Analysis on the Control Effect of Enhanced Cushion on the Difference Settlement of New and Old Subgrade in Soft Foundation Area

Zhenhua Jiang¹, Dongxing Yang¹, Zhiwei Yang², Zhe Wang³ and Xiaochun Zhang³, *

¹China Design Group Co., Ltd
²Zhongshan Transportation Project Construction Limited Company, Zhongshan, Guangdong 528403
³Intelligent Transportation System Research Center, Southeast University, Nanjing, Jiangsu 211189

*Corresponding Author Email: zxc01@263.net

Abstract. In order to reduce the differential settlement of the extended urban highway splicing segment, we monitored the junction of the new and old subgrade in the practical engineering, analyzed the value of pavement deformation. It found that the smaller the modulus ratio of the new and old subgrade, the greater the non-uniform settlement value. At the same time, the uneven settlement and lateral displacement of the road can be effectively reduced by using the pile-reinforced cushion structure. So the results show that the pile-reinforced cushion structure can effectively reduce the uneven settlement and lateral displacement of the old and new roads, strengthen the links between old and new roads; To enhance the stability of subgrade, it can be used for widening the old road in soft soil foundation.

1. Introduction

In recent years, due to economic development, the traffic volume keeps increasing, and the existing roads can no longer meet the traffic demand. So it is imperative to widen the old roads. However, most of the finite element studies on road widening now are focused on high embankment roads, and few studies on road widening projects around towns where the ground on both sides of the road is at the same elevation as the road or even higher than the road.

PLAXIS finite element software is used by Q Ma to simulate the reinforcement effect of geogrid in subgrade widening. At the same time, the variation law of geogrid tension under different loads is analyzed. The application of geosynthetic reinforced piles (GRPS) in the construction of soft soil embankment is studied by Priyanath Ariyarathne, and the load transfer mechanism is studied by finite element method. Through the comparison of different pile diameters, spacing and embankment heights, it is found that the treatment form of subgrade is relatively simple, mostly using the combined effect of geogrid and pile, and the effect of using geogrid alone is limited. In this paper, a new upper reinforcement structure at the junction of new and old subgrade is presented. Taking a urban highway in the Pearl River Delta as an example, ABAQUS is used to establish a model to analyze its influence on the effect of uneven settlement control, and field monitoring is used to verify it.

As the project is located in the south of the Pearl River Delta, the strata along the line is covered by loose sedimentary layers with a relatively large thickness and a relatively thick soft soil. It is a delta facies dark gray mucky soil, silt fine sand and fluvial sand gravel layer, and the thickness of the quaternary overburden is about 38~54m. The soft soil is characterized by high water content, large...
pore ratio, high compressibility, poor properties and low strength [3]. Since the original road has been in operation for many years, the soil foundation of the old road has been basically consolidated after years of vehicle loads, and the settlement tends to be stable. However, the soil foundation of the new road is not compacted, and the property of the soil is quite different from that of the old road. Large settlement will occur at the junction of the new road and the old road under the load of the road superstructure and the vehicle load. After years of consolidation, the properties of old road subgrades often change significantly. In The Taizhou highway test section of Fang Hanhui [4], the elastic modulus of the soil after half a year’s overload preloading is at most 1.25 of the original state. Due to the disturbance to the soil samples during the process of drilling and taking soil at the project site, no measured data has been obtained for the modulus ratio of the old and new roads. By applying loads on the soil foundations of the new and old roads with different modulus ratios, the deformation of the old roads under different compaction states is studied.

2. Research on Subgrade Deformation with Different Modulus Ratio of New and Old Soil Foundation

2.1. Finite Element Model Establishment

When the road is long enough, its transverse width is far less than its longitudinal length. Therefore, the plane strain problem is considered and the model is simplified to a two dimensional model. The typical section of the urban highway test section is selected this case to establish a geometric model, as shown in Figure 1. ABAQUS finite element software is used for numerical simulation, and the finite element model is constructed according to the actual project 1:1. Because the road is symmetrically distributed on the left and right sides, only half of the model is constructed. The original cement pavement is retained. The half width of the original cement pavement is 7m and the thickness is 0.26m. The bottom of the original cement slab is defined as the old subgrade with a depth of 3m. Under the old subgrade is the soil foundation, and the rest is defined as the new road soil foundation. On the top of the original pavement slab, 0.8m-thick earth filling with compaction is laid, followed by the main road structure with 0.24m-thick cushion, 0.54m-thick base and 0.18m-thick surface respectively. The slope of embankment is 1:1.5. And the traffic load is equivalent to the pavement uniformly distributed load of 13kPa.

