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Synergistic Effects and Mechanical Properties of Adjacent Composite Pile-Sheet Wall in Embankment Widening Project

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Abstract

To address the technical challenges caused by terrain constraints in existing embankment widening projects, the innovative "Adjacent Composite Pile-Sheet Wall (ACPSW)" supporting system is proposed. This structure forms a compo-site supporting system by adding parallel new pile-sheet walls among existing pile-sheet walls. Combined with the engineering practice of the Lanzhou Hub Project of the Zhongwei-Lanzhou Railway, the numerical simulation method is adopted to systematically study the horizontal displacement of piles, distribu-tion characteristics of soil pressure behind the wall, and the collaborative bear-ing mechanism between old and new piles of the ACPSW structure throughout the construction process. The research reveals that under the coupled action of new embankment filling and train operation loads, the old and new pile-sheet walls can achieve collaborative deformation, forming a load distribution ratio of 0.6:1 between old and new piles. The research results provide a design basis and engineering practice reference for new supporting structures in existing railway reconstruction and projects adjacent to existing railway lines.

Keywords

Composite retaining structure; Numerical simulation; load sharing

1. Introduction

With the improvement of China's railway network, newly built railways need to connect with existing railways before entering stations, and the number of new construction projects adjacent to existing lines will increase year by year. When the existing line adopts a cantilever retaining wall for slope closing, determining the form of the composite retaining structure by integrating the design and usage requirements of existing and new structures becomes one of the engineering challenges. Defining the collaborative force mode between the new and existing retaining structures, as well as determining their stress and deformation, represents the core of such engineering projects.

The pile-sheet retaining wall evolved from anti-sliding piles for slope protection, forming a pile-sheet wall through the interconnection of various pile-intermediate plates. Tang et al.[1] focused on applying pile-sheet walls to cutting structure projects, employing numerical simulation and field measurement. By analyzing the distribution law of earth pressure on both sides of the pile, they explored the influence of pile length, stiffness, position, and soil parameters on structural performance, proposing an optimal pile length of 14 m. Zhang et al.[2]considering the anisotropy of soft clay, used numerical calculations to analyze how the stiffness of pile-sheet walls affects lateral earth pressure. For the cantilever pile-sheet wall—where pile-top displacement often exceeds standards or to reduce pile cross-section size—Fall et al.[3]studied the changes in pile bending moment, displacement, and anchor rod reaction force during surrounding soil excavation, proposing optimization parameters. Xu et al.[4]utilized numerical analysis to investigate the horizontal displacement and pile bending moment of different long-short pile-sheet walls, optimizing the quantity and length of short piles to design a reliable and economical retaining structure for specific projects. Building on previous research, for special topographic conditions, diverse pile-sheet wall forms and composite structures have emerged. For existing subgrades with cantilever retaining walls, to ensure the upper structure has sufficient lateral width, a “existing–newly built side-by-side composite pile-sheet wall” was proposed based on the practical project of introducing the third and fourth lines of the Zhonglan Passenger Dedicated Line into the Lanxin Line.

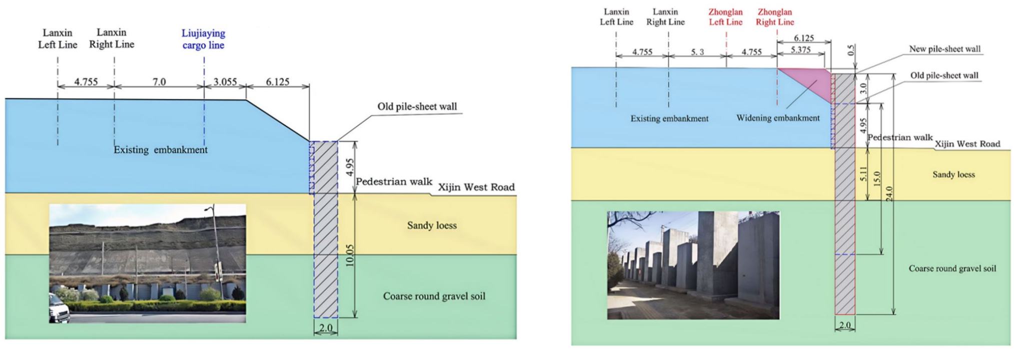
This paper establishes a numerical model consistent with actual project conditions using ABAQUS, comparing the stress changes and deformation characteristics of new and old piles under different construction conditions. It clarifies how the two structures jointly bear loads and collaborate. The research results provide a new composite structural form for subgrade widening projects and offer technical support for applying this structure in railway engineering.

