Original Research Article

Study on the Treatment Technology of Silty Clay in Reconstruction and Expansion Project

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Abstract: According to different geological conditions and different soft foundation thicknesses, this paper uses Terzaghi's one-dimensional consolidation theory, finite element simulation condition calculation and combined with code requirements to analyze the effects of replacement, cement mixing piles, and prestressed pipe piles on the foundation treatment of silty silty clay, and finally through the comparison and selection of plans, from the perspective of economic and technical rationality, determines the specific treatment method used.

Keywords: Terzaghi one-dimensional consolidation theory; Finite element simulation condition calculation; Soft foundation treatment; Settlement difference.

1. Introduction

The renovation and expansion project of the Shuikou to Baisha section of the Shenhai Expressway has been expanded from a two-way four lane road to a two-way eight lane road. The roadbed width has been expanded from 28m to 42m, mainly by splicing and widening along both sides of the old road to maintain the same horizontal and vertical sections of the old road. The treatment of soft soil foundation in highway expansion and expansion projects mainly encounters two engineering problems: stability and settlement. Due to the generally small height of highway embankments, stability issues are not very prominent and can be prevented and controlled through reasonable treatment measures. However, there is a high demand for the problem of inconsistent deformation of the roadbed caused by differential settlement.

This article uses Terzaghi's one-dimensional consolidation theory, finite element simulation conditions calculation, and analyzes in combination with regulatory requirements. Terzaghi's one-dimensional consolidation theory establishes a differential equation for the variation of pore water pressure u with time t and soil depth z, and determines boundary conditions for solution based on drainage conditions. Finally, a binary function equation for pore water pressure u with soil depth z and time t is obtained. Finite element simulation condition calculation: When conducting finite element modeling, due to the fact that the axial size of the highway is much larger than the lateral size, the spatial strain problem can be approximated as a plane strain problem to consider. Therefore, in this project, the cross-section of the highway is selected for simulation calculation. In addition, based on the symmetry of the structure, half of the roadbed is selected for analysis. Based on actual conditions, select 54.5m below the road surface (with a roadbed height of 4m and a foundation thickness of 50.5m) in the y-axis direction as the calculation range for this simulation; In the x-axis direction, extend 50m from the centerline of the roadbed to the side as the calculation range for this simulation; In the z-axis direction, considering it as a plane problem, one unit length is selected for calculation.

2. The Impact of Different Soft Foundation Treatment Methods on Engineering Safety

For each type of foundation soil, different thicknesses of soft foundation are set and different soft foundation treatment methods are used to analyze and calculate the stability of the foundation. Based on the

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survey report, the soft foundation soil with different soft soil characteristics in the project mainly includes three types: soft plastic silty clay, silt, and muddy silty clay. Below, the soft soil type for the foundation soil is muddy silty clay, and the working conditions are taken for research.

Take the starting and ending pile numbers K3217+470 Yao K3217+550, and reference the drilling hole number QZK43 as the research working condition.

According to the geological column chart of drilling hole QZK43 in the survey report in Figure 1, the soil layer parameters for this working condition are shown in Table 1. The soft soil type of the foundation soil is silty clay, with a thickness of 1.6m and a bottom depth of 2.1m. Using finite element analysis to calculate whether the safety of the three treatment methods of replacement filling, cement mixing pile, and prestressed pipe pile meets the requirements of engineering specifications, and then setting different soft foundation thicknesses to explore their impact on safety. The numerical simulation results are as follows:

Table 1 Parameters of each soil layer under QZK43 working condition.

Soil layer	Density ρ /g/cm3)	Moisture content w/%	Pore ratio e	Permeability coefficient k/(cm/s)	Poisson's ratio υ	Compressive modulus Es/MPa	Cohesive force c/kPa	Internal friction angle ψ (°)
1-2 Miscellaneous fill soil	1.90	27.3	0.815	5.8×10^{-7}	0.3	3.81	10.2	15.7
2-1 Silty Silty Clay	1.72	41.1	1.156	6.8×10^{-8}	0.4	3.10	9	16.2
2 Silty clay	1.90	28.3	0.818	6.1×10^{-7}	0.3	4.65	19.3	17.8
3-9 Pebble	1.92	22.3	0.721	2.3×10^{-7}	0.25	4.86	9.6	17.5
5 Silty clay	1.82	33.0	0.959	4.7×10^{-7}	0.3	4.04	8.4	16.3
11-1-1y Silty clay	1.91	24.9	0.766	5.4×10^{-7}	0.3	4.20	18.7	19.9
16b-27s Strongly weathered sandstone	1.89	26.0	0.801	3.2×10^{-7}	0.25	4.43	19.3	21.8
16c-27 Moderately weathered sandstone	1.92	24.4	0.788	2.7×10^{-7}	0.25	4.68	22.9	22.6

2.1 Consider the Safety and Effectiveness Differences of Different Foundation Treatment Methods

(1) Maintain a soft soil thickness of 1.6m for working condition QZK43, without considering external loads, and simulate and calculate the settlement results after 15 years of construction for three treatment methods: replacement and filling, cement mixing pile, and prestressed pipe pile.

