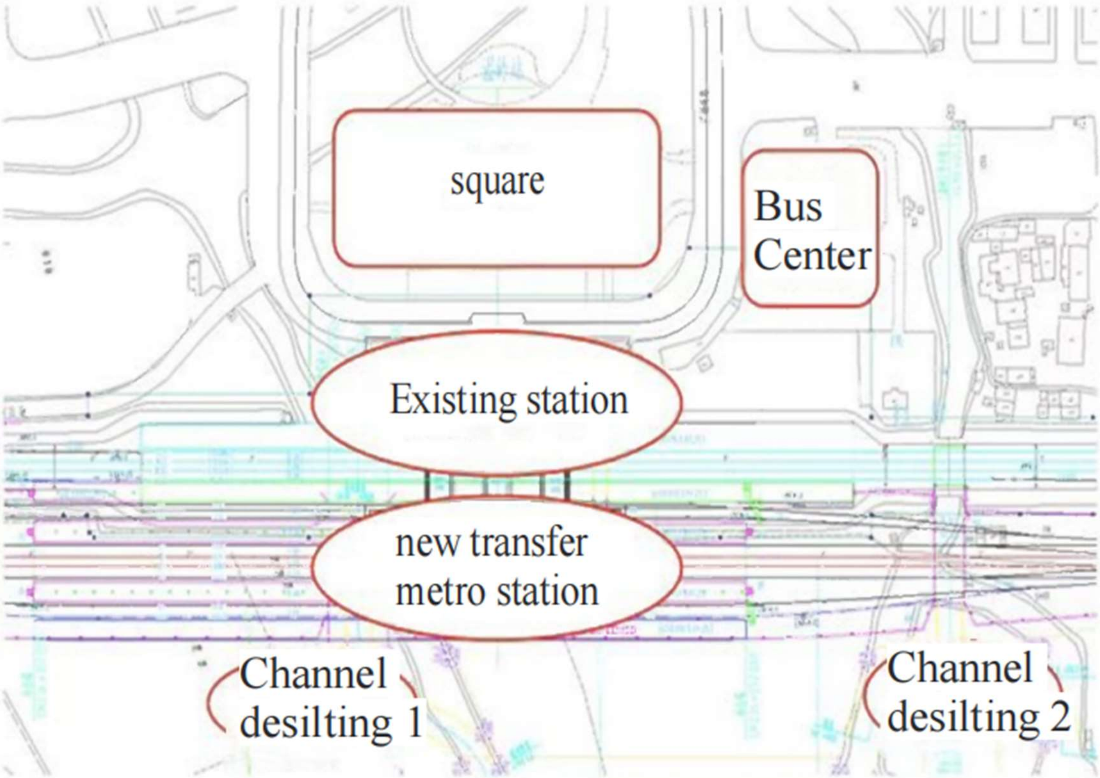

Figure 1. Project Plan View

2.2 Soil Layer Profile

2.2.1 Overview of Marine Soft Soil

Silt, silty clay, and silty silty clay are often in a saturated state, hence they are collectively referred to as saturated soft clay. They belong to the category of weak and unfavorable soil bodies, commonly known as soft soil, and their engineering properties significantly differ from those of general clays. Based on statistical values of physical and mechanical properties of soft soil in certain areas of our country and a wealth of engineering practice, the main physical and mechanical properties of saturated soft clay in coastal areas are high water content, high compressibility, low permeability, low shear strength, and significant structural and rheological properties.

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2.2.2 Stratigraphic Distribution

The geological formations at the construction site are Quaternary System Holocene artificially deposited fill, including gravelly silt and rubble, Quaternary System residual slope deposits containing silt and gravel, Quaternary System fluvial-marine deposits of silt, Quaternary System marine deposits of mud and muddy silt, Quaternary System fluvial-alluvial deposits of silt, sand and gravel, and Quaternary System upper Pleistocene fluvial-alluvial deposits of silt and gravel. The underlying formation is the Jurassic tuff.

2.2.3 Pile Foundation Load

Based on the pile foundation layout provided in the station foundation design data, the subsequent design is carried out, and the pile body is generally required to be embedded in weathered rock layers and other rock layers. The method of determining the bearing capacity of the pile foundation for each structure is as follows:

1) For the newly built waiting room, the pile foundation calculation takes the upper vertical load as approximately half of the characteristic bearing capacity, which is 3000 kN.

2) For the newly built intermediate bridge and the waiting room's 10-axis combined structure, the load on each column is evenly distributed to each pipe pile of the intermediate bridge foundation, resulting in a pile top load of 300kN for the intermediate bridge foundation.

3) The newly built main line pile raft foundation is covered with about 6 to 7 meters of subgrade fill, consisting of AB group fill, graded crushed stone, etc., with a specific weight of about 15kN/m^3. Therefore, the upper load of the newly built main line is about 100kPa. Multiplying this by the line area and dividing by the number of pile foundations, the final pile top load taken for the newly built main line area is 2110kN, and for the newly built arrival and departure line area, it is 514kN.

4) The newly built underpass area is covered with about 4 meters of reinforced concrete, with a specific weight of about 24kN/m^3. Therefore, the upper load of the newly built underpass is about 100kPa. Similarly, multiplying this by the underpass area and dividing by the number of pile foundations, the final pile top load taken for the newly built underpass area is 845kN.

2.2.4 Computational Conditions

The construction period of the structural elements of the new parking lot overlaps significantly with the construction period of the surrounding excavations. According to the actual progress of the project, the construction of the middle bridge, roadbed, and tunnel of the new parking lot has been basically completed by 2021. Additionally, the deep excavation of the square and the bus center has also been basically completed. In order to investigate the influence of the surrounding excavations on the new parking lot, this calculation scenario sets the calculation of settlement due to the loading of the new bridge, road, and tunnel first, followed by the calculation of settlement due to the excavation of the surrounding pits.

3. Numerical Modeling and Numerical Simulation

3.1 Three-dimensional Geological Model

To ensure that the calculations are not affected by boundary conditions, a geological body size of X×Y×Z=564m×419m×120m is used for modeling and analysis. The positive direction of the X-axis is towards the city, and the positive direction of the Y-axis is towards the square.

Firstly, based on the geological survey data from the engineering geological map, the geological body is divided into six layers from top to bottom, which are miscellaneous fill layer, silty clay soft soil layer, clay layer, gravelly clay layer, fully weathered tuff layer, and strongly weathered tuff layer, with average depths of 4m, 18m, 25m, 25m, 28m, and 20m, respectively. Since the undulation of the ground surface within the model range does not exceed 3m, the ground surface is considered as a plane for the convenience of upper structure layout and modeling. The stratigraphic model is based on the survey data from nearly 50 exploration points within the scope of the new yard, and the stratigraphic models are generated using interpolation methods. Since there are no survey data points

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outside the new yard, the edge of the stratigraphic model of the new yard is extended to obtain the distribution of the overall model's strata. Partial stratigraphic sections of the model are shown in Figures 2 and 3.