2. Numerical simulation

2.1. Introduction of test site

The newly-built Zhongwei-Lanzhou Railway is a double-track railway with a design speed of 250 km/h, adopting ballasted track. In the Lanzhou Hub section of this project, the Adjacent Composite Pile-Sheet Wall (ACPSW) was used to achieve embankment widening. Figure 1a shows the cross-section of the existing embankment before widening. To the south of the cross-section is the existing Lanxin Railway, and to the north is the existing Liujiaying Freight Railway. To prevent the embankment slope from occupying Xijin West Road, a pile-sheet retaining wall was used for slope support. Figure 1b presents the cross-section of the embankment after widening. It can be seen that the left line of the

Zhongwei-Lanzhou Railway was constructed at the location where the existing Liujiaying Freight Railway was dismantled, and the right line was built on the widened subgrade. Constrained by topographic conditions, new pile-sheet walls were installed side-by-side among the old pile-sheet walls to balance new loads such as additional embankment loads and train loads.



(a) (b)

Fig.1 Sectional drawing of embankment:a embankment before widening;b embankment after widening

2.2. Establishment of finite element model

The 3D model of ACPSW with the same cross-section as the field test is established using finite element software Abaqus, and its dimensions are shown in Figure 11. To mitigate the boundary effect, the model adopts a larger size: the length along the line direction is 28.5 m, and the cross-sectional height in the pile length direction is 35 m with a length of 40 m. The model comprises soil layers, existing piles, new piles, existing retaining sheets, and new retaining sheets. There are five soil layers: filling soil in the subgrade widening section, artificial fill, sandy loess, coarse rounded gravel soil, and pebble soil. Both existing and new piles have rectangular cross-sections. The pile cross-sectional dimension is 1.5×2 m, with a pile spacing of 3 m. The existing piles are 15 m long (with a 5 m cantilever segment), while new piles are 24 m long (with a 7.95 m cantilever segment). The retaining sheet is 0.5 m in height and 0.4 m in thickness

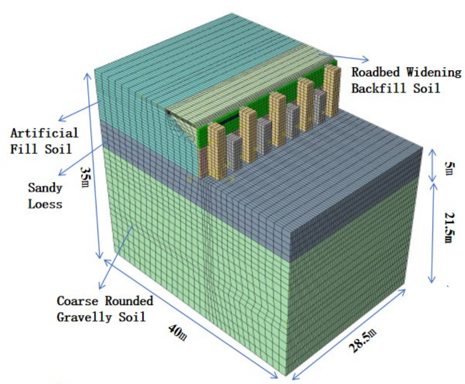


Fig.2 Numerical Model of Existing - Newly-built Side-by-Side Composite Pile-Sheet Wall

2.3. Constitutive mode

The M-C model describes the failure behavior of materials based on the classical Mohr-Coulomb criterion, applicable to simulating the shear failure of granular materials under monotonic loading. Its greatest advantage lies in simplicity and practicality—only parameters like internal friction angle and cohesion are needed to describe the ultimate shear strength. Additionally, it aligns well with the yield state of soil, shows close consistency with test results, and can effectively depict the ultimate bearing state of soil. In this section, the M-C model is adopted as the constitutive model for soil.