The calculation period for post construction settlement is set to 15 years, and the post construction settlement of the top surface of the new embankment treated with prestressed pipe pile method is 8.02cm after 15 years, which has the best effect; The cement soil mixing pile method has a thickness of 8.80cm, which is the second most effective method; The maximum post construction settlement treated by the replacement method is 9.50cm. The post construction settlement results of the three treatment methods all meet the requirements of the engineering specifications for general road sections with a post construction settlement of less than 15cm, indicating that their settlement deformation meets safety requirements.

Taking the replacement method as an example, in Figure 2, the horizontal axis of the curve represents the consolidation time (unit: s), and the vertical axis represents the settlement at a point on the top of the new embankment (unit: m). It can be seen that after the replacement treatment, the post construction settlement of the top of the new embankment is 9.5cm after 15 years of consolidation (i.e. 0.47×10^{9}s) . It has been settling for 15 years, and the rate of change gradually decreases. By 15 years, the consolidation is basically completed, which conforms to the consolidation settlement law.

From the plastic strain cloud map in Figure 3, it can be seen that there is no obvious red sliding failure surface in the soil, indicating that the soil has not reached the ultimate bearing capacity state, the structure is safe, and meets the bearing capacity requirements.

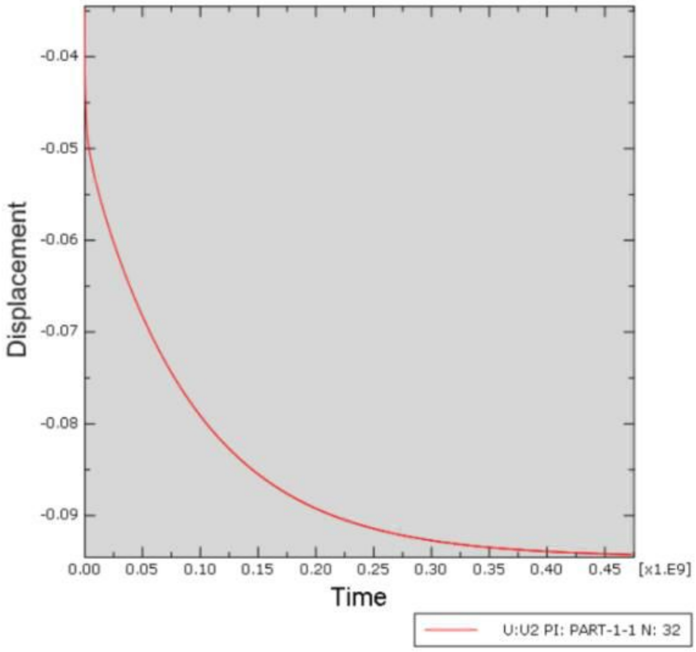

Figure 2 Settlement time curve at the top surface of the new embankment using the replacement method (without external load).

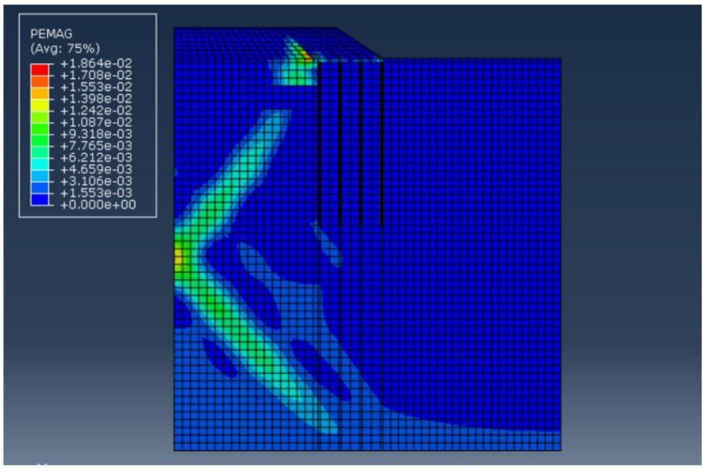

Figure 3 Plastic strain cloud map under QZK43 working condition (without external load).