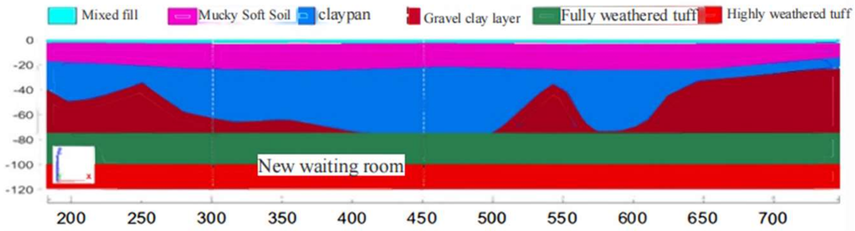

Figure 2. Newly Built Line Central Cross-Sectional Geological Profile

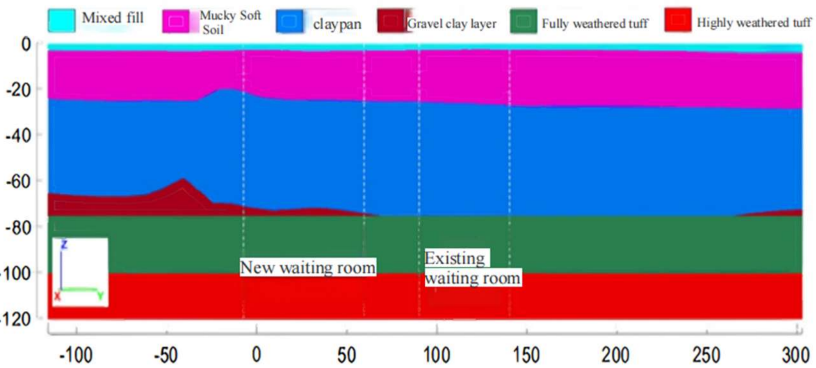

Figure 3. Cross-Sectional Geological Profile in the Direction Perpendicular to the Center Line of the Newly Built Waiting Room

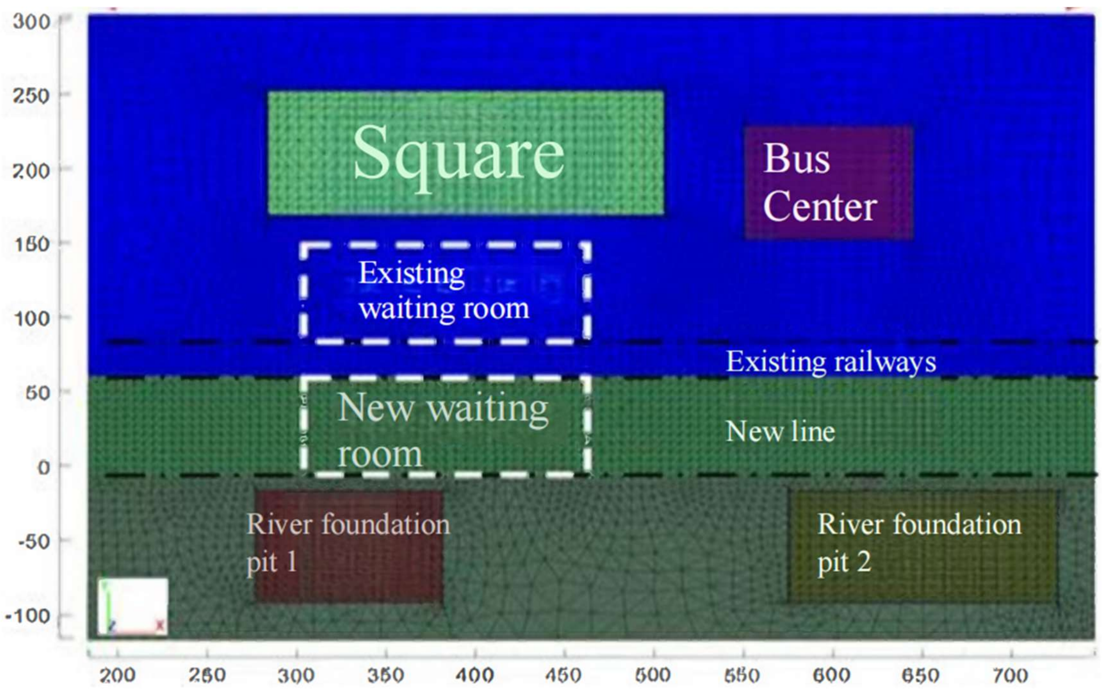

Figure 4. Foundation pit layout plan

The construction of the square transportation hub and bus center involves pre-excavation of pits and the construction of retaining structures. The river channel dredging project is simplified to a pit excavation project with an equivalent volume of soil removed. The model's upper boundary is 50

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meters from the upper boundary of the square pit, the lower boundary is 20 meters from the lower boundary of the river channel pit, the left boundary is 100 meters from the left boundary of the square pit, and the right boundary is 20 meters from the right boundary of the river channel. The pit layout plan is shown in Figure 4 below.

According to the minimum mesh width of 5m and maximum mesh width of 20m, the model is mainly composed of tetrahedral mesh. The surface part of the new line is encrypted, the mesh size of this part is set to 5m, and the total number of model grids reaches 370,000. The 3D geological model and grid division after the establishment and completion of the grouping are shown in Figure 5.

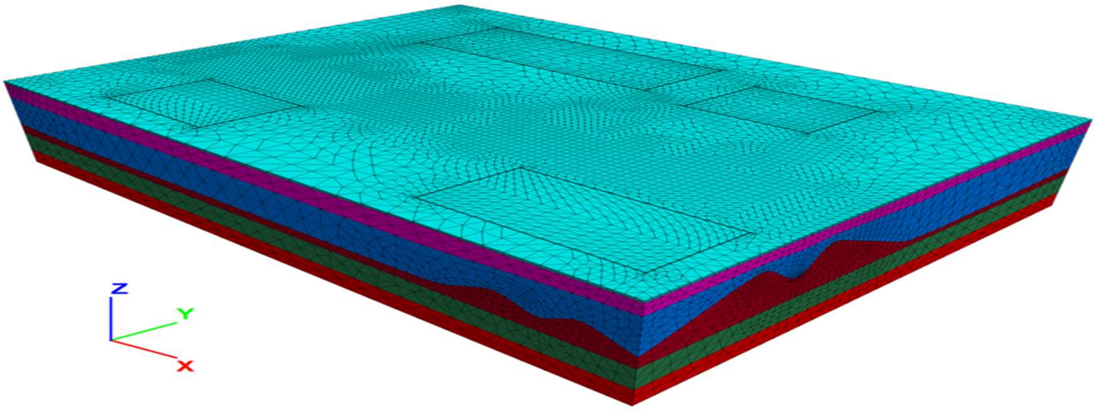

Figure 5. New 3D geological model of high-speed rail yard

3.2 Infrastructure Simulation

In the simulation of pile foundation of a new high-speed railway yard, because the diameter of pile foundation is smaller than that of the model as a whole, and there are thousands of pile foundations in the new yard within the scope of the model, it is very difficult to establish solid units for grid division, and the calculation is huge. FLAC3D has built-in structural units such as pile, which have many parameters with clear meaning and can directly obtain structural internal forces, so it is widely used in numerical simulation of geotechnical structures [8-10]. In this numerical calculation, pile foundation was simulated by the built-in pile element of FLAC3D. According to the pile foundation design data of the new yard, the pile foundation established is shown in Figure 6 below.

