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Research Paper

The static test of non-embedded pile-board subgrade in deep soft soil of Shanghai-Hangzhou passenger dedicated line

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ABSTRACT

The non-embedded pile-board subgrade (NEPBS) is a new type of roadbed structure widely used in constructing China's high-speed railways. The paper selects the typical section of the NEPBS project of the Shanghai-Hangzhou Passenger Dedicated Line (SHPDL). It establishes an in-situ static load test system to study and analyze the bearing mechanism and applicability of the NEPBS in deep and soft soil areas. The test results show that the NEPBS has good engineering properties; as time changes, the reinforcement internal force of the loading plate and supporting beam is shown clearly; the converted bending moment agrees with the theoretical bending moment, and the plate-soil contact stress is minor. The test results can explain and analyze the theoretical calculation results. The three-way coordination of the pile-board subgrade can effectively improve the bearing capacity of the foundation soil. The deformation of the NEPBS is reasonable. One year after the completion of the roadbed and track structure, the maximum cumulative settlement of the top surface of the loading plate is 3.29mm, which meets the settlement control requirements.

1 Introduction

The soft soil in Shanghai is mainly composed of silt, silty clay and silty sand layers, which have anisotropy characteristics, high liquid limit, high compressibility, large porosity, high sensitivity and low mechanical strength [1, 2]. The road construction problems in this area are prominent, and many roads are prone to wave-shaped uneven settlement [3]. The construction of high-speed railways faces new issues and challenges due to their high smoothness requirements. The newly built SHPDL is a high-standard passenger dedicated line built in a deep soft soil area. The soft soil below the

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surface is buried more than 60 m deep, and its thick layer can reach 10 to 20 m. Among them, a section of the SHPDL passes under the G50 Shanghai-Chongqing Expressway overpass [4, 5].

In the roadbed plan, the slope foot intrudes into the overpass limit, and the line is close to many existing bridge piers. The outer edge of the overpass pier is 2.5m to 3.5m away from the center line of the line at the closest point, making it impossible to carry out large-scale excavation. At the same time, if the difference in settlement between the soil roadbed and the adjacent piers during the operation period is too significant, it will cause the overpass piers to tilt and even cause the existing bridge pile foundation to produce a sizeable negative friction resistance [6], endangering the everyday use and safety of the overpass.

NEPBS is a new roadbed structure with good bearing capacity, effective settlement control and economic efficiency. The NEPBS consists of a reinforced concrete pile, roadbed and upper reinforced concrete bearing plate. The sheet pile fixation forms a bearing structure with the roadbed soil. The pile foundation transfers the load to the deeper strata, thereby improving the stress state of the soft soil of the roadbed and effectively controlling the settlement of the roadbed. The NEPBS structure is widely used in high-speed railway and road engineering, especially in steep slope sections in mountainous areas or low embankments and cuttings with complex engineering geological conditions. In China, NEPBS has been used in new passenger-dedicated lines, such as the Zhengzhou-Xi'an Passenger Dedicated Line and the Suining-Chongqing Railway and has achieved remarkable results [7, 8].

Considering various limiting factors and the fact that the NEPBS has strong applicability in crossing structures, it can effectively control the foundation settlement deformation in deep soft foundations and does not require a large construction site. A lot of interchange along the SHPDL passes through weak, loose soil foundations. Hence, applying the NEPBS in the SHPDL has practical significance. However, NEPBS has been used for the first time in areas with deep, soft soil and many adjacent structures. The application research of NEPBS in complex geological terrain areas has yet to mature, so it is necessary to conduct relevant research on this. More research is needed on the engineering properties and applicability of NEPBS in deep soft soil areas. Therefore, this paper combines the actual project of the SHPDL to conduct in-situ test research on NEPBS in deep soft soil base section to verify the technical and economic feasibility of NEPBS in deep soft soil areas, to provide a scientific basis for the application of NEPBS in particular geological areas such as deep soft soil areas.