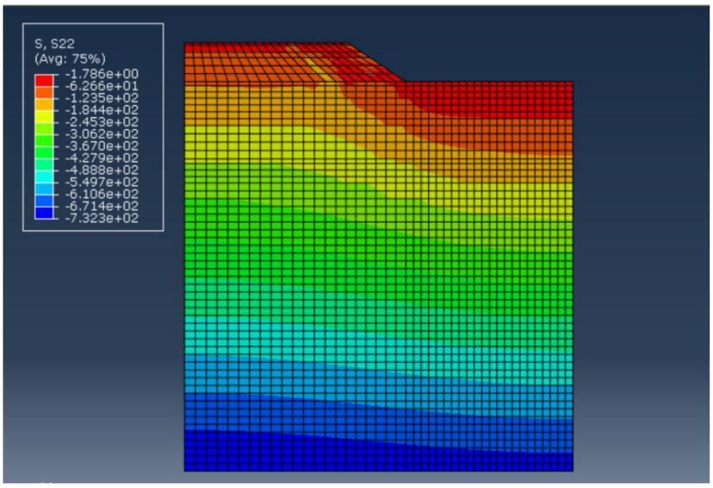

Figure 4 Vertical stress cloud map under QZK43 working condition (without external load).

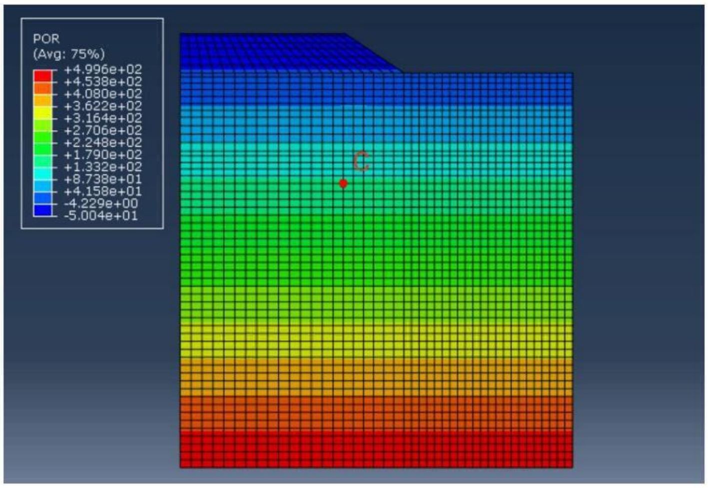

Figure 5 Cloud diagram of pore pressure under QZK43 working condition (without external load).

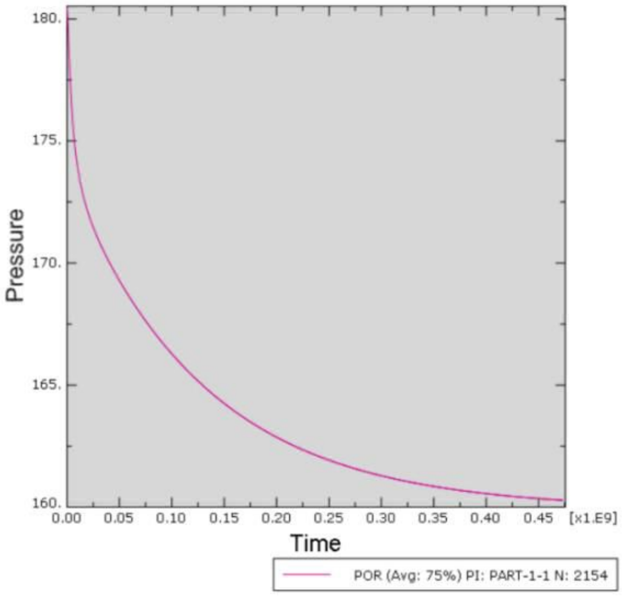

Figure 6 Time dispersion curve of pore pressure at point C.

From Figure 6, it can be seen that the distribution of pore pressure after the dissipation of pore pressure is completed under this working condition. At this time, the pore pressure should be equal to the static pore pressure $r_w h$, which corresponds to the pore pressure distribution in the figure (the water level position is given by the drilling parameters in the survey report as a stable water level of 1.00 m in the section). The results and distribution of pore pressure dissipation conform to the consolidation law.