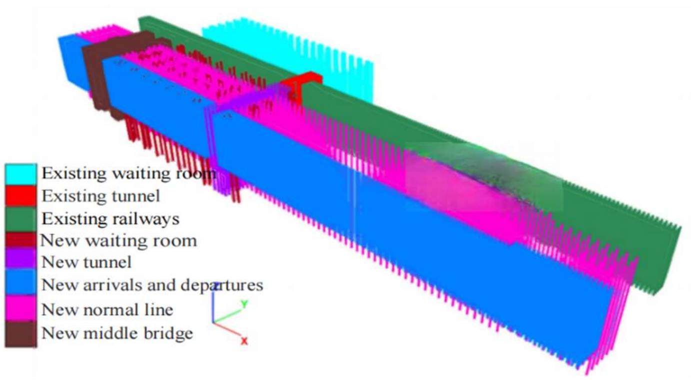

Figure 6. Simulation of pile foundation of new high-speed railway yard

3.3 Foundation Pit Excavation Simulation

According to the "General Construction Organization Design of the Square", the retaining structure of the foundation pit of the square adopts the reinforcement scheme of bored pile combined with the water curtain of three-axis mixing pile. The diameter of the bored pile is Φ=1000mm, the spacing d=1200mm, and the pile length is 33.5-38.5m. The exposed soil between the supporting piles is hung with a steel mesh surface, and 80mm thick C20 concrete is sprayed. The water stop curtain is made

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of A650@450 three-axis cement mixing pile, the pile length is 14.5m, and the horizontal clear distance between the water stop curtain and the retaining pile is 200mm. The pile foundation of the project adopts the drilled pile diameter of 0.8m, the estimated effective pile length of 59m, the construction pile length adopts the estimated effective pile length and the depth of the load layer. The characteristic value of the compressive bearing capacity of both compressive pile and pull out pile is 2700kN, the characteristic value of the pull out bearing capacity of single pile is 1600kN, and the load layer of the pile end is 7-1 clay layer. The depth of the full section of the pile end into the clay layer is ≥1.6m, and the strength of the pile concrete is C35 underwater. Numerical simulation of the retaining structure is simplified to all thickness is 1 m, a depth of 35 m concrete enclosure wall, palisade structure strength choose C35 underwater concrete strength, compressive strength and the pile engineering USES the pile length of 59 m pile spacing, pile diameter 0.8 m, 6 m * 6 m, a total of 520. Transit center and foundation pit without giving a detailed design parameters of the channel, the simulation of foundation pit design according to the square approximation. Among them, the retaining structure of the bus center is a retaining wall with a depth of 12m and a thickness of 1m. The pile length is 45m, the pile diameter is 0.8m, and the pile spacing is 6m×6m. The strength of the engineering pile and retaining wall is C35 underwater concrete strength. The retaining structure of the watercourse foundation pit is a retaining wall with a depth of 9m and a thickness of 1m. The engineering piles are 12m long, 0.6m diameter and 6m×6m distance. The strength of engineering pile and retaining wall is C25 underwater concrete,The design parameters of the surrounding foundation pit are shown in Table 1.

Table 1. Design parameters of surrounding foundation pit (unit: m)

location	pile length	pile diameter	pile distance	Depth of retaining wall	Thickness of retaining wall	strength
square	59	0.8	6×6	35	1.0	C35
bus center	45	0.8	6×6	12	1.0	C35
River Course 1	12	0.6	6×6	9	1.0	C25
River Course 2	12	0.6	6×6	9	1.0	C25

3.4 Constitutive Model and Material Parameter Selection

The choice of material constitutive model is related to the stress and deformation characteristics of the material in the model. The materials involved in this analysis include rock and soil mass, pile foundation, foundation pit enclosure structure, etc. Among them, for the geological soil layer, the plastic deformation of the material needs to be considered,The Mohr-Column elastoplastic constitutive model was used for simulation.For the foundation pit retaining structure material in the model, elastic constitutive model is adopted. The pile foundation is simulated by structural elements, all of which are elastic constitutive models. The boundary conditions of the model are: the bottom of the model constrains the displacement in the z direction, the boundary in the x direction constrains the displacement in the y direction, and the boundary in the y direction constrains the displacement in the x direction.

According to the geotechnical layer design parameters given in the Soft Soil Engineering Geological Survey Report of the Station and related literature in the area, the design calculation parameters of each geotechnical layer of the station are comprehensively determined as shown in Table 2.

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Table 2. Rock and soil layer information and calculation parameters

Soil layer name	depth h/m	severe γ/kN·m^{-3}	elasticity modulus E/MPa	Poisson's ratio μ	internal friction angle φ/°	cohesion c/kPa
Mixed fill	0~4	1.80	50	0.35	12	10
mucky clay	4~22	1.75	1	0.4	8	4
silty clay	22~50	1.85	40	0.3	10	15
Pebbly silty clay	50~75	1.90	50	0.28	18	20
Fully weathered tuff	75~100	2.00	70	0.25	24	15
Highly weathered tuff	100~120	2.10	200	0.23	30	20
pit support structure	/	2.40	1000	0.2	/	/

According to the pile foundation design parameters given in the "Station Structure Chart" and other materials, and combined with relevant literature in the region, the design calculation parameters of each pile foundation of the station are determined comprehensively as shown in Table 3.