2 Methods

2.1 Project overview

The area through which the new SHPDL passes is a coastal plain with flat and open terrain. The distance between the centre line of the left line and the edge of the highway bridge pier is 1.50-3.05m, the closest distance is 1.5m, and the lowest elevation of the bottom of the highway bridge at the line position is 11.4m. Due to height restrictions, foundation excavation is required for ordinary soil roadbeds. However, it is affected by the adjacent overpass piers, and construction is rugged, so the traditional roadbed structure is not applicable. The surface water in the site is ditch water with a water depth of about 0.5-1.5m, and the groundwater is pore water with a water level of about 0.5-2.0m, and the water volume is abundant.

To conduct the field experiment, the authors select a standard section of NEPBS for static testing at the underpass construction site of the G50 Shanghai-Chongqing Expressway Interchange. The test section of the NEPBS consists of an upper loading plate, a lower support beam and bored cast-in-place piles. The existing pier on the left side of this section is only 2.15m away from the edge of the pile foundation. The plane layout of the test section of the NEPBS is shown in Fig. 1.

This section of the NEPBS is 30.0m long and arranged in three equal spans; each span is 10m. The loading plate adopts a split-width design, with a single width of 4.4m, a plate thickness of 1.0m, a support beam length of 9.64m, a width of 1.6m, a height of 1.5m, a pile foundation diameter of 1.25m, and a pile length of 45.0m. The cross-sectional layout of the test section of the NEPBS is shown in Fig. 2.

The foundation soil under the structure of this test section is mainly soft clay, silt, etc. Geological Survey data show that within 60m below the surface, the foundation soil has a high moisture content, large pores, and generally low bearing

capacity. The primary bearing capacity of the maximum bearing layer is only 180kPa. The physical and mechanical indicators of the soil layer at the test site under the G50 Shanghai-Chongqing Expressway overpass are shown in Table 1.

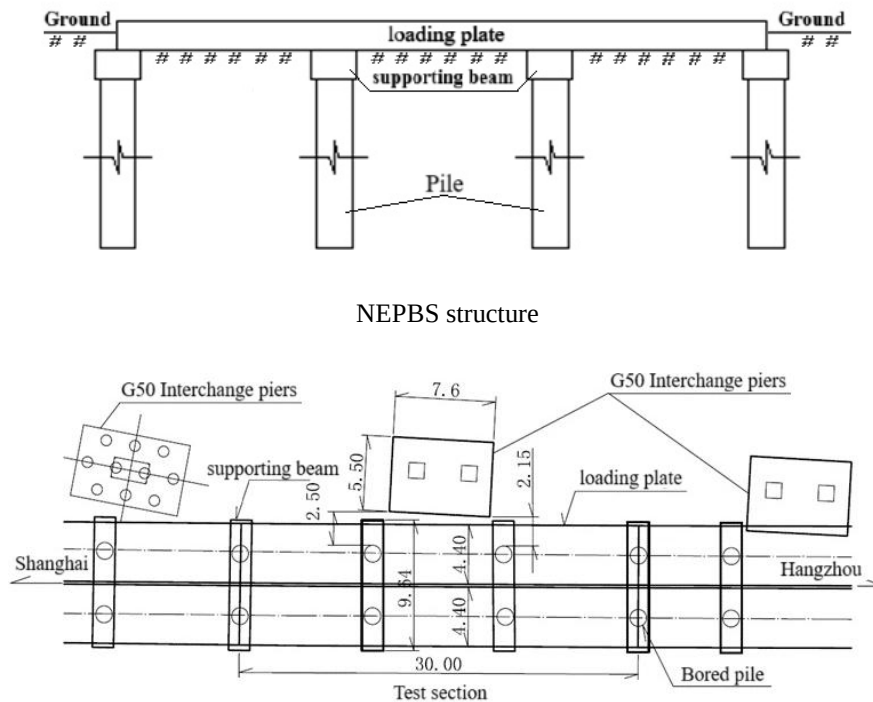


Fig. 1 – Plan of NEPBS test section (Unit: m)

