Finite element analysis of contact between new-built structure and old subgrade in pile-plank structure

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Abstract. Under different working conditions of two vehicle load and four vehicle load, the changes of contact normal stress and friction normal stress between contact surfaces of pile-plank structure were systematically simulated by FEM respectively. The results show that the contact normal stress and friction normal stress are both maximum under the condition of four-vehicle load, and condition 23 is the most unfavorable overall stress situation in which the maximum contact normal stress reached 302.936kPa and the maximum friction normal stress reached 90.881kPa.

1. Introduction

The traditional subgrade filling scheme has some serious problems, such as difficult land acquisition, large amount of filling and long construction period. The proposed pile-plank structure can effectively solve the above problems, with less environmental pollution. However, the applications of pile-plank structure in highway reconstruction and expansion project have only begun to appear in recent years, and the related research is less.

In 2017, Yang Fei [1] proposed two structural forms of pile-plank structure and hollow slab girder bridge for highway bridges under passing through high-speed railway in soft soil area, and carried out numerical simulation research. Under the condition of meeting the requirements of high-speed railway structure protection and operation safety, the pile-plank structure has better integrity and less maintenance workload than hollow slab beam. Xu Daqing [2] put forward the pile-plank beam bridge structure. The design ideas of pile-plank connection, slab and existing subgrade connection are provided. In 2018, Zheng Wucong [3] connected the solid elements and beam elements in the integrated pile column by using the MPC184 rigid beam, so as to achieve the purpose of collaborative stress, transfer force, force moment and coordinate displacement and deformation of pipe piles with different element forms. Based on the background of Hefei Zongyang expressway, Zhu Jun [5] and others carried out preliminary calculation on the fatigue performance of pile-plank connection, and verified that the fatigue performance of core filled sleeve pile plate connection mode can meet the requirements of relevant specifications. Yang Qingyun [6] took the prefabrication and installation of pile-plate structure as the research object, and introduced the construction process of new pile-plank structure applied to highway. In 2019, Lei Jin [7] established the nonlinear finite element model of pile plate connection structure based on the reconstruction and expansion project of Lintou to Longxi interchange section of G5011.
Wuhe expressway, and verified that the designed pile-plate connection structure meets the practical application of the project.

Summarizing the previous research, the research paper of pile-plank structure in the field of highway is less, and the systematic research on the structure under the action of highway load is lack. Therefore, it is necessary to carry out reasonable parameter design and put forward favourable suggestions for the subsequent engineering application.

2. Project overview
The engineering research object of this paper is the pile-plank structure in expressway reconstruction and expansion project, as shown in Figure 1. The expressway plans to adopt the overall expansion scheme of "double side widening as the main part and local separation as the auxiliary" to expand into a two-way eight Lane Expressway with a standard subgrade width of 42m and a design speed of 120km / h.

3. Establishment of finite element model
In this project, the independent pier column pile-plate structure is applied. The bearing plate of this kind of structure is a two-way slab, and the structure and boundary conditions of the slab are complex. Therefore, in order to better understand the stress and deformation of pile-plate structure, in this paper, ANSYS finite element analysis software is used to analyze the pile-plate structure, in which the bearing plate, pavement, pile column, soil and old subgrade are discretized by spatial entity element.

3.1. Selection of element type and constitutive model

3.1.1. Unit type. The bearing plate, pile, soil, subgrade surface, base and asphalt pavement are simulated by SOLID45 element, as shown in Figure 2. The finite element model is meshed by hexahedral.
3.1.2. Drucker-Prager elastoplastic model.
A generalized Mises yield and failure criterion considering the effect of hydrostatic pressure in Drucker-Prager elastoplastic model. Its strength theory reflects the influence of volume stress, shear stress and intermediate principal stress on rock strength. Drucker-Prager yield criterion is based on Mohr-Coulomb yield criterion and Mises yield criterion.

\[ F = \alpha I_1 + \sqrt{J_2 - K} \]  
\[ \alpha = \frac{2\sin\phi}{\sqrt{3(3 - \sin\phi)}} \]  
\[ K = \frac{6C\cos\phi}{\sqrt{3(3 - \sin\phi)}} \]

Where \( C \), \( \phi \) represent cohesion and internal friction angle of geotechnical materials, \( I_1 \) is first invariant of stress, \( J_2 \) is second invariant of deviatoric stress.

