Numerical Simulation Study on Mechanical Performance of Prefabricated Cable Conduit under Wheel Load

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Abstract: In order to improve the prefabricated assembly degree of cable conduit, make up for the shortcomings and deficiencies of cast-in-place cable conduit, and realize the standardization, industrialization and modular production of cable conduit, the mechanical performance of a new type of prefabricated cable conduit (PCC) is investigated numerically in this study. Finite element simulations are employed to decipher more details on the compressive behaviour of numerous archetypes with different thickness of covering soil and wheel loads. The results show that the stress and deformation of prefabricated cable conduit can meet the requirements under the design load, the vertical displacement and tensile stress of steel bars are significantly affected by the location of wheel load and the thickness of overburden. The conduit wall is the control component of the main compressive stress, and the top plate is the control component of tensile stress. The results show that the vertical displacement of the top plate and the tensile stress of the bottom plate are 4.2 times and 4.0 times of the corresponding values when the thickness of the covering soil is 2 m. Under the action of wheel pressure, the tensile stress at the bottom of the roof concrete decreases at first and then increases with the increase of the covering soil thickness.

1. Introduction

With the development of urban modernization and economic growth, the effective land use area is becoming increasingly tense, the urban power density is increasing, and the power consumption is increasing day by day. Overhead line power supply can not meet the power demand of the city. In addition, in the urban construction and reconstruction planning, all pipelines are often required to go underground in the newly-built area and prosperous area.Buried cables and pipelines not only save space resources and land resources, but also improve the ability of urban power grid to resist natural disasters such as ice, snow, flood and typhoon [1]. In recent years, the cast-in-place cable conduit has been vigorously promoted and used because of its convenient construction, flexible operation and relatively low cost, and has become the main laying method of underground cable [2]. However, the cast-in-place cable conduit has many disadvantages, such as large seasonal impact, long construction period, unsuitable construction quality control, difficult maintenance or local replacement in the later stage, and has adverse impact on the living, traffic and environment of residents around the construction site [3].

With the in-depth application of automation technology, the development of large-scale prefabricated assembly machinery and equipment, and the urgent demand of people for an environment-friendly society, prefabricated structures have been rapidly developed in the world, and have been widely used in construction, comprehensive pipe gallery, bridge and culvert engineering [4-8]. Compared with cast-in-place concrete cable conduit, prefabricated cable conduit can improve labor efficiency and construction quality, and the operation area of site construction is small, which can reduce part of the cost of early demolition and road restoration, and can minimize the impact of construction on road traffic and residents' life, and its social and economic benefits are significant. In this paper, a kind of PCC with the function of rapid assembly was proposed. The finite element numerical simulation was carried out by ABAQUS finite element software, in order to find out the stress characteristics and failure mode of the reconstructed structure, as well as the stress and deformation law under different load conditions, so as to provide reference for the popularization and application of PCC.

2. Design of PCC

The PCC structure proposed in this paper is shown in Figure 1. The modified pipe consists of four parts: pipe wall, cover plate, bottom plate and pipe support. The standard section length is 2m, and the transverse width is achieved by adjusting the bottom plate width, According to the relevant provisions in GB 50217, the bottom plate width is proposed to be 360mm, 620mm, 880mm, 1140mm and 1400mm. The conduit wall and bottom plate are divided into spigot and socket, and connected through the notch, as shown in Figure 2.

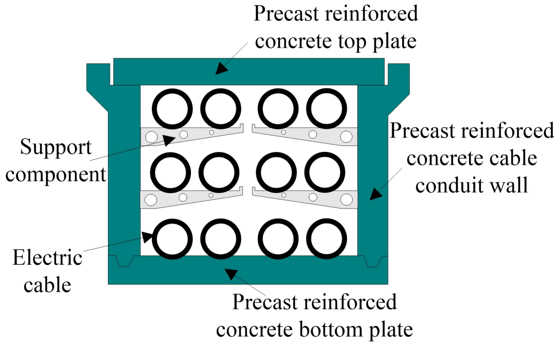


Figure 1: PCC with support component.