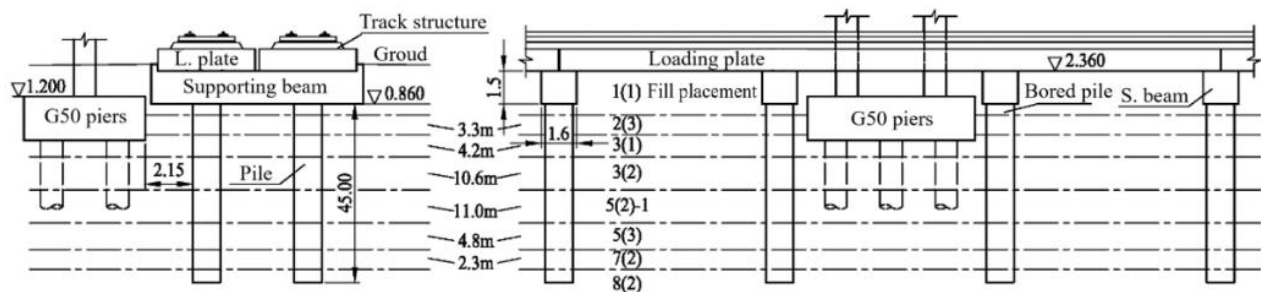


Fig. 2 – Profile of NEPBS test section (Unit: m)

A field observation system was established at the test site under the G50 Shanghai-Chongqing Expressway overpass to study and monitor the stress and deformation characteristics, load transfer rules, working status under static load conditions, and stress-deformation characteristics of the NEPBS. According to the selected test section NEPBS, the half-standard section was divided into seven equally spaced monitoring sections. The test established a fully automatic all-weather observation system through the automatic acquisition system to achieve long-term, unmanned and efficient monitoring.

According to the test requirements, the main contents of the test include internal forces of the loading plate, internal forces of the supporting beam, contact stress between the slab and the soil, and settlement of the loading plate. The calculation results of the pile foundation design and reference to relevant studies [9, 10] show that the bored pile design at this work site can meet the bearing and deformation requirements of the deep and soft soil foundation. The design bearing capacity of the pile foundation far exceeds its design load, so this in-situ test does not observe the internal forces of the pile foundation and only tests the vertical deformation of the pile top.

A steel bar gauge is arranged at the top and bottom of the slab along the centre line of the single-span loading plate to observe the internal forces of the steel bars and then inversely calculate the bending moment of the loading plate. Similarly,

a steel bar gauge is buried inside the supporting beam. Under the centre line, an earth pressure gauge is buried in sections III and VII to observe the contact stress between the slab and the soil. In addition, a settlement observation point is set on one side of the loading plate in sections III and V to observe the settlement and deformation of the NEPBS.

Table 1 – Physical mechanical properties of soil layers

Soil layer number	Name	Soil depth (m)	State	Moisture content w (%)	Density ρ (g/cm ³)	Porosity e	Compression modulus $E_{s0.1\sim0.2}$ (MPa)	Cohension c (kPa)	Internal friction angle φ (°)
2(3)	Silt, silty sand	3.3	Loose ~ slightly dense	27.65	1.94	0.78	8.90	9.21	20.77
3(1)	Muddy clay	4.2	Flow plastic	41.06	1.79	1.16	3.12	9.11	6.66
3(2)	Silty mixed with silty clay	10.6	Slightly dense	30.27	1.84	0.92	6.33	8.75	12.26
5(2)-1	Silty sand	11.0	Slightly dense ~ medium dense	30.27	1.87	0.89	5.45	8.53	15.86
5(3)	Silty clay	4.8	Soft (plastic)	32.59	1.82	1.02	4.40	11.51	10.34
7(2)	Fine sand	2.3	Dense	23.35	2.05	0.64	5.79	19.00	22.40
8(2)	Fine clay mixed with silty sand	13.1	Soft (plastic) or medium plastic	32.00	1.87	0.93	5.20	15.88	12.64

The test components are shown in Fig. 3, including the test points for the loading plate reinforcement gauge (P1~P14), the supporting beam reinforcement gauge (B1~B4), the earth pressure gauge (T1 and T2), and the settlement observation points (S1 and S2).