The yield surface of Drucker-Prager yield criterion in the principal stress space is a cone. When Drucker-Prager model is used in ANSYS software, not only the parameters of internal friction angle and cohesion, but also the parameters of expansion angle \( \phi_f \) are needed. The expansion angle \( \phi_f \) controls the amount of volume expansion that will occur. When \( \phi_f = \phi \), there will be obvious volume expansion; if \( \phi_f < \phi \), small volume expansion will occur; if \( \phi_f = 0 \), no volume expansion will occur.

3.2. Unit parameters of contact interface
In this paper, the surface to surface contact element is used and the augmented Lagrange multiplier method is used to simulate the constraint relationship. Because the stiffness of pile and slab is obviously greater than that of soil and old subgrade, the contact surface of pile and slab is set as TARGE170 target surface, and the contact surface of soil and old subgrade is set as CONTA174 contact surface. The target element can invade the contact surface, while the contact element is constrained and cannot invade the target surface. The normal contact stiffness factor \( F_{KN} \) is 1.0, and the penetration tolerance factor \( FTOLN \) is 0.1. It is assumed that the friction between the contact surfaces is Coulomb friction. The interface friction coefficient is taken as 0.3.

3.3. Calculation parameters and boundary conditions

3.3.1. Dimension parameters of pile-plate structure.
Referring to the test section form of pile-plate structure in the engineering project, the standard span is 6m, five spans are set, and half span is extended to both sides of the longitudinal direction. The bearing plate is 36m long, 6.6m wide and 0.3m thick. The cast-in-place section is 0.9m wide and 0.7m thick. The width of transverse approach slab is 3.75m and the thickness is 0.3m. The cast-in-place section is 0.9m wide and 0.7m thick. The width of transverse approach slab is 3.75m and the thickness is 0.3m. The precast bearing plate is provided with a longitudinal rib with a height of 0.6mThe bottom width of the rib is 0.7m, the chamfer size is 0.3m, and the distance between the center of the longitudinal rib and the cantilever end of the precast bearing plate is 1.75m. The width and height of cushion block are 0.3m and 0.3m respectively. The asphalt pavement with a thickness of 10 cm is set.

The cross-section of the pile is round, with a diameter of 0.6m and a length of 15m. According to the actual situation of the project site, combined with the effective calculation amount and accuracy of ANSYS software, the length of soil longitudinal length and bearing plate longitudinal length is 36m, the soil depth is 15m, the top surface width of soil is 8.4m, the bottom width is 33m, and the soil slope ratio is 1:1.5. The old subgrade section is provided with original surface course, original base course and original subbase with thickness of 0.2m, 0.3m and 0.2m respectively. The original surface course, original base and original subbase are continuous. In the finite element modeling, X-axis is the cross-
sectional direction, Z-axis is the vertical section direction, and Y-axis is the vertical direction. The cross section and vertical section of pile plate structure are shown in Figure 3 (a) and Figure 3 (b) respectively.

3.3.2 The main materials
The main materials include bearing plate, pile column, cast-in-place section, transverse approach slab, asphalt pavement, original surface course, original base course, original subbase and soil mass. The bearing plate, cast-in-place section and transverse approach slab are C40 concrete, and pile column is C80 concrete.