Table 3. Pile foundation design calculation parameters

structure	underlying type	pile length(m)	pile diameter(m)	Load(kN)
existing railways	**tubular pile**	46	0.6	461
Existing waiting room	**tubular pile**	51	0.6	1000
Existing tunnel	**tubular pile**	39	0.5	444
New line	**bored pile**	70	1.25	2110
New arrivals and departures	**tubular pile**	45	0.6	514
New waiting room	**bored pile**	78.5	1.25	3000
New tunnel	**bored pile**	75.5	1.25	845
New middle bridge	**tubular pile**	64	1.0	300

3.5 Numerical Calculation Flow

The numerical simulation solution process is as follows (Figure 7) :

1) Conduct self-weight stress analysis of the geological model to obtain the initial stress conditions, stress-strain field, etc., and reset the displacement velocity to zero;

2) Import the pile foundations of the existing yard structures and apply the corresponding loads;

3) After resetting the displacement velocity to zero, import the pile foundations of the newly built yard structures and apply the corresponding loads to obtain the settlement data of the new line caused by the construction of the new yard, see Chapter 3 'Analysis of Settlement Influence by Loading of New Yard Structures';

4) After resetting the displacement velocity to zero, perform the excavation, protection, and reinforcement of the square pit to obtain the settlement data of the new line caused by the construction of the square pit, see Chapter 4 'Analysis of Settlement Influence by Square Construction';

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5) Return to step 3, reset the displacement velocity to zero, and perform the excavation, protection, and reinforcement of the bus center pit to obtain the settlement data of the new line caused by the construction of the bus center pit, see Chapter 4 'Analysis of Settlement Influence by Bus Center Construction';

6) Return to step 3, reset the displacement velocity to zero, and perform the excavation, protection, and reinforcement of the river dredging pit to obtain the settlement data of the new line caused by the construction of the river dredging pit, see Chapter 4 'Analysis of Settlement Influence by River Dredging Construction';

7) Return to step 3, reset the displacement velocity to zero, and perform the drilling for the bored pile foundation construction to obtain the settlement data of the new line caused by the pile foundation construction, see Chapter 5 'Analysis of Settlement Influence by Bored Pile Construction'.

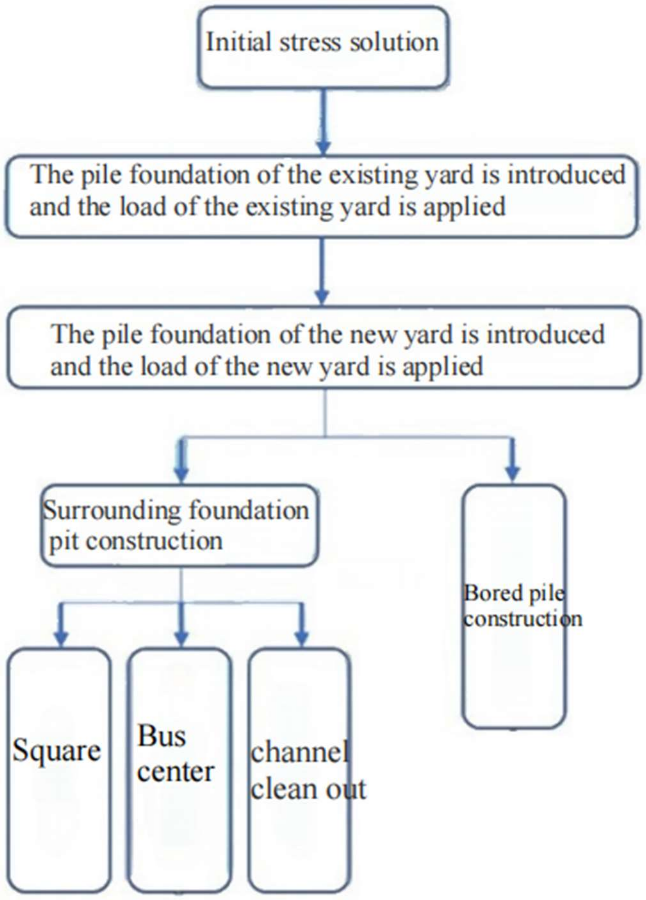

Figure 7. Flow chart of numerical calculation

4. Analysis on the Influence of Loading and Settling on the Superstructure of the New Depot

This section mainly discusses the vertical displacement of soil mass, that is, settlement. The value given by the arrow marking the maximum value in the cloud image is the absolute value of the maximum settlement, in meters. The piles have been embedded into the weathered rock as required, and the displacements are specified according to the type of loading method used in the new yard. The structure layout around the new yard is shown in Figure 4. The upper boundary of the model is 50m from the upper boundary of the square foundation pit, the lower boundary is 20m from the lower boundary of the river foundation pit, the left boundary is 100m from the left boundary of the square foundation pit, and the right boundary is 20m from the right boundary of the river.

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After loading, it can be seen from FIG. 8 that the subsidence mainly occurs in the range of the new and existing car yards. The settlement along the new line generally reaches more than 15mm, and the largest settlement area appears in the existing station building (X=310~470m, Y=90~140m), and the maximum settlement reaches 30.2mm. The center line of the line outside the new station building (X=490~660m, Y=20~35m) also has a large settlement, reaching 27.3mm. In the direction of the vertical line, Y=-10~150m in the range, there is generally more than 10mm settlement.