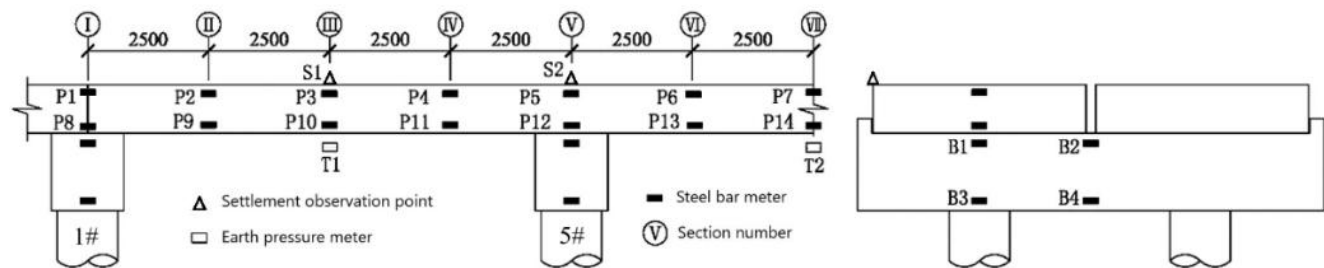


Fig. 3 – Arrangement of test components (Unit: mm)

2.2 Calculation method

The allowable stress method and the probabilistic limit state method are the two primary approaches for designing NEPBS. According to relevant studies [11], the allowable stress approach is used in this work.

The NEPBS is an over-determined spatial structure that needs to be simplified before it can be analyzed. According to Su et al. [8], the NEPBS structure is divided into a frame structure, which only partially considers the interaction characteristics between the pile and soil. As a result, this paper proposes a new plane calculation model based on the elastic foundation beam method, which is calculated and analyzed using general bar system finite element software.

For simplicity, the calculation takes into account the following streamlined conditions [11, 12]:

- Temporarily ignoring the supporting effect of the soil under the plate, the foundation coefficient $K = 0$;
- The loading plate, support beam and pile foundation are simplified as frame structures according to their equivalent stiffness;
- The lateral resistance constraint of the soil on the pile is simplified to a spring simulation distributed along the pile body and calculated according to the Winkler elastic foundation beam theory;
- In the longitudinal section, the side span end support is a vertical spring, and its spring stiffness k is determined according to the pile body's deformation modulus and the soil's deformation parameters at the pile end.

According to the above-simplified conditions, the plane calculation model of the NEPBS is shown in Fig. 4.

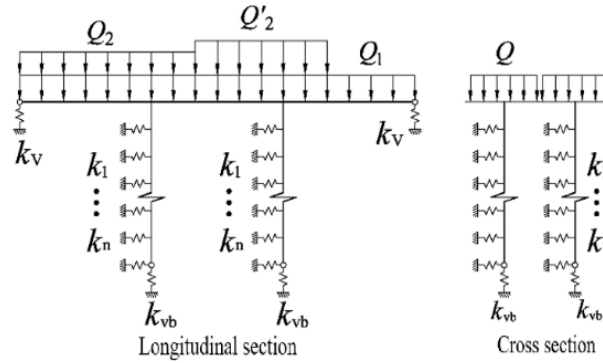


Fig. 4 – Plane calculation model

The design of the NEPBS must consider the effects of permanent loads (Q_1), variable loads, and accidental loads (Q_2, Q'_2). This experimental study is a static test study. The train's live load is not considered during the test. The calculation is a uniformly distributed load.

According to the Winkler theory, the spring coefficient k_z at depth z is calculated as

$$k_z = m \cdot b_0 \cdot h_z \cdot z \quad \delta = \sum_{i=1}^s e^H(\omega_t) e(\omega_t) \quad (1)$$

In the formula, m is the proportional coefficient of the soil foundation coefficient with depth, which is taken as $m=5000\text{kN/m}^4$; b_0 is the calculated width of the pile; h_z is the thickness of the soil layer at the depth z (spring spacing).