The horizontal axis of the curve in the figure represents the consolidation time (unit: s), and the vertical axis represents the pore pressure (unit: kPa) at point C, 16m from the natural ground below the new embankment. The location of point C is shown in Figure 5. Analyze the dissipation process of pore pressure under the new embankment and verify the correctness of the model consolidation calculation process. Taking point C at a distance of 16m from the natural ground below the new embankment as an example, the dissipation curve of pore pressure with consolidation time is shown in Figure 6. When the consolidation is basically completed in 15 years, the dissipation of pore pressure is basically completed. At this point, the pore pressure at point C should be basically equal to the static pore water pressure, i.e. $r_w h = 10 \times 16 = 160$ (the stable water level of the section is given by the drilling parameters in the survey report as 1.00 m), which is basically consistent with the finite element simulation calculation results, verifying the correctness of the consolidation calculation process of this model.

(2) Maintain a soft soil thickness of 1.6m for working condition QZK43, and consider an external load of 10.5kN on the embankment surface. Simulate and calculate the settlement results after 15 years of construction for three treatment methods: replacement and filling, cement mixing pile, and prestressed pipe pile.

The calculation period for post construction settlement is set to 15 years, and an additional external load of 10.5kN is added to the embankment surface. After 15 years of treatment with prestressed pipe pile method, the post construction settlement of the new embankment top surface is 8.75cm, which still has the best effect. The cement soil mixing pile method has a thickness of 9.46cm, followed by the effect. The maximum post construction settlement treated by the replacement method is 10.27cm. The post construction settlement results of the three treatment methods considering external loads are all greater than those without considering external loads, and the increase is generally between 0.6-0.8cm. However, the post construction settlement of general road sections that still meet the requirements of engineering specifications is less than 15cm, indicating that their settlement deformation meets safety requirements.

The settlement process is still taking the replacement method as an example. The horizontal axis of the curve in Figure 7 is the consolidation time (unit: s), and the vertical axis is the settlement at a point on the top of the new embankment (unit: m). It can be seen that after the replacement treatment, considering an additional external load of 10.5kN on the top of the embankment, the post construction settlement of the new embankment top is 10.27cm after 15 years of consolidation (i.e. 0.47×10^9s), which is slightly higher than the settlement when external load is not considered. It has been settling for 15 years. And the rate of change gradually decreases, and by 15 years, the basic consolidation is completed, which conforms to the consolidation settlement law.

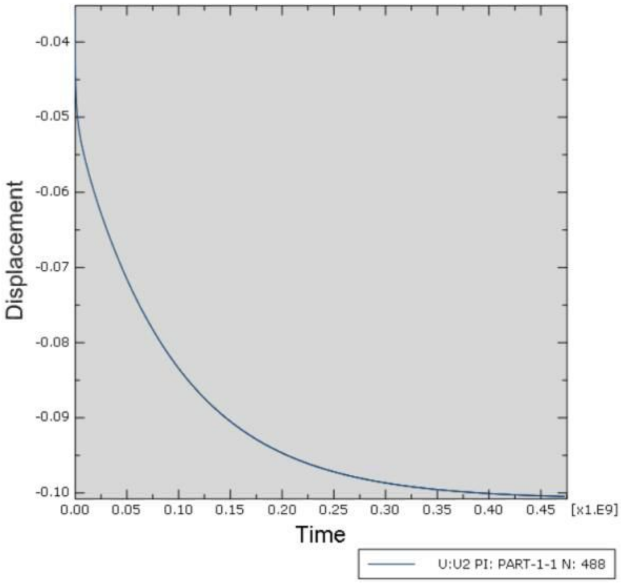

Figure 7 Settlement time curve at the top surface of the new embankment using the replacement method (with external load).

From the plastic strain cloud map in Figure 8, it can be seen that after adding an external load of 10.5kN to the embankment, there is still no obvious red sliding failure surface in the soil, indicating that the soil has not reached the ultimate bearing capacity state, the structure is safe, and meets the bearing capacity requirements.

The distribution diagram of pore pressure and effective stress considering external loads follows the same pattern as the distribution diagram without considering external loads, and will not be repeated here.

Based on the comprehensive analysis of the above content, it can be concluded that the post construction settlement deformation results of the three treatment methods of replacement, cement mixing pile, and prestressed pipe pile for the foundation soil type with soft soil characteristics of silty clay are within the range of engineering specifications, considering external loads and not considering external loads. Their bearing capacity also meets safety requirements, and the overall structure is safe. In terms of treatment methods, the overall treatment effect of prestressed pipe piles is better than that of cement mixing piles and replacement filling methods.