In actual field construction, the newly built piles are cast with C40 concrete, while the existing piles use C35 concrete. Both new and old piles exhibit high material stiffness and minimal deformation, with the nonlinear behavior of pile materials being insignificant. Therefore, in the numerical model, the piles are simplified as an elastic model.

2.4. Simulated procedure

In the numerical simulation, initial in-situ stress equilibrium is first carried out. Subsequently, a finite element model is used to explore the mechanical behavior of existing piles under the loads from the existing embankment, existing freight line, and widened embankment. The numerical simulation procedure is consistent with the actual construction stages, as detailed in Table 1. According to the specification TB10025-2019, the load at Stage 3 is 54.1 kN/m^2 with a distribution width of 3.4 m.

Table 1. The numerical simulation stages

Stage no	Description
1	Apply existing cargo line loads
2	Filling height
3	Apply train loads

3. Results and discussion

3.1. Horizontal displacement of the pile

Figures 3a and 3b respectively show the distribution diagrams of the horizontal displacement of the existing piles and newly-built piles under three steps.

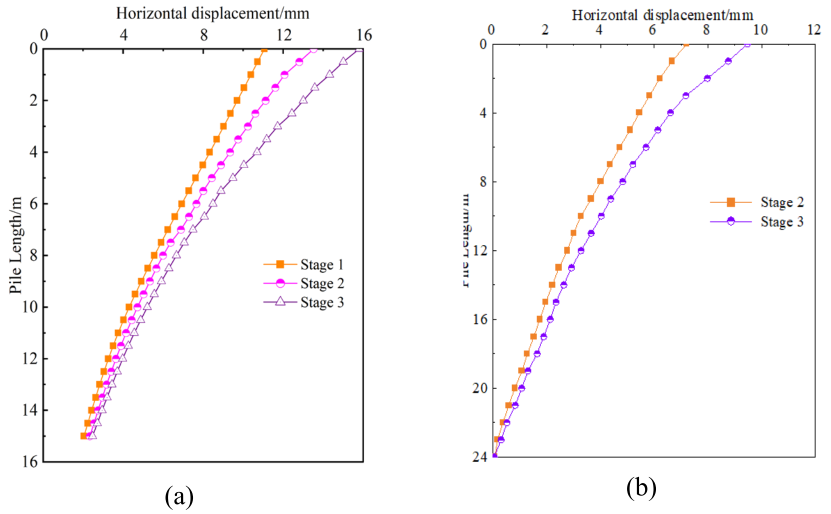


Fig.3 Horizontal displacement curves of old pile and new pile:**a** old pile;**b** new pile

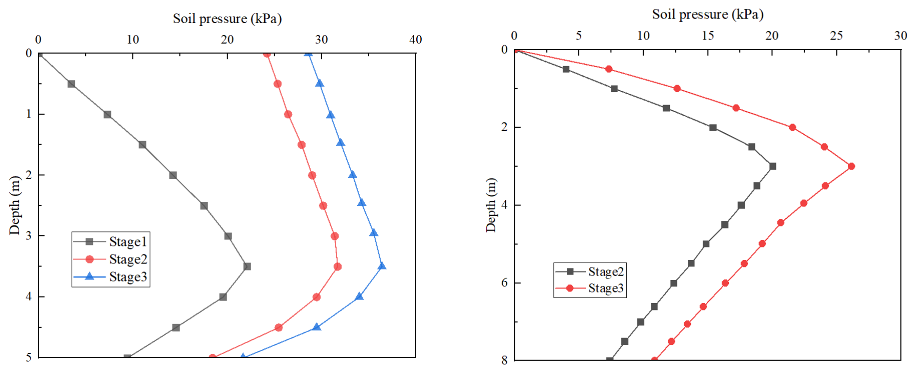
As indicated in Figure 3a, in Step 1, the top displacement of the existing pile is 11.06 mm; in Step 2, the pile top displacement increases to 13.82 mm; in Step 3, the horizontal displacement at the pile top further rises to 15.81 mm. After the subgrade widening section is filled, the horizontal displacement at the top of the existing pile increases by 2.76 mm; under the newly applied train load, the pile top horizontal displacement increases by 1.99 mm compared with stage 2. This change reflects the cumulative influence of filling load and train load on existing piles, and also shows that existing piles bear the additional load.