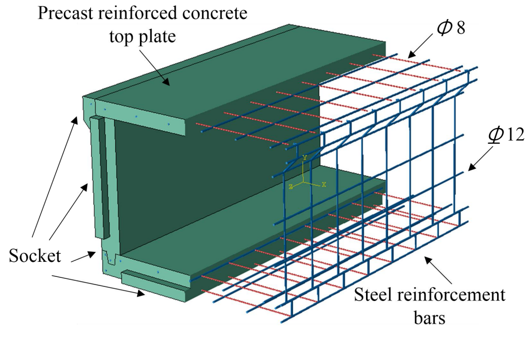


Figure 2: Schematic diagram of PCC structure.

As shown in Figure 2, the length of cover plate is consistent with the length of standard section, and the thickness is proposed to be 100 mm, 120 mm and 150 mm.The length direction of PCC standard section is also connected by notch and external prestress. In order to facilitate the maintenance and local replacement of cables, and to consider the thermal expansion and cold contraction of the line caused by the change of load, the support structure is used to erect cables in PCC.

3. Finite Element Modelling

3.1.General

Finite element numerical simulation software ABAQUS was used to calculate the performance of PCC in this study. The length of PCC was 2m, the width of bottom plate was 1400mm, and the thickness of top plate was 100 mm. Separate models were considered for reinforcement bar and concrete. Eight node linear hexahedral element (C3D8R) was selected to simulate concrete. Two node linear three-dimensional truss element (T3D2) was used for reinforcement bar. The finite element model (FEM) of PCC was shown in Figure 3. There were 165998 nodes and 140854 elements in FEM.

In this paper, the bond relationship between steel and concrete is simulated through *Embedded region* method in ABAQUS. *Embedded region* method is usually designated to deal with one or a group of cells located in other units arrested problems, the method can handle tendons and steel mesh. The *surface-to-surface* contact with finite sliding in ABAQUS was defined as the contact characteristic between plate and conduit wall and between PCC and soil, which was set as hard contact and *Coulomb* friction, with a friction coefficient of 0.6 in the normal and tangential directions, respectively. Fixed boundary conditions were applied to the bottom surfaces of the members, and the top surfaces of the members were free boundaries. *Newton-Raphson* method is used for iteration calculation.

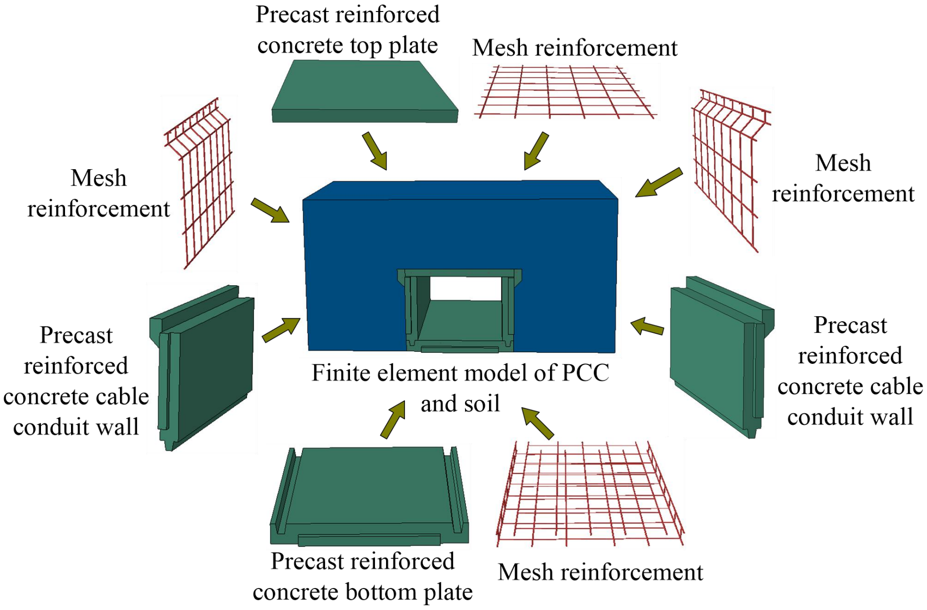


Figure 3: The finite element model (FEM) of PCC.

3.2.Material properties

The strength grade of PCC concrete was C30, and hpb300 and HRB400 were used for reinforcement bar. The damage plasticity (CDP) model defined in ABAQUS was used in the analysis [9], which can simulate the nonlinear behavior of pipe gallery concrete structure, the double broken line model was used for steel constitutive model, and linear elastic model was used for soil constitutive model. Figure 5 shown the constitutive model of concrete in this paper, the rising section of which was used the formula proposed by mander [10], the decreasing section adopted by the formula proposed by Guo

Zhenhai [11], other parameters in CDP model were shown in Table 1. The material model for all steel elements was based on elastic-perfectly plastic behavior [12].