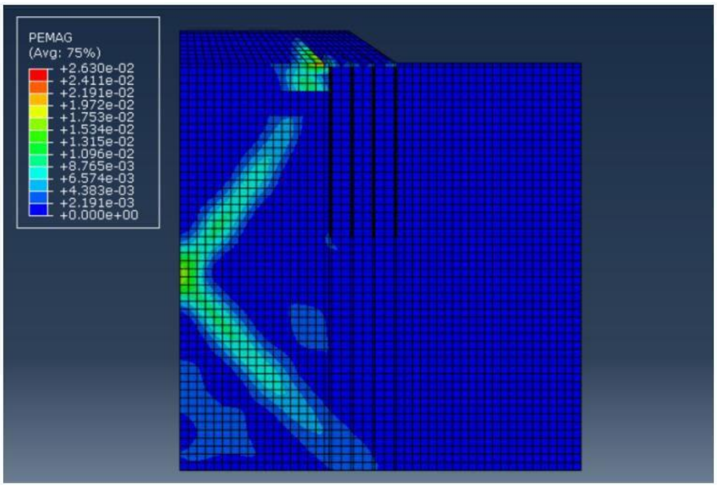

Figure 8 Plastic strain cloud map under QZK43 working condition (with external load).

2.2 Consider the Influence of Different Soft Soil Thicknesses

Research and calculation were conducted on three different treatment methods with different soft soil thicknesses for working condition QZK43. The original soft soil thickness was 1.6m, and additional soft soil thicknesses of 0.6m and 2.6m were added here. The differences in post construction settlement were compared and analyzed when the soft soil thicknesses were 0.6m, 1.6m, and 2.6m, respectively, to explore their patterns.

(1) The influence of different thicknesses of soft soil under the replacement method.

Under the replacement method, when the thickness of the soft soil is 0.6m, 1.6m, and 2.6m, the post construction settlement after 15 years is 9.21cm, 9.50cm, and 9.79cm, respectively. It can be seen that as the thickness of the soft soil deepens, the post construction settlement gradually increases, and for every one meter change in the thickness of the soft soil, the post construction settlement increases by about 0.3cm.

When an external load of 10.5kN is added to the top of the embankment, under the replacement method, when the thickness of the soft soil is 0.6m, 1.6m, and 2.6m, the settlement after 15 years of construction is 9.98cm, 10.27cm, and 10.56cm, respectively. Compared with not considering external loads, the settlement under each type of soft soil thickness has increased by 0.6-0.8cm. However, it can still be seen that as the thickness of the soft soil deepens, the settlement after construction gradually increases, and for every one meter change in soft soil thickness, the settlement after construction increases by about 0.3cm.

(2) The influence of different thicknesses of soft soil under cement mixing pile treatment.

Under the treatment of cement mixing piles, when the thickness of soft soil is 0.6m, 1.6m, and 2.6m, the post construction settlement after 15 years is 8.48cm, 8.79cm, and 9.06cm, respectively. The post construction settlement under each soft soil thickness is smaller than that of the replacement method, indicating that the treatment effect of cement mixing piles is better than that of replacement. It can also be seen that as the thickness of soft soil deepens, the post construction settlement of cement mixing piles treatment gradually increases, and the thickness of soft soil changes by one meter, the increase in post construction settlement is approximately 0.3cm.

When an external load of 10.5kN is added to the top surface of the embankment, under the treatment of cement mixing piles, when the thickness of the soft soil is 0.6m, 1.6m, and 2.6m, the settlement after 15 years of construction is 9.11cm, 9.45cm, and 9.74cm, respectively. Compared with not considering external loads, the settlement under each thickness of soft soil increases by 0.6-0.8cm. However, it can still be seen that as the thickness of soft soil deepens, the settlement after construction gradually increases, and the thickness of soft soil changes by one meter, The increase in post construction settlement is approximately 0.3cm.

(3) The influence of different thicknesses of soft soil under the treatment of prestressed pipe piles.

Under the treatment of prestressed pipe piles, when the thickness of soft soil is 0.6m, 1.6m, and 2.6m, the post construction settlement after 15 years is 7.73cm, 8.02cm, and 8.27cm, respectively. The post construction settlement under each thickness of soft soil is smaller than that of cement mixing piles, indicating that the treatment effect of prestressed pipe piles is better than that of cement mixing piles. Similarly, it can be seen that as the thickness of soft soil deepens, the post construction settlement of prestressed pipe piles gradually increases, and the thickness of soft soil changes by one meter. The increase in post construction settlement is approximately 0.3cm.