![Figure 1. Model schematic diagram](image)

The Mohr-Coulomb ideal elastoplastic constitutive model is adopted for foundation soil and subgrade. Linear elastic model is adopted for road surface, base and subbase. The specific parameters are as follows. Since the original road has been in operation for many years, the soil foundation of the old road has been basically consolidated after years of vehicle loads, and the settlement has stabilized. However, the new subgrade is not compacted, and the soil properties are quite different from that of the old subgrade.

In order to further study the influence of the difference in strength of the new and old road foundations on the deformation of the widened subgrade, now the elastic modulus of the old subgrade is respectively set as 1:1.3, 1:1.6, 1:1.9, 1:2.2 and 1:1.25 of the elastic modulus of the new subgrade for comparison.
Table 1. Road material parameters table

| position               | Material model     | Density (kg/m³) | Elastic modulus (MPa) | Poisson’s ratio | Cohesive force (kPa) | Internal friction angle(°) |
|------------------------|--------------------|-----------------|------------------------|-----------------|-----------------------|---------------------------|
| Surface course         | Linear elasticity  | 2420            | 1500                   | 0.35            | /                     | /                         |
| Base course            | Linear elasticity  | 2300            | 1300                   | 0.3             | /                     | /                         |
| Subbase course         | Linear elasticity  | 2100            | 1000                   | 0.25            | /                     | /                         |
| New subgrade           | Mohr-Coulomb       | 1850            | 30                     | 0.3             | 130                   | 25                        |
| Old subgrade           | Mohr-Coulomb       | 1900            | 40                     | 0.3             | 150                   | 25                        |
| New soil foundation    | Mohr-Coulomb       | 1700            | 8                      | 0.35            | 40                    | 18                        |
| Old soil foundation    | Mohr-Coulomb       | 1800            | undetermined           | 0.25            | 100                   | 25                        |

2.2. Calculation Results

Figure 2 shows the deformation of the road surface when there is a difference in modulus between the old and new subgrade soil in the natural untreated state.

![Deformation curve of road surface](image)

**Figure 2. Deformation curve of road surface**

It can be seen in the original untreated state that if there is a difference in modulus of the new and old road foundation, the smaller the modulus ratio of the old and new road foundations, the greater the absolute value of the settlement of the road, and the closer to the center of the old road, the greater the absolute value of settlement. When the modulus ratio is smaller, the uneven settlement between the junction of the new and the old subgrade and the center of the old road is larger, which is more likely to cause problems such as road cracking. Figure 2 is the horizontal strain curve under different conditions of the modulus ratio of the new and old road soil foundation. It can be found in the figure that the central area of the old road moves to the outside of the road, and the new section outside the old road starts to move horizontally to the inside of the road. The greater the modulus ratio, the greater the displacement toward the outside of the road. And the smaller the modulus ratio, the greater the displacement toward the inside of the road.

3. Research on Foundation Treatment of Composite Reinforced Cushion Structure

3.1. Finite Element Model Establishment

In the original model, the new subgrade soil is treated with cement mixing piles. The length of cement
mixing piles is 12m, the pile spacing is 1.3m, and the pile diameter is 0.5m. A double layer of reinforcement net with soil-cement structure layer is added above the old road plate of the original model, as shown in Figure 3. The reinforced plate is 5m in length, 0.2m in width and 0.005m in thickness. The steel plastic grid is 4m in length. The geotechnical grid and the cement soil layer are 16m long, and the cement soil layer is 0.3m thick.

![Figure 3. Schematic diagram of the model](image)

**Table 2. Material parameters of reinforced structure**

| position             | Material model   | density(kg/m³) | Elastic modulus(MPa) | Poisson’s ratio |
|----------------------|------------------|---------------|----------------------|-----------------|
| geogrid              | Linear elasticity| 2420          | 3.95e4               | 0.35            |
| Steel-plastic grille | Linear elasticity| 2400          | 8.5e4                | 0.3             |
| cement               | Linear elasticity| 2300          | 600                  | 0.3             |
| Plastic stiffened plate | Linear elasticity | 2100          | 2e4                  | 0.5             |
| Steel reinforcement plate | Linear elasticity | 7850          | 2e5                  | 0.3             |
| Cement mixing pile   | Linear elasticity| 2200          | 300                  | 0.3             |