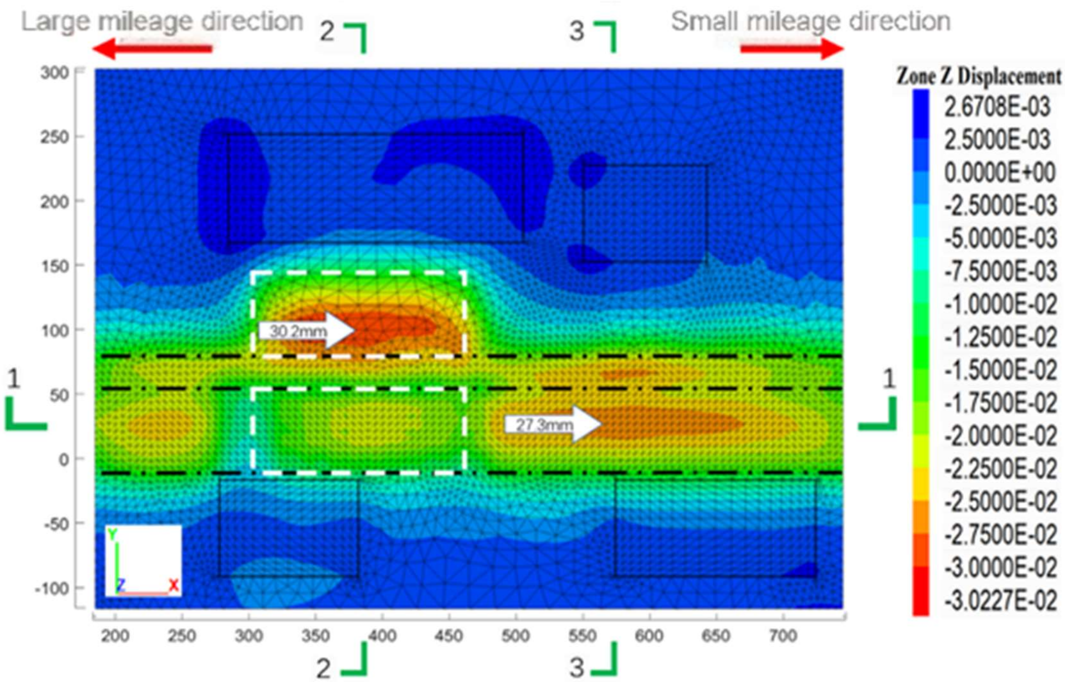

Figure 8. Surface subsidence cloud map

5. Analysis of Settlement Influence of Foundation Pit Construction

5.1 Square Construction

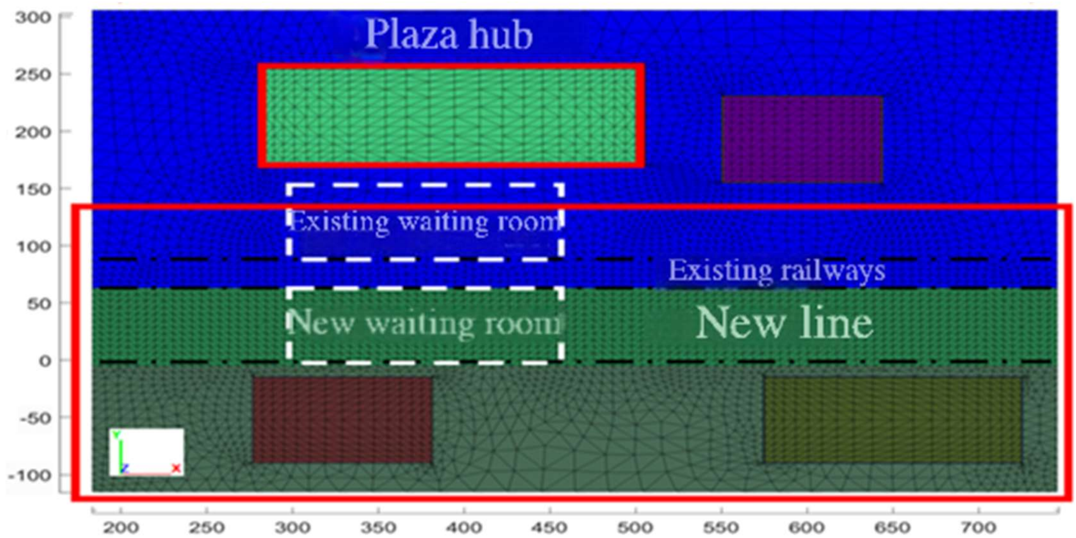

Figure 9. Model interception range diagram

After applying the superstructure load of the existing and the new parking lot, the excavation calculation of the foundation pit of the square traffic hub is carried out. In order to display the vertical displacement cloud image and obtain the surface settlement curve, a part of the overall model was

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captured for display. The range of Y=-116~140m was captured along the vertical line direction, and the full length of the model along the route direction was captured. The schematic diagram of the model was shown in Figure 9 below.

It can be seen from Figure 10 that the average settlement of the new depot after load application is 9mm, and the maximum settlement occurs from the outermost part of the new line to the departure line (X=570m, Y=-5m), reaching 14.6mm.

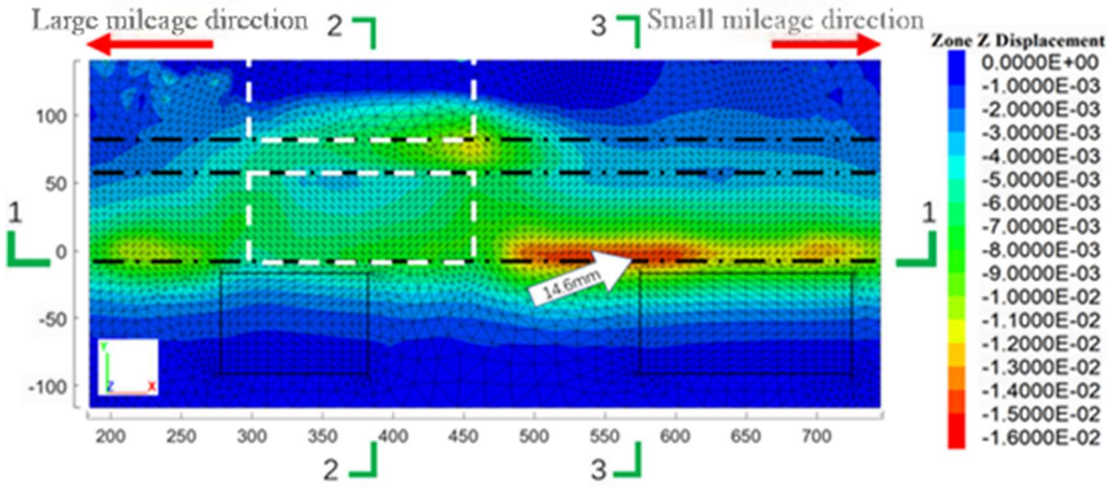

Figure 10. Surface subsidence cloud map

5.2 Bus Center Construction

In this section, the construction excavation calculation of the foundation pit of the bus center is carried out after the superstructure load of the existing and new parking lot is applied. In order to display the vertical displacement cloud image and obtain the surface settlement curve, a part of the overall model is captured for display. The range of Y=-116~80m is captured in the vertical line direction, and the full length of the model is taken along the route direction. The schematic diagram of the model is shown in Figure 11 below.

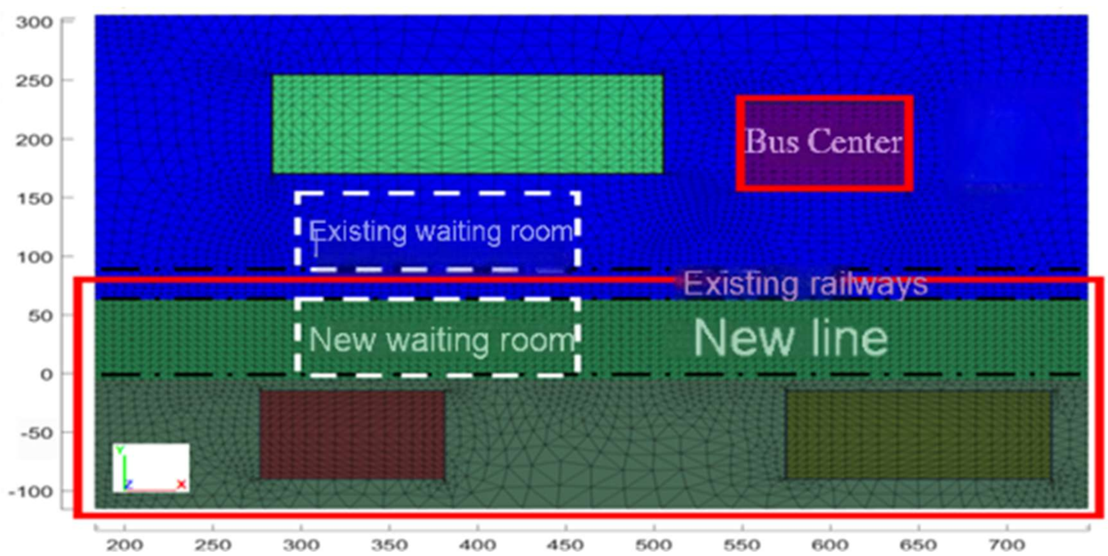

Figure 11. Model interception range diagram

It can be seen from Figure 12 that the settlement of the new line after loading is generally about 7mm, and the maximum settlement occurs from the outermost part of the new line to the distribution line (X=570m, Y=-5m), with the maximum settlement reaching 12.7mm.