When an external load of 10.5kN is added to the top surface of the embankment, under the treatment of prestressed pipe piles, when the thickness of the soft soil is 0.6m, 1.6m, and 2.6m, the settlement after 15 years of construction is 8.41cm, 8.75cm, and 9.01cm, respectively. Compared with not considering external loads, the settlement under each thickness of soft soil increases by 0.6-0.8cm. However, it can still be seen that as the thickness of soft soil deepens, the settlement after construction gradually increases, and the thickness of soft soil changes by one meter. The increase in post construction settlement is approximately 0.3cm.

Summarize the settlement values of various working conditions in this section, as shown in Tables 2 and Tables 3.

Table 2 Settlement table of silty silty clay foundation after earthwork (no external load).

Sedimentary silt clay type foundation settlement after geotechnical engineering (unit: cm)			
Thickness of weak foundation / Processing method	0.6m	1.6m	2.6m
Replacement filling	9.21	9.50	9.79
Cement soil mixing pile	8.48	8.79	9.06
Prestressed pipe pile	7.73	8.02	8.27

Table 3 Settlement table of silty silty clay foundation after earthwork (with external load).

Sedimentary silt clay type foundation settlement after geotechnical engineering (unit: cm)			
Thickness of weak foundation / Processing method	0.6m	1.6m	2.6m
Replacement filling	9.98	10.27	10.56
Cement soil mixing pile	9.11	9.45	9.74
Prestressed pipe pile	8.41	8.75	9.01

Based on the comprehensive analysis of the data in the table, it can be concluded that changing the thickness of the soft foundation has brought about changes in the post construction settlement of the three treatment methods for this type of soft soil with silt and silty clay. As the thickness of the soft foundation deepens, the post construction settlement gradually increases. However, multiple sets of calculation data show that the increase in post construction settlement is only about 0.3cm per meter of soft soil deepening. Combined with the survey report, the maximum thickness of this type of soft soil with silty clay in the entire road section is 3.0m. Based on the data in the table, the settlement increase with the change of soft soil thickness and the settlement results of the three treatment methods on the soft foundation treatment can be obtained. It can be concluded that the settlement amount caused by the different thicknesses of the soft foundation soil with silty clay characteristics in the entire road section is within the safe range.

3. Differences in settlement between new and old embankments under different soft soil foundation treatment methods

The original Kaiyang Expressway has been in operation for many years. Due to the repeated action of vehicle loads, without major diseases, the original embankment has basically completed its own settlement after years of operation. However, the newly filled new embankment will inevitably produce certain compression, and there will inevitably be a certain settlement difference between the new and old embankments. To reduce uneven settlement, it is necessary to minimize the settlement of the new embankment itself. Under the condition of not increasing the cost significantly, the settlement difference between the new and old embankments can be reduced by appropriately increasing the compaction degree of the new embankment and selecting a reasonable soft foundation treatment method.

In terms of improving the compaction degree of the roadbed, this project combines the requirements in the survey report during finite element calculation, and models and calculates according to the given compaction degree requirements of the roadbed. Below is an analysis of the impact of different soft foundation treatment methods on the settlement differences between new and old embankments.

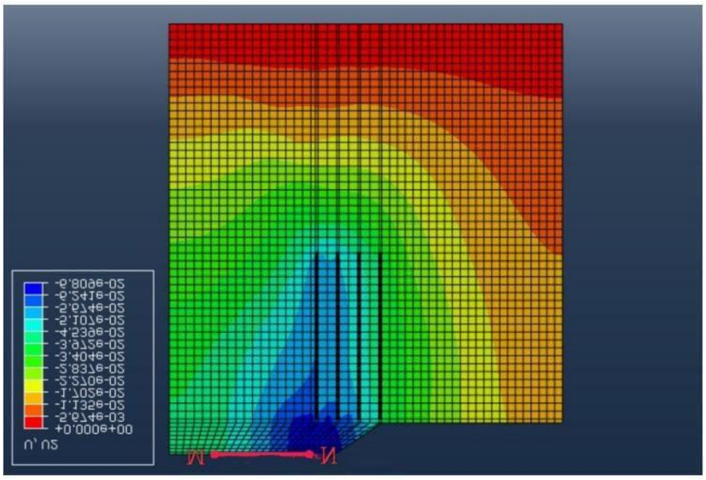

Figure 9 **V**ertical displacement cloud map of cement mixing pile under QZK115 working condition (without external load).