From Figure 3b, it can be observed that in Step 2, the horizontal displacement at the top of the new pile is 7.19 mm; in Step 3, the pile top horizontal displacement increases to 9.47 mm. This means that under the newly added line load, the horizontal displacement at the top of the newly-built pile increases by 2.28 mm. Compared with existing piles, the displacement increment of the newly-built pile is larger under the action of the added filling load, indicating that the newly-built pile plays a more significant role in sharing external loads.

With the increase of filling embankment load and the application of the newly-built train load, the top displacements of both existing piles and new piles show a synchronous increasing trend. The total horizontal displacement of existing piles is always greater than that of new piles, but the displacement increment of new piles is larger than that of existing piles. This demonstrates that both piles jointly share external loads during the collaborative deformation process.

3.2.Earth pressure

Figures 4a and 4b respectively show the distribution diagrams of earth pressure behind the existing piles and newly-built piles under different stages.



(a) (b)

Fig.4 The distribution of soil pressure behind new pile and old pile:a old pile;b new pile

As indicated in Figure 4a, for the existing pile, the earth pressure behind the pile under each step exhibits a single-peak distribution pattern with depth. The peak consistently occurs 3.5 m below the pile top, with maximum values of 22.1 kPa, 31.7 kPa, and 36.4 kPa. The peak value increases as additional loads grow, demonstrating that existing piles bear part of the new loads.

From Figure 4b, the earth pressure distribution behind the newly-built pile aligns with that of the existing pile. The peak appears 3 m below the pile top (i.e., at the top of the old pile), with maximum values of 20.04 kPa and 26.17 kPa. Notably, the earth pressure behind the new pile starts to decrease after reaching the old pile's top. Combined with Figure 4a, it can be inferred that part of the additional load borne by the new pile transfers to the old pile. Thus, the new and old piles jointly share external loads, effectively realizing the synergistic effect between them.

3.3. Load sharing

To analyze the load-sharing of additional loads between old and new piles, a numerical quantitative comparison method is adopted. The total earth pressure behind the new pile is denoted as F_{new} and the total additional earth pressure behind the old pile is denoted as F_{old},The calculation formula is as follows:

$$ration = F_{new} / F_{old} \tag{1}$$

This formula numerically quantifies the collaborative load-bearing contribution between the new and existing piles under combined embankment widening and train loads.

According to the above formula, it is calculated that in Step 3, the newly-built piles bear approximately 62% of the additional loads, while the existing piles assume 38% of the additional loads. The load-sharing ratio between new and existing piles reaches 1:0.6, indicating that the installation of new piles not only primarily shoulders the additional loads but also effectively utilizes the bearing capacity of existing piles. This synergistic interaction fully demonstrates the advantages of this combined old-new retaining system.

4. Conclusions

(1)The analysis of pile displacement characteristics indicates that under the step conditions, the maximum horizontal displacements of both old and new piles occur in the pile top region, decreasing progressively along the pile body to reach the minimum value at the pile base. With the increase of additional loads, the displacements at the tops of old and new piles exhibit a synchronous growth trend. Specifically, the total horizontal displacement of existing piles is consistently greater than that of newly-built piles, while the dispacement of existing piles is consistently greater than that of newly-built piles, while the displacement increment of new piles is more significant.

(2)Results of earth pressure analysis reveal that the earth pressure behind both old and new piles first increases and then decreases with soil depth. Newly-built piles bear 62% of the additional loads, whereas existing piles assume 38%, demonstrating that the installation of new piles not only primarily shoulders the additional loads but also effectively mobilizes the bearing capacity of existing piles. This synergistic interaction between old and new piles highlights the advantages of this combined retaining system.

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