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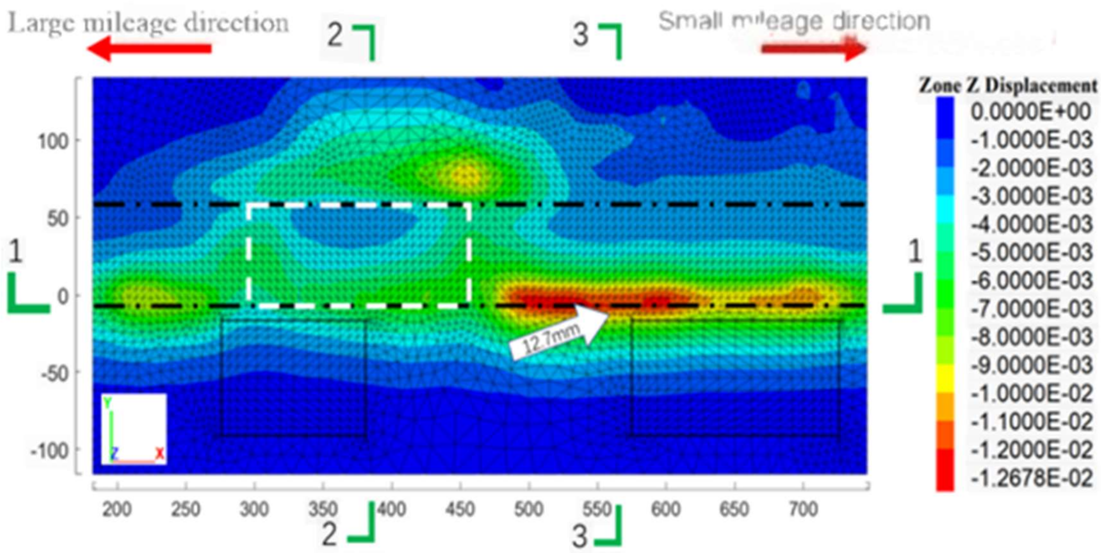

Figure 12. Surface subsidence cloud map

5.3 River Dredging Construction 1

① river dredging construction 1

In this section, the construction excavation calculation of the river dredging project is carried out after applying the load of the superstructure of the existing and new car yards. In order to display the vertical displacement cloud image and obtain the surface settlement curve, a part of the overall model is captured for display. The range of Y=-5~140m is captured in the vertical line direction, and the full length of the model is taken along the route direction. The schematic diagram of the captured model is shown in Figure 13 below.

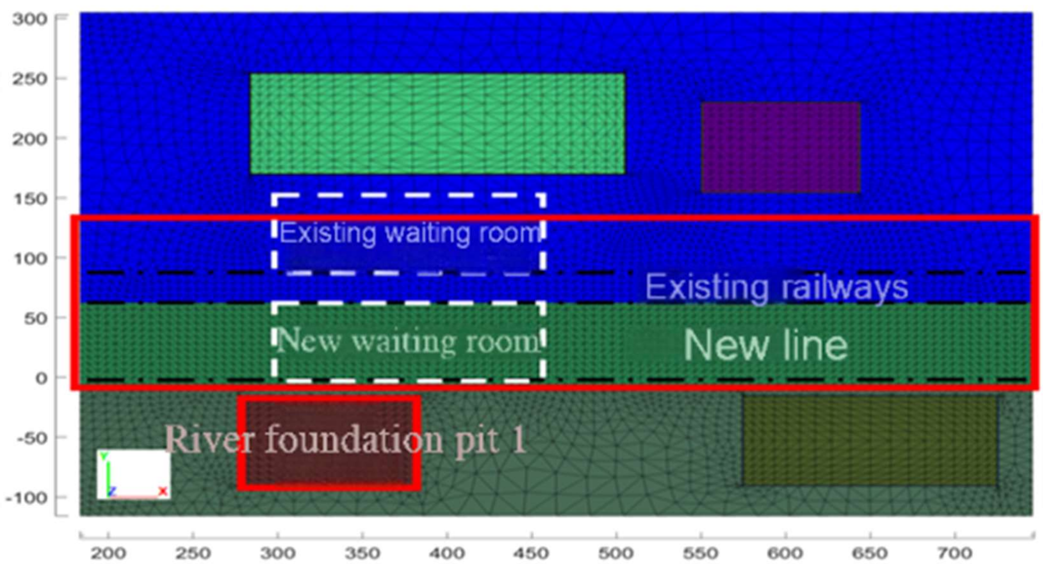

Figure 13. Model interception range diagram

It can be seen from Figure 14 that the settlement of newly built lines after loading is generally more than 2mm, and the maximum settlement occurs from the outermost part of the new line to the distribution line (X=570m, Y=-5m), and the maximum settlement reaches 5.6mm.

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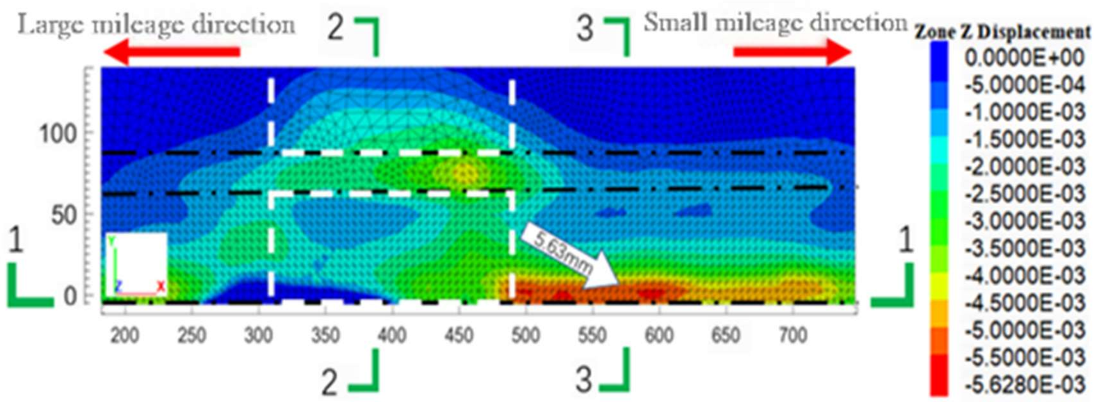

Figure 14. Surface subsidence cloud map

② River dredging construction 2

In this section, the construction excavation calculation of the river dredging project is carried out after applying the load of the superstructure of the existing and new car yards. In order to display the vertical displacement cloud image and obtain the surface settlement curve, a part of the overall model is captured for display. The range of Y=-5~140m is captured in the vertical line direction, and the full length of the model is taken along the route direction. The schematic diagram of the model is shown in Figure 15 below.