Table 1: Other calculation parameters in CDP model.

Ψ/(°)	ε	σb0/σc0	Kc	η
40	0.1	1.16	0.6667	0.0005

4. Influence of Buried Depth on Stress and Deformation of PCC

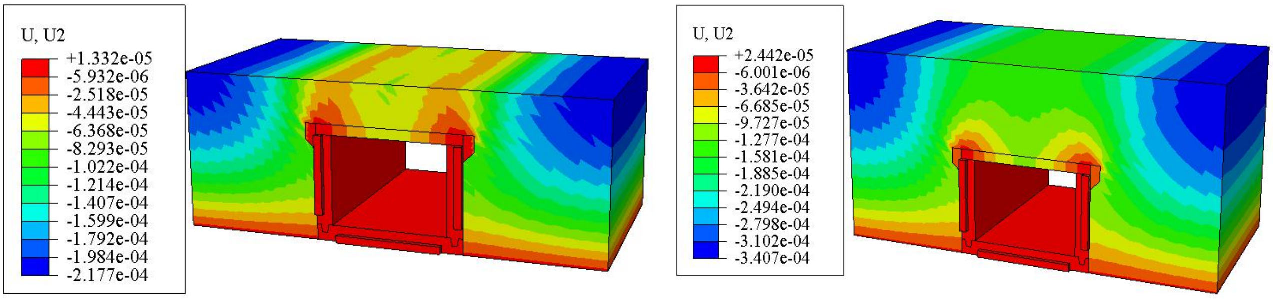
4.1.Introduction of Parameter Analysis Models

The buried depth is the key factor to ensure the safe operation of PCC. Buried PCC bear the static load of overlying soil, ground vehicle dynamic load and ground occupation load. If PCC is buried too shallow, it is easy to be damaged under the action of various loads on the ground; if the buried depth of PCC is too deep, it will bring about the uneconomical construction of the project, and the earth pressure when the soil is too thick is also a load that can not be ignored, which makes PCC and the internal cable still exist in the destruction of hidden dangers. Therefore, it is very important to explore a safe, economical and reasonable buried depth.

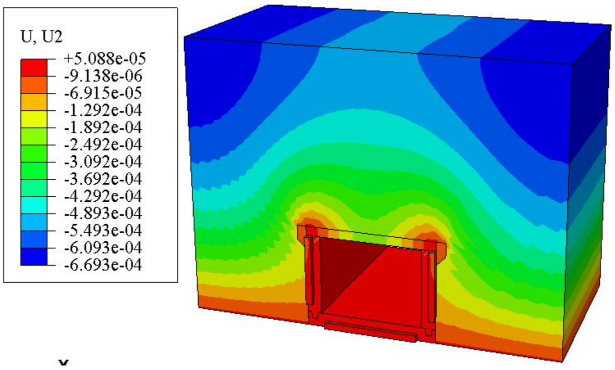
In order to study the influence of the buried depth and the thickness of soil on PCC array, three buried depths of 0.5 m, 1.0 m and 2.0 m were calculated by FEM.

4.2.Results

In this FEM, the PCC and soil were affected by gravity, and the pressure generated by the gravity of covering soil will act on the top plate. The vertical displacement nephogram was shown in Figure 4.



(a) Covering soil thickness was 0.5m (b) Covering soil thickness was 1.0m



(c) Covering soil thickness was 2.0m

Figure 4: Displacement nephogram of FEM.

It can be seen from Figure 4 that the displacement distribution of soil and PCC was significantly different under different buried depth. When the buried depth was small, the PCC supported the upper covering soil. In order to further analyze the stress distribution and deformation of PCC with different buried depths, the element data on different paths of the finite element were extracted, as shown in Figure 5, Figure 6 and Figure 7.