3.2. Simulation of Upper Reinforced Structure and Soil-structure Interaction

The cement mixing piles can be regarded as a whole with the surrounding soil, which can be divided directly on the PART unit. Because the plane model is used to simplify the problem, when the cement mixing piles are used in the two-dimensional model, it is necessary to replace the parameters of cement mixing piles from three-dimensional to two-dimensional model. The piles in the two-dimensional model correspond to the three-dimensional Sheet piles extending along the road in the model. Since the piles are simplified into sheet piles extending along the road, the longitudinal length of the sheet piles are much larger than the piles diameter, which meets the basic conditions of the plane strain problem. The equivalent stiffness principle of material mechanics can be used to make the piles equivalents by reducing the elastic modulus in the two-dimensional model, as shown in Figure 4. In the principle of equivalent stiffness, the total stiffness remains unchanged, and the thickness of the sheet piles are equal to the original piles diameter. The transformation process is shown in the figure. For the piles group, the total stiffness before transformation is [5]:

$$ s = m \cdot n \cdot \frac{AE}{H} $$  \hspace{1cm} (1)

Among them, m is the number of rows of horizontal piles; n is the number of vertical piles; A is the cross-sectional area of the piles (m²); E is the elastic modulus of the piles (MPa); And H is the piles length (m). The total stiffness of the sheet piles after simplification is as follows:

$$ s' = m \cdot n \cdot \frac{DLE'}{H} $$  \hspace{1cm} (2)

Among them, D is the plate thickness (m); L is the plate length (m); E’ is the elastic modulus of the
sheet piles.
Let equation (1) and equation (2) be equal, and get

\[ E' = \frac{E}{\frac{nA}{DL}} \]  

(3)

Figure 4. Schematic diagram of equivalent stiffness

Since the longitudinal length of the stiffened slab is much greater than the thickness of the slab, it can be two-dimensionally equivalent to a slab extending in the direction of the road by using the principle of equivalent stiffness like a pile. The geogrid and steel reinforced slab are simulated by truss (T2D2) and beam (B21) elements due to the large gap between the horizontal dimension and the longitudinal dimension, and the time contact between the grid and the steel reinforced slab and the soil is handled by Embedded region constraints.

3.3. Treatment of Upper Reinforced Structure Combined with Cement Mixing Pile

Figure 5 is a comparison diagram of road surface deformation between the use of upper reinforced structure combined with cement mixing piles foundation treatment and the use of cement mixing piles alone.

Figure 5. Comparison diagram of deformation of road surface treated by combined foundation

In Figure 5A), the settlement difference between the center of the old road and the junction of the old and new subgrade has been reduced by 21%. This shows that in the case of uneven settlement in the new subgrade treatment with cement mixing piles, the use of the upper reinforcement structure can effectively play an auxiliary role and further reduce the uneven settlement. Figure B) clearly shows that the lateral displacement curve of the road surface with the reinforced superstructure becomes more gentle and the maximum value decreases.

Figure 6 is a comparison diagram of the plane deformation of the upper reinforced structure combined with cement mixing piles foundation treatment and the cement mixing piles alone.
In the figure A), it can be seen that the plane settlement curve of the piles top is uneven when only the piles are used. This is caused by the uneven settlement between the piles top and the soil foundation. After adding the upper reinforcement structure layer, the settlement curve of the piles top plane becomes smoother, which reduces the uneven settlement between the piles top and the piles. In Figure B), it can be seen that the horizontal displacement is effectively reduced after the upper reinforcement structure is added, and the step-like mutation at the junction of the new and old subgrade has also disappeared. The upper reinforcement structure effectively increases the stability and integrity of the subgrade.

The middle of the above figure 7A) is the comparison curve of the settlement between the upper reinforced structure with 12m cement mixing piles for the treatment of new and old subgrade and the road surface settlement without treatment. The maximum settlement of the road surface with joint treatment is 93.71mm, while the maximum settlement of the road surface without treatment is 132.15mm. After treatment, the absolute settlement is significantly reduced. The maximum settlement difference between the center of the old road and the junction of the old and new roads is 9.97 mm and 44.76 mm respectively. After treatment, the uneven settlement is obviously controlled, and the settlement value is only 22.28% of that in the untreated state. It shows that the use of the upper
reinforced structure combined with cement mixing piles to treat the soft foundation can better solve the problem of uneven settlement when the modulus of the new and old soil foundation is relatively large. In the horizontal displacement showed in Figure B), it can also be clearly seen that compared with the displacement in the untreated state, the horizontal displacement after the cement mixing pile treatment is significantly reduced, and the curve is also more moderate.

4. Monitoring Results and Analysis

Figure 8 shows the road surface settlement value detected at the junction of new and old roads 90 days after road construction.