In Fig. 4, the values of $k_1 \sim k_{n-1}$ are calculated according to formula (1), and when calculating k_n , z is taken as the distance from the bottom of the pile to the ground, and h_z is taken as $1/2$ of the length of the pile bottom unit. Referring to the paper of Xing Shiling et al. [13], k_v and k_{vb} can be calculated according to formulas (2) and (3)

$$k_{vb} = C_0 A_0$$

$$A_0 = \pi \left[\frac{d}{2} + h \tan \frac{\varphi}{4} \right]^2 \quad (2)$$

$$k_v = \frac{0.67}{\frac{0.5h}{EA} + \frac{1}{C_0 A_0}} \quad (3)$$

In the above formula, C_0 is the vertical foundation coefficient of the pile bottom soil; A_0 is the compressive area of the pile bottom soil; d is the pile diameter; φ is the soil internal friction angle; and the average value is taken for multi-layer soil. E is the compressive elastic modulus of the pile body; h is the length of the pile buried below the ground line.

3 Results and discussions

3.1 The stress of the primary reinforcement of the loading plate and supporting beam

Due to the lateral effect of the supporting beam and the ratio of the long side to the short side of the loading plate being more significant than 2, the loading plate can be calculated as a one-way plate. The test results of the primary reinforcement of the loading plate are shown in Fig. 5.

After reaching a stable temperature field, the rebar meter reading was selected as the analysis object during the experiment. In Fig. 5, the internal force value was positive for tension and negative for compression. The maximum tensile

stress of the primary reinforcement at the support was 27.6MPa, and the maximum compressive stress was 24.0MPa; the maximum tensile stress of the primary reinforcement at the mid-span was 17.9MPa, and the maximum compressive stress was 30.8MPa (HRB400 steel, $d=25\text{mm}$).

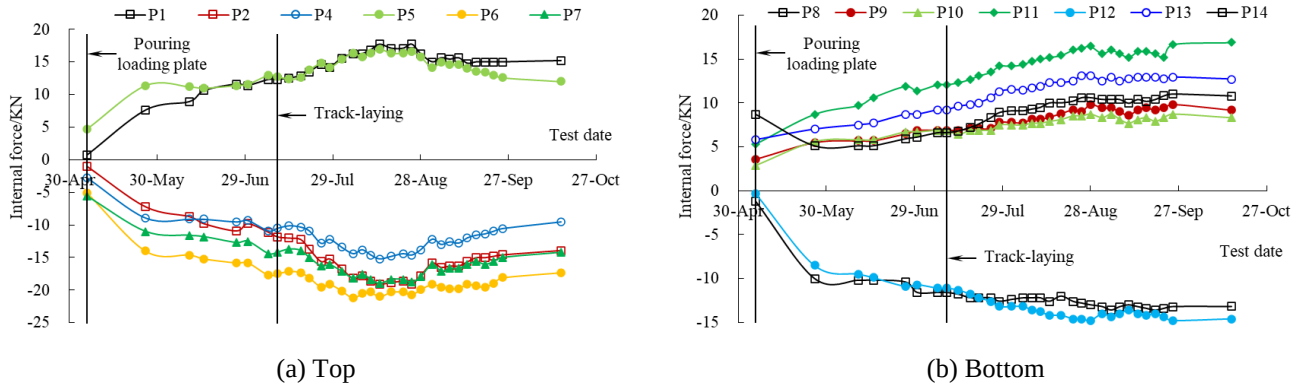


Fig. 5 – Time-history curves of reinforcement stress of loading plate

After the construction of the roadbed and track engineering, the internal force of the primary reinforcement first increased and then decreased slightly, tending to be flat. This was because the initial load was mainly transmitted to the pile foundation through the loading plate, causing the internal force of the loading plate to increase. As the pile foundation gradually settles, the soil's supporting role under the plate is enhanced, decreasing the loading plate's internal force. However, after a long period of action, as the soil under the plate settles, its shared load decreases, resulting in an increase in the internal force of the loading plate and an increase in the rebar meter test value, as shown in Fig. 5.