It can be seen from FIG. 16 that the settlement of the newly built line after loading is generally more than 3mm, and the maximum settlement occurs from the outermost part of the new line to the distribution line (X=530m, Y=-5m), and the maximum settlement reaches 6.3mm.

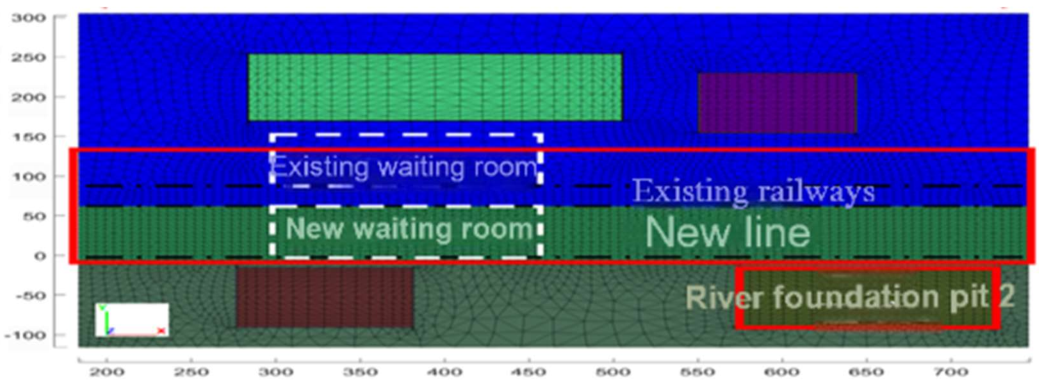

Figure 15. Model interception range diagram

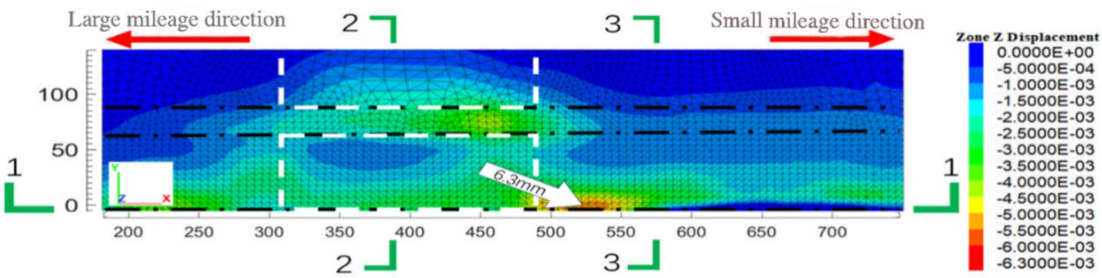

Figure 16. Surface subsidence cloud map

5.4 Surrounding Foundation Pit Construction at the Same Time

In order to explore whether the four foundation pit projects have coupling effects on the settlement of the line, this section carries out the construction excavation calculation of the four foundation pit

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projects at the same time after applying the superstructure loads of the existing and the new depot. In order to facilitate the display of vertical displacement cloud image, a part of the overall model is captured for display. The range of Y=-10~140m is captured in the vertical line direction, and the full length is taken along the route direction. The schematic diagram of the captured model is shown in Figure 17 below.

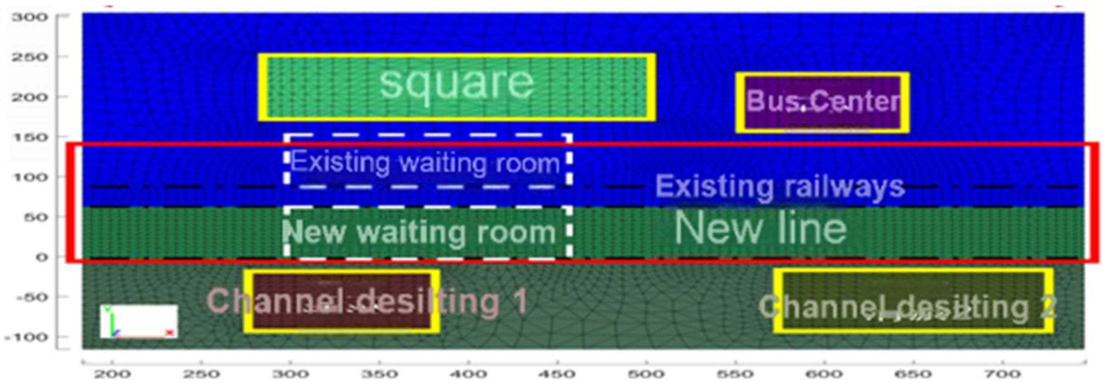

Figure 17. Model interception range diagram

After loading, it can be seen from FIG. 18 that the settlement of the newly built line is generally more than 5mm, and the maximum settlement occurs from the outermost part of the new line to the distribution line (X=570m, Y=-5m), and the maximum settlement reaches 14.8mm. The settlement of the waiting room area is between 4 and 7mm, and the settlement of the middle line of the line is within the range of 5 to 7mm.

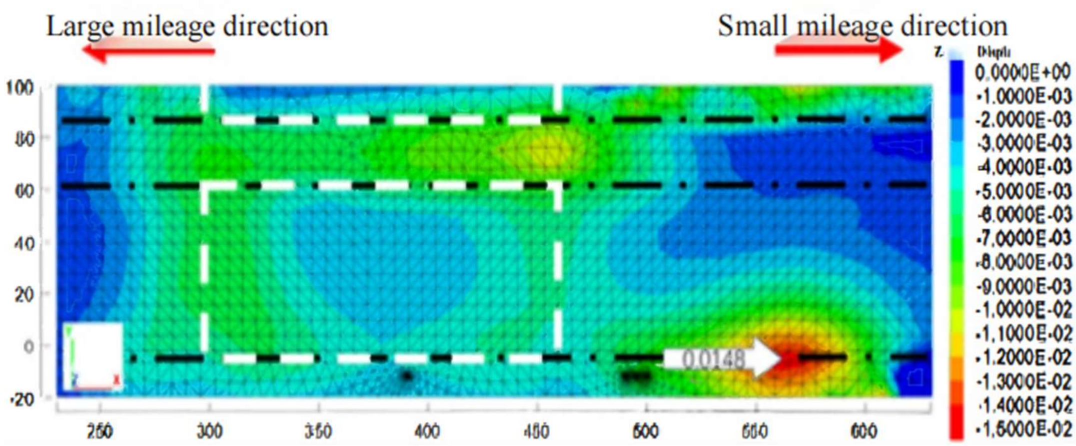

Figure 18. Surface subsidence cloud map

Compared with the above analysis, it can be seen that when the four foundation pit projects are constructed simultaneously and separately, the position of the maximum settlement area of the line is the same, which is located from the outermost part of the new line to the departure line. However, the maximum settlement generated by the simultaneous construction is not the superposition of the settlement generated by the four separate construction, but is close to the maximum settlement generated by the separate construction of the square 14.8mm. This may be due to the fact that square construction is the main factor causing the settlement of the line. The unloading of the square foundation pit causes the soft soil of the new depot to have a certain settlement and consolidation, and the settlement of the soft soil is not obvious after the construction of other foundation pits.