Under the QZK115 working condition of soft plastic silty clay type foundation soil, a point M in the middle of the old embankment pavement is taken as the starting point, and a point N in the middle of the new embankment pavement is taken as the ending point. The specific positions of points M and N are shown in Figure 9. The settlement curves between the starting point and the ending point under three different soft foundation treatment methods are plotted as shown in Figures 10 to 12.

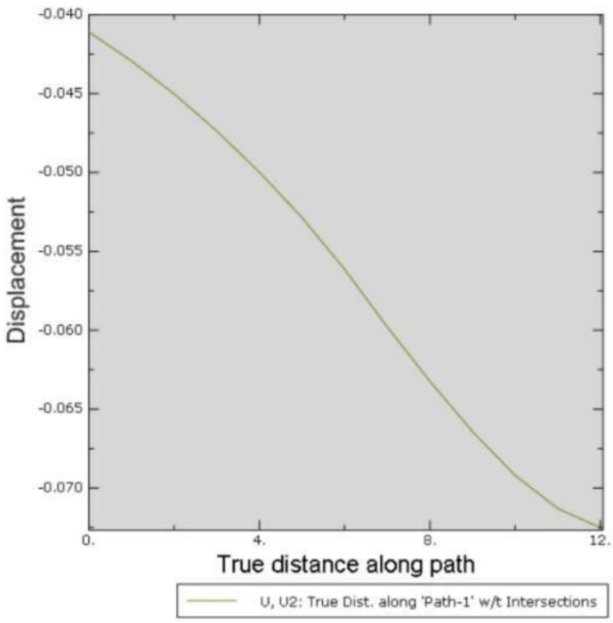

Figure 10 Settlement curve from point M to point N in the replacement method.

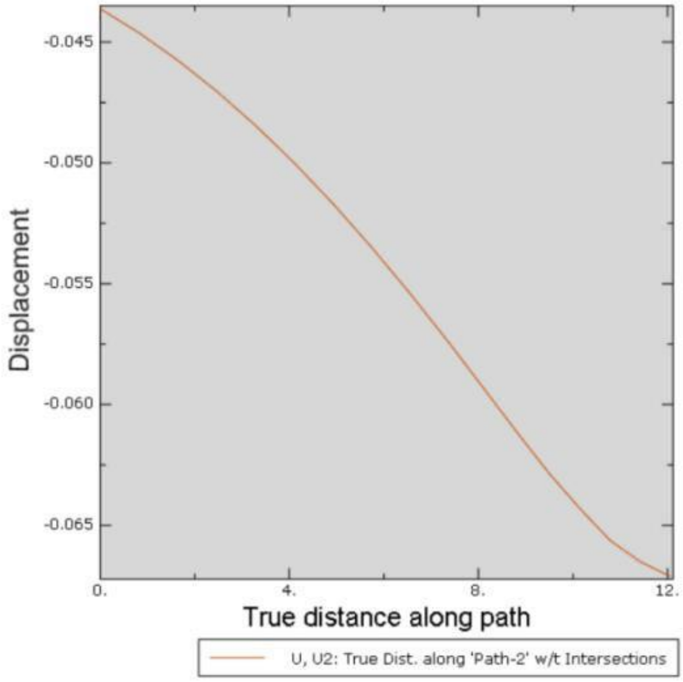

Figure 11 Settlement curve of cement mixing pile from point M to point N.

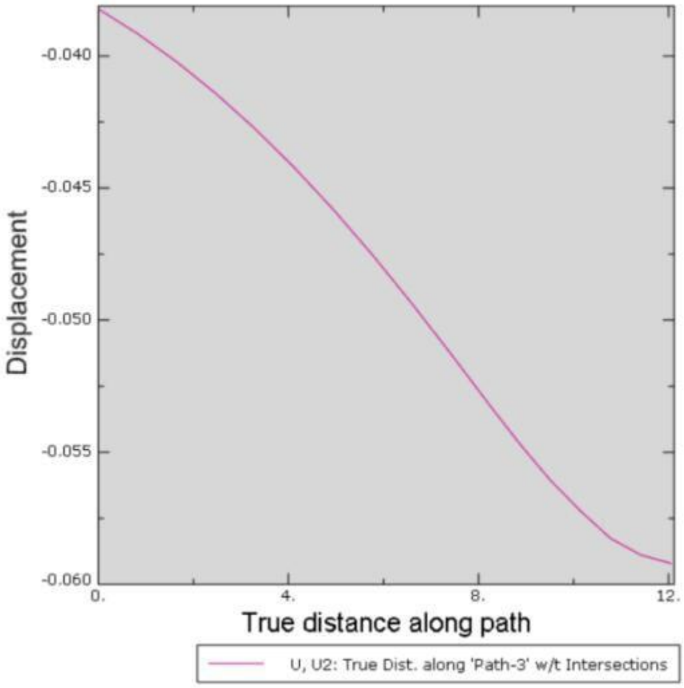

Figure 12 Settlement curve of prestressed pipe pile from point M to point N.