According to the double-reinforced beam theory and the steel bar stress values of each test section, the bending moment value is calculated according to formulas (4) to (6)

$$\sigma_c = \sigma'_s E_c / E_s \quad (4)$$

$$\sigma_s A_s = \sigma'_s A'_s + \sigma_c b x \quad (5)$$

$$M = \sigma'_s A'_s (h - a_s - a'_s) + \sigma_c b x (h - a_s - x / 2) \quad (6)$$

Where: σ_c is the stress of concrete compression zone; σ_s (σ'_s) is the stress of tensile (compressive) steel bar; E_c is the elastic modulus of concrete; E_s is the elastic modulus of compressive steel bar; A_s (A'_s) is the area of tensile (compressive) steel bar; b is the width of the loading plate; x is the height of the concrete compression zone; a_s (a'_s) is the distance from the centroid of the tensile (compressive) steel bar to the tensile (compressive) edge of the section; M is the section bending moment. The values of the above material parameters correspond to the actual engineering material mechanics parameters.

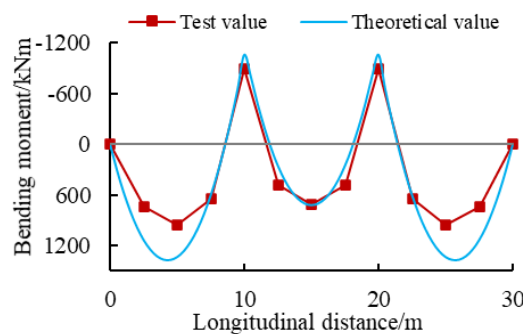


Fig. 6 – Comparison between test and theoretical bending moment of loading plate

The bending moment converted to the loading plate is shown in Fig. 6. The maximum value of the converted bending moment of the NEPBS measured in the middle span is 709kNm, and the side span is 952kNm.

The measured values are consistent with the theoretically calculated bending moment, with the main difference being in the side span position. In the theoretical calculation process, this factor is considered safe, and the back is hinged, so the theoretical calculation is reasonable, which also reflects the rationality of the difference between the measured converted bending moment and the theoretically calculated bending moment. In addition, the measured bending moment values are much smaller than the design resistance bending moment of the loading plate, indicating that the design bearing capacity is reliable.

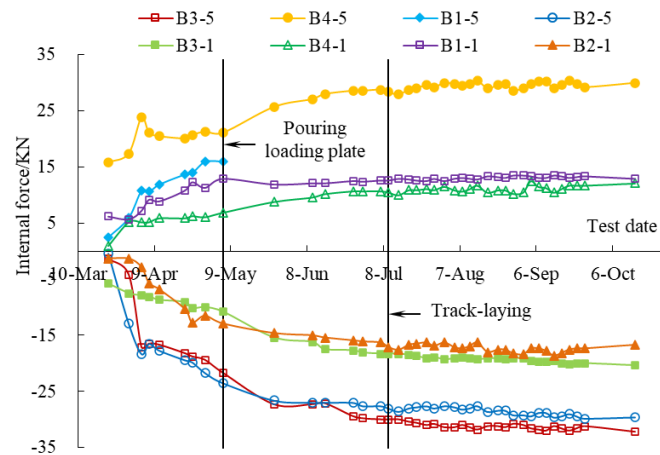


Fig. 7 – Time-history curves of reinforcement stress of supporting beam

The stress characteristics of the supporting beam were analyzed through on-site testing of the internal force of the primary reinforcement of the supporting beam. The internal force of the primary reinforcement of the supporting beam is shown in Fig. 7.

Similarly, the supporting beam is in the working state of a double-reinforced beam. The maximum tensile stress of the primary reinforcement at the supporting beam support is 26.0MPa, and the maximum compressive stress is 52.3MPa. The maximum tensile stress of the primary reinforcement at the mid-span is 49.4MPa, and the maximum compressive stress is 48.4MPa. After the construction of the roadbed and track engineering is completed, the internal force of the primary reinforcement tends to stabilize.