Figure 5 and Figure 6 shown that under the action of overburden load, the top plate was bent, the top of PCC wall moved outward, and the midspan bending deformation occurred under the compression of lateral soil. Figure 5 and Figure 7 shown that the vertical displacement in the middle of the top plate span was 0.2mm and 0.048mm when the soil thickness was 2m and 0.5m, respectively, thus the tensile stress of the concrete at the lower edge of the roof was 1.49MPa and 0.37MPa, respectively. The vertical displacement of the top plate and the tensile stress of the bottom plate were 4.2 times and 4.0 times of those of the 0.5m overburden thickness, respectively. It can be seen that the deformation and stress of PCC can meet the relevant requirements at normal buried depth. In addition, when the buried depth is large, the gravity effect of overburden will have adverse effect on PCC, and the top plate may be subject to bending failure. In this case, a thicker top plate should be used.

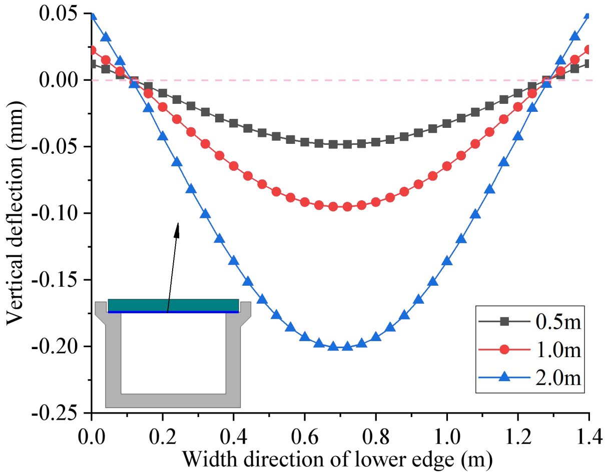


Figure 5: Deflection curves of top plate.

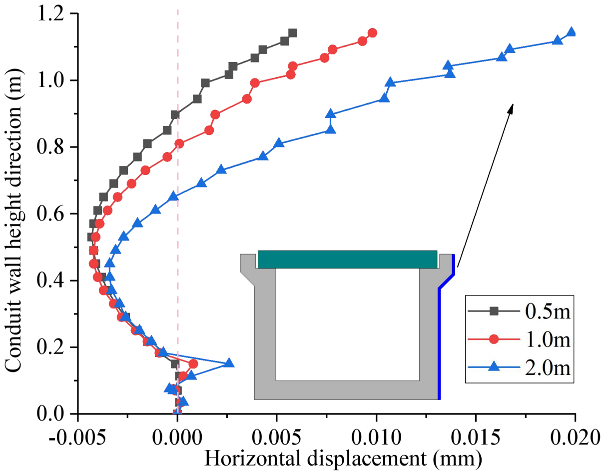


Figure 6: Displacement curves of conduit wall.

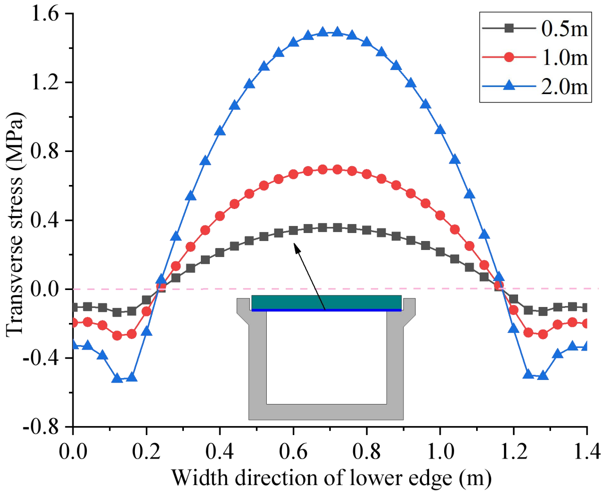


Figure 7: Stress curves of top plate lower edge.

5. Stress Analysis of PCC under Different Wheel Load

5.1.Simulation of Wheel Load

The real contact area between the wheel and the road surface is approximately elliptical, and it is considered that the vehicle axle load is evenly distributed on the contact area, but the ellipse is not convenient for load loading and grid division. Therefore, the contact area needs to be simplified in the study of traffic pavement. In this paper, according to the method in the literature [13], the contact area was simplified as a rectangular loading block of 0.6m × 0.2m in the finite element model, the Tie constraint in ABAQUS was selected to simulate the contact properties between the rigid loading block and soil.

There are two load steps in the model, the first step only counted the response of PCC under the gravity. The second step was gradually applying wheel