![Figure 8. Road surface settlement at the junction of old and new roads in 90 days](image)

It can be seen that the settlement value at the junction of the old and new roads without treatment is the largest, reaching 21.03mm. The settlement of the section treated by the reinforced structure of plastic strip and steel strip is far less than that of the untreated section, with the difference reaching 4.01mm and 4.8mm respectively. This indicates that the reinforced structure can effectively reduce the value of differential settlement and play a key role in preventing road cracks. According to the current data, the performance of the upper reinforced structure with steel slats is better.

![Figure 9. Lateral displacement of 2m underground at the junction of old and new roads](image)

Figure 9 shows the value of the lateral displacement at 2m underground at the junction of the old and new roads. It can be found that the lateral displacement of the untreated section at a depth of two meters underground is slightly larger than the section of steel slats and plastic slats. The reinforced structure is arranged at a position near 2 meters below the ground surface, which shows that the reinforced structure plays a role of reinforcement and reduces the lateral soil displacement at a position of two meters underground.
Figure 10 shows the earth pressure monitoring values of each section. It can be seen in the figure that the soil pressure readings placed between the cement mixing piles and the piles at the initial stage are similar, and the pressure on the cement mixing piles increases rapidly with the increase of time. The pressure on the three-section piles increased by more than 10%, while the pressure between the cement-mixed piles increased slowly, and the three sections all increased by less than 5%. The difference between the soil pressure at the top and between piles with plastic sheet section reaches 0.011mpa, 0.06mpa without treatment, and 0.01mpa with steel sheet section. This may be due to the reinforced structure on the section of the steel sheet and plastic slats, and the soft soil between the piles will tend to sink. The pressure of the soil between the piles is transmitted to the piles through the reinforced structure layer, which increases the piles top pressure. This shows that the upper reinforced structure helps to give full play to the supporting role of the piles, strengthens the integrity of the piles foundation, and plays a positive role in controlling the deformation of the new and old subgrade.

Synthesizing the above experimental analysis, it can be found that adding the upper strengthening structure does help reduce the uneven settlement at the junction of the new and old roads, enhance the integrity of the new and old subgrade, and control the deformation of the subgrade.

5. Conclusion
By using ABAQUS finite element software and comprehensively considering the interaction between pile-soil-upper reinforced structure, a numerical analysis model is established for the piles-upper reinforced structure to deal with the widening road without embankment in soft soil foundation towns. Comparing the post-construction settlement and lateral displacement laws of the road surface with no treatment, the upper reinforced structure alone, and the upper reinforced structure combined with cement mixing pile treatment, the following main conclusions are obtained:

1. Under the condition of not being disposed, the settlement amount of the old road decreases with the decrease of the new and old soil modulus ratio. At the same time, the settlement difference between the old road center and the junction of the new and old subgrade is greater.

2. Compared with the cement mixing piles alone, the settlement and lateral displacement of the pavement surface are significantly reduced when the enhanced cushion is adopted. Moreover, the uneven surface of piles top and abrupt transitions at the boundary can be eliminated, making the settlement and lateral displacement curves more gentle.

3. Compared with the untreated, the uneven settlement is obviously controlled after the upper reinforced structure combined with cement mixing piles treatment, and the settlement value is only 22.28% of the untreated state. The lateral displacement to the inside of the road basically disappears, and the displacement to the outside is also effectively controlled.

6. References
[1] Ma Q, Xing W, Li L, et al. Effectiveness of Geogrid Reinforcement in Splicing Region in Embankment Widening[J]. Ejge, 2016, 21(16): 5193-5201.
[2] Ariyarathne P, Liyanapathirana D S. Review of existing design methods for geosynthetic-reinforced pile-supported embankments[J]. Soils and foundations, 2015, 55(1):17-34.

[3] Du Changjun, Su Jie, Jiang Zhenhua. Design of Soft Soil Foundation Treatment of Widening and Heightening Urban Existing Road[J]. Modern Transportation Technology, 2014, 11(6): 1-3, 10. DOI:10.3969/j.issn.1672-9889.2014.06.001.

[4] FANG Hanhui. Analysis on Comprehensive Treatment Effect of Soft Ground Foundation in Period I Taizhou Superhighway Project, Zhejiang—A case study for the Tested Part of the Way in Taizhou’Huangyan, Zhejiang Soft Ground Foundation [J]. Carsologica Sinica, 2003(04):27-32.

[5] ZHANG Dingwen. Research on the Deformation Features of Widening of Highway on Soft Ground [D]. Southeast University. 200