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6. Analysis of Construction Settlement Effect of Bored Pile

This section mainly analyzes the influence of drilling holes on the settlement of nearby lines during the construction of bored pile after the superstructure load outside the waiting room is applied.

The areas X=250~500m, Y=-50~100m, Z=0~120m of the original model were intercepted, and the construction holes of the bored pile were calculated. This area contains all the structures of the new depot and the existing lines. The schematic diagram of the interception model is shown in Figure 19 below.

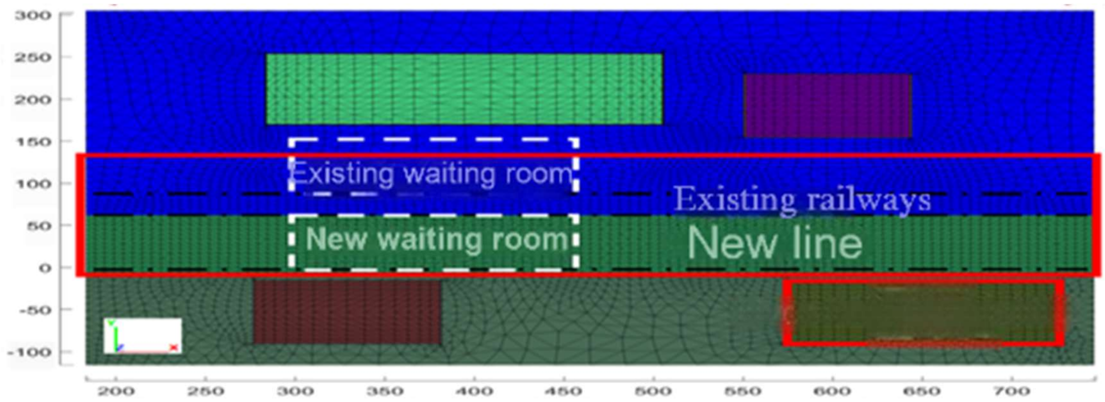

Figure 19. Model interception range diagram

At the position 10m outward from the outermost pile foundation of the new line to the transmission line, three rows of 20 piles per row with a total of 60 solid unit bored piles are set. The pile diameter of each pile is 1.25m, the pile length is 78.5m, and the pile spacing is 5.0m, which is consistent with the design parameters of the pile foundation of the new line. The layout of bored pile holes is shown in Figure 20 below. After applying the load of the superstructure of the existing depot and the subgrade load of the new depot, the velocity displacement is cleared. After the solid bored pile foundation is assigned to the empty model, the calculation is carried out.

Figure 20. Layout of bored pile holes

The influence of construction disturbance on bored pile is analyzed below.

As can be seen from Figure 21, after the bored pile is drilled into a hole, there is a large surface settlement. The main settlement area is around the hole position, the maximum settlement area is located at the lower center of the hole position and away from the line side, and the maximum ground settlement reaches 31.9mm. The settlement law of the main settlement area is analyzed from two directions. In the direction of the road, the settlement of the ground soil is less than 2mm away from the hole 30m on both sides. In the direction where the vertical line is close to the new line (Y positive), the settlement decrease rate is faster, and the settlement is less than 5mm when the new line is reached

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to the originating line; in the direction near the lower boundary of the model (Y negative), the settlement decrease rate is slower, and the land surface settlement 25m away from the maximum settlement center remains above 25mm.

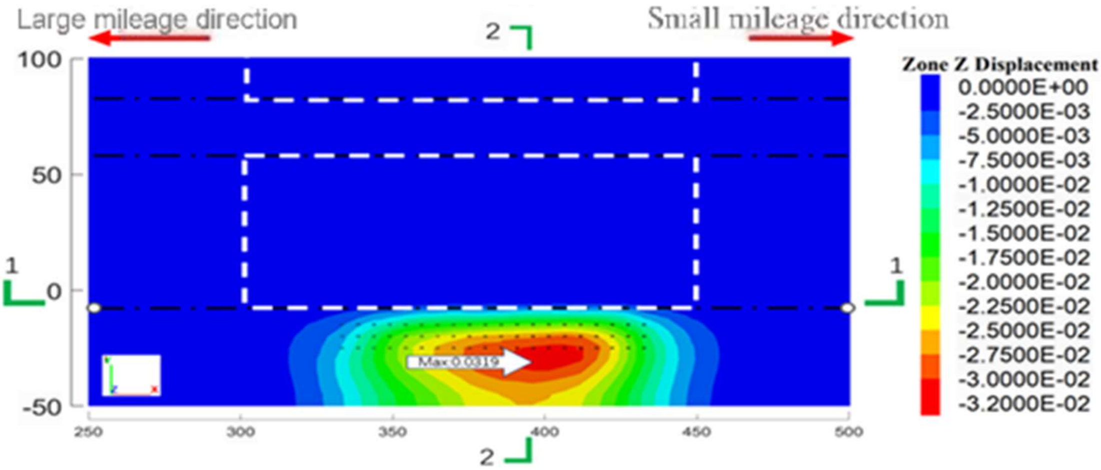

Figure 21. Surface subsidence cloud map

7. Conclusion

(1) Excavation of foundation pit or loading and unloading of building structure construction at a certain distance around the project in soft soil area can cause further settlement of soft soil foundation, among which the small deformation modulus of soft soil and the lag of deformation and the change of stress field of foundation caused by loading and unloading are important reasons.

(2) Numerical simulation shows that the settlement caused by square foundation pit construction and bus center construction is large, accounting for about 33% and 30% respectively, while the influence of river dredging construction 1 and river dredging construction 2 is relatively small, accounting for about 12% and 15% respectively.

(3) In the numerical simulation, the post-construction settlement of the new yard is about 20~40mm, while in the actual observation, the maximum post-construction settlement of the new yard is 42.2mm. The actual post-construction settlement data is similar to the numerical simulation results in general. The calculation model can reflect the real settlement well.

(4) The settlement of the site has been continuously monitored and now tends to be stable. Experts have studied the renovation plan of the track structure grouting uplift and linear fitting adopted by the site.

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