The horizontal axis of the curve in the figure represents the distance to the starting point M (in meters), and the vertical axis represents the settlement amount (in meters). From the graph, it can be seen that the closer the curve is to the middle, the higher the slope, indicating a significant difference in settlement changes here. It is precisely at the junction of the new and old embankments that the appropriate technology for overlapping the new and old embankments can effectively reduce the settlement differences between the new and old embankments. And from the graph, it can be calculated that the settlement difference between point M-N under the replacement method is 3.08cm, the settlement difference between point M-N under the cement mixing pile treatment is 2.46cm, and the settlement difference between point M-N under the prestressed pipe pile treatment is 2.15cm. From this, it can be concluded that the use of prestressed pipe piles can minimize the settlement difference to the greatest extent, followed by cement mixing piles. The settlement difference between new and old embankments is the largest under the replacement method.

4. Economic Comparison of Different Soft Foundation Treatment Methods

From the perspective of safety, the treatment effects of different soft foundation treatment methods were calculated and analyzed. Considering project costs, three different soft foundation treatment methods were compared from an economic perspective. Simplify the calculation of the cost of three soft foundation treatment methods for a certain area of soft soil, and compare the economic benefits of various soft foundation treatment methods.

The bottom burial depth of the soft soil layer in the silty clay type foundation soil is 2.1m, and the area of the soft soil is taken for calculation. The cost of replacing and filling materials is 50 yuan per cubic meter, the cost of cement mixing piles is 60 yuan per meter, the cost of prestressed pipe piles is 80 yuan per meter, the pile length is 21m, and the pile spacing is 2.4m.

The burial depth of soft soil is 2.1m, and the cost of soft soil treatment under this working condition is calculated as follows:

Replacement: 50×21×16=20160 (yuan); Cement mixing pile: 60 ×12×12×2.1=15120 (yuan); Pre stressed pipe pile: 80×21×16=26880 (yuan)

From the calculation of the above working conditions, it can be seen that when the bottom burial depth of the soft soil layer is shallow, the cost of replacement is less than that of cement mixing piles and prestressed pipe piles; When the bottom of the soft soil layer is deeply buried, the cost of cement mixing piles is lower than that of prestressed pipe piles and replacement. After further calculation, it can be concluded that when the depth of the soft soil bottom is 3m:

Replacement: 50×12×12×2. 1=15120 (yuan); Cement mixing pile: 60×21×16=20160 yuan; Pre stressed pipe pile: 80×21×16=26880 (yuan)

At this time, the cost of replacement and filling is slightly higher than that of cement mixing piles. It can be concluded that when the depth of the soft soil bottom is less than 3m, using the replacement and filling method for soft foundation treatment is more cost-effective; When the depth of the soft soil bottom is greater than 3m, using cement mixing piles or prestressed pipe piles for soft foundation treatment is more cost-effective.

5. Conclusion

Through an overall research and evaluation of the safety and economy of different soft soil foundation treatment methods, the following soft soil treatment schemes have been summarized:

(1) For soft soil with a depth of less than 3 meters, the replacement method can ensure that the settlement deformation and bearing capacity requirements meet the engineering needs, and it can also reduce the cost compared to cement mixing piles and prestressed pipe piles. Therefore, the replacement method is recommended. During excavation, temporary support and protection measures should be fully considered, combined with monitoring and analysis of the original roadbed stability during construction.

(2) For soft soil buried at a depth of $3 < H \leq 8m$, the cost of using the replacement method is significantly higher than adding piles. The cost of using cement mixing piles is lower than that of prestressed pipe piles. However, considering that some sections have high organic matter content and rock blocks in the formation, it is difficult to form cement mixing piles. Therefore, it is advisable to use cement mixing piles or prestressed pipe piles according to specific working conditions.

(3) For soft soil with a burial depth of $8 < H \leq 12m$, the use of cement mixing piles is no longer sufficient to meet the safety requirements of the project. Through calculation, it is found that prestressed pipe piles can still play a good safety role in high burial depth soft foundation soil. Therefore, it is advisable to use prestressed pipe

piles for treatment.

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