As shown in Fig. 8, the trend of the converted bending moment of the 1# and 5# supporting beams agrees with the theoretical calculation value. However, some differences remain, mainly reflected in the bending moment at the centre of the supporting beam exceeding the theoretical calculation result. In the theoretical calculation, the load distribution on the cross-section is treated as a uniformly distributed load according to the distribution position of the pedestal plate. The measured results show that the actual situation may not be uniformly distributed, and this assumption needs further study. In addition, the measured bending moment values are much smaller than the design resistance bending moment of the supporting beam, indicating that the design bearing capacity is reliable.

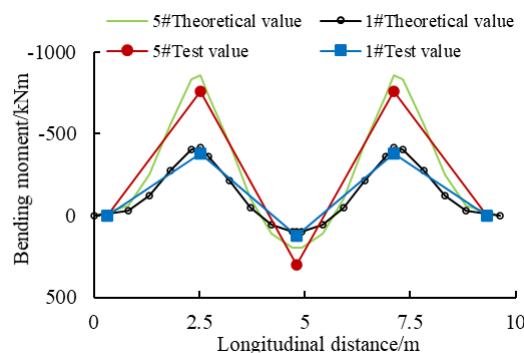


Fig. 8 – Comparison between test and theoretical bending moment of supporting beam

3.2 Contact stress between loading plate and soil

The maximum internal force of the loading plate is greatly affected by the soil under the plate and changes with the foundation coefficient K . The theoretical calculation process, combined with the actual working conditions, did not consider the foundation soil's support effect on the plate to simplify the calculation.

Therefore, it is necessary to study the support degree of the foundation soil on the loading plate to calculate the foundation coefficient K inversely. Figs. 9 and 10 show the development and distribution of plate-soil contact stress along the length of the plate.

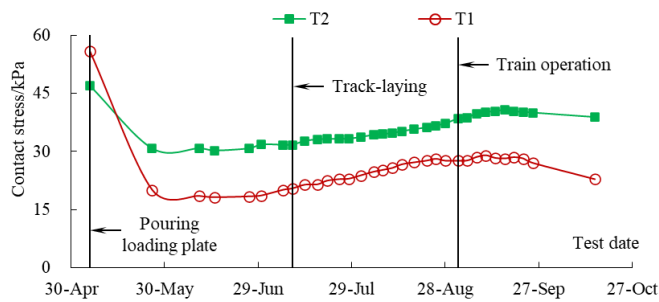


Fig. 9 – Loading plate and soil contact stress

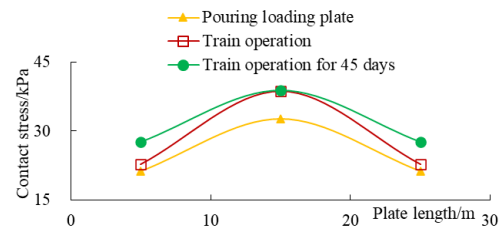


Fig. 10 – Longitudinal distribution of plate soil contact stress

The plate-soil contact stress is generally small, with a maximum value of 40.75kPa after the temperature stabilizes. As shown in Fig. 9, the plate-soil contact stress exhibits a pattern of initially increasing and then decreasing after the track laying is completed, reflecting the process where the supporting effect of the soil under the plate on the loading plate first increases and then decreases. In the early stage, under the load action and settlement of the pile foundation, the load shared by the soil under the plate gradually increases. However, with long-term action and soil settlement development, the upper load gradually transfers to the pile foundation, decreasing the load shared by the soil under the plate. Furthermore, Fig. 10 indicates that the plate-soil contact stress in the middle of the middle span is higher than in the middle of the side span. This is due to the greater vertical load the pile foundation bears in the middle span, resulting in more considerable pile body settlement and a more substantial contact effect between the middle span loading plate and the soil under the plate. The higher contact stress in the middle span suggests that the foundation coefficient K of the soil under the middle span plate is more significant, explaining why the mid-span bending moment of the middle span loading plate is less than that of the side span from a foundation coefficient perspective.