3.3.3 Calculated
The calculated load includes dead load and live load. Dead load is self weight load and live load is vehicle load. The lateral arrangement of vehicle load is shown in Figure 4, and the vertical and plane dimensions of vehicle load are shown in Figure 5 and Figure 6.
3.4. Calculation conditions

The finite element model of pile-plate structure has three lanes. There are hard shoulder and the third lane on the bearing plate. When the vehicle load acts on different positions, the effect on the structure varies greatly, and the most unfavorable working condition under the load cannot be determined. Therefore, transverse double vehicle load, and four vehicle loads of two longitudinal vehicles will be added on the basis of transverse double vehicle load respectively, and the lateral movement along a certain width in the way of traversal is used to realize loading.

3.4.1. Dual vehicle lateral loading.

Working condition 8 ~ 17: the distance between dead load + outermost wheel and cantilever end of bearing plate is 1.05m ~ 10.05m (every 1m is a working condition). The transverse position and longitudinal position of vehicle are shown in Figure 7(a) and Figure 7(b) respectively.
3.4.2. Four vehicle lateral loading.

Working condition 18 ~ 27: the distance between dead load + outermost wheel and cantilever end of bearing plate is 1.05m ~ 10.05m (every 1m is a working condition). The transverse position and longitudinal position of four vehicles are shown in Figure 8(a) and Figure 8(b) respectively.
4. Analysis of finite element calculation results

4.1. Dual vehicle lateral loading
The stress and deformation of the contact surface under dead load and transverse double vehicle load are shown in Figure 9 and Figure 10. The transverse double vehicle load is arranged in accordance with Figure 9, and the vehicle load moves with the width of each meter in the transverse direction. It can be seen from Figure 11 that in case 8-13, with the lateral movement of double vehicle load, the maximum compressive stress on the contact surface increases continuously, and in case 13-17, the maximum compressive stress first decreases and then increases. Figure 12 shows the same trend as Figure 12, and reaches the maximum value in condition 13, that is, condition 13 can generate the maximum compressive stress and friction stress. At this time, both vehicles act on the concrete structure, and the wheel on the side closest to the old subgrade section acts on the joint between the transverse approach slab and the old subgrade.

4.2. Lateral loading of four vehicles
According to figure 9 (a), the lateral arrangement of four vehicles is the same as that of two vehicles, but the difference is that two vehicles are added in the longitudinal direction. The stress and deformation of the contact surface under dead load and four vehicle loads are shown in figures 14 and 15. The vehicle load moves with the width of each meter in the transverse direction. It can be seen from figures 14 and 15 that with the lateral movement of the four vehicle loads, the overall trend is to increase first and then decrease. At condition 23, the compressive stress, friction stress and total stress of the contact surface are the largest. At this time, all four vehicles act on the concrete structure, and the wheel on the side closest to the old subgrade acts on the joint between the new structure and the old subgrade.
5. Conclusion

Through detailed analysis, the following conclusions are drawn:

1. Under the lateral loading of two vehicles, the maximum stress of the contact surface increases with the distance between the outermost wheel and the cantilever end of the bearing plate. When both vehicles act on the concrete structure, and the wheel on the side closest to the old subgrade acts on the joint of the transverse approach slab and the old subgrade the maximum normal stress reaches 276.94kPa, and the change trend of friction stress is the same as that of normal stress, and reaches 83.082kPa under condition 13.

2. Under four vehicle loading conditions, with the distance between the outermost wheel and the cantilever end of the bearing plate increasing, the change trend of the contact surface normal stress and friction profit is the same as that of single vehicle and double vehicle. When the four vehicles act on the concrete structure and the wheel on the side closest to the old subgrade acts on the joint between the new structure and the old subgrade, the maximum normal stress reaches 302.936kPa and the maximum friction stress reaches 90.881kPa.

3. Under different vehicle loads, with the vehicle load continuously moving to the old subgrade section, the compressive stress, friction stress and total stress of the contact surface show a trend of first increasing and then decreasing, and all of them are the maximum values under four vehicle loads. When the vehicle load is under condition 23, this is the most unfavorable overall stress condition.

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