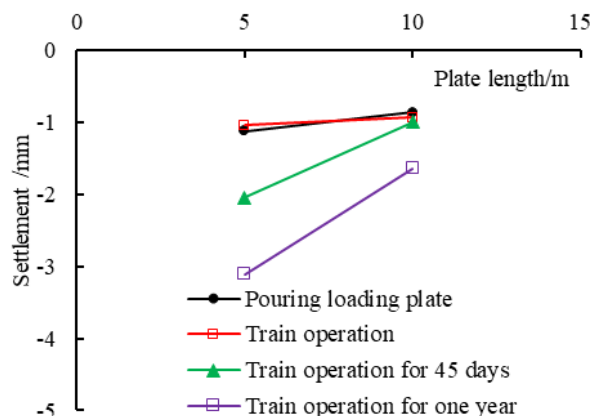


Fig. 11 – Longitudinal distribution of deformation

3.3 Deformation of the loading plate

The deformation of the loading plate includes the settlement of the pile foundation, the settlement and flexural deformation of the loading plate itself, and the shrinkage and creep of concrete. The deformation composition and law in

deep and soft soil areas are analyzed by testing the settlement of the main section of the pile slab roadbed. The test data is shown in Fig. 11.

As shown in Fig. 11, the deformation of the loading plate is consistent with the theoretical calculation results. At the same time, the deformation of the mid-span of the side span is more significant than the deformation of the span end, and the deformation of the span end is mainly due to the settlement of the pile foundation. The test results show that under static load (track-laying is completed), the deformation of the loading plate at 5m is 1.12mm, and the deformation at 10m is 0.86mm. The difference between the two is that the deflection of the mid-span of the side span is 0.26mm. In the theoretical calculation, the deflection value is 0.30mm, which agrees with the theoretical calculation. After the train runs, the deformation of the loading plate further develops.

Furthermore, one year after the completion of the roadbed and track structure, the maximum settlement of the NEPBS was 3.29mm, and the settlement of the NEPBS had stabilized, meeting the requirement that the settlement deformation of the high-speed railway roadbed was less than 15mm [14].

4 Conclusions

Based on the results obtained, we have the following conclusions:

For the first time, the NEPBS was used in deep and soft soil areas, passing through many adjacent structures. Its strength is apparent, the force transmission path is clear, and it has a sound engineering shape. In addition, it has little impact on the site and can effectively improve the force state of the soft soil of the roadbed.

The internal force test of the loading plate and the support beam shows that the internal force law of the two is consistent with the theoretical calculation, and the measured conversion moment is in good agreement with the static load theoretical moment, indicating that the simplified idea of the theoretical calculation model is reliable.

After the construction of the roadbed and track engineering, the change process of the primary reinforcement internal force of the loading plate “increase-decrease-stable-slightly increase” and the change process of the plate-soil contact stress first increasing and then decreasing, all reflect the coordinated work of the pile-slab-soil system. In the early loading stage, the force on the loading plate increases, and the pile foundation mainly bears the load. As the pile foundation settles, the supporting effect of the soil under the plate is enhanced. The increase in the load shared by the soil under the plate aggravates the consolidation settlement of the soil, causing the upper load to be transferred to the pile foundation again. This process forms a cycle; eventually, the three reach stability after a long coupling period.

The foundation coefficient of the soil under the slab greatly influences the NEPBS. However, considering that the mechanical properties of the deep and soft soil foundation are poor and the supporting stiffness is weak, the supporting effect of the soil under the slab is not considered during the design process, which is safe for the design.

The deformation observation of the loading plate shows that the deformation of the NEPBS is consistent with the theoretical calculation result, and the deflection value of the loading plate is very close to the theoretical calculation value. The post-construction settlement of the NEPBS is generally minimal. According to the long-term observation results, the settlement meets the specification requirements. It can effectively control the settlement of the passenger dedicated line's ballastless track roadbed in Shanghai's soft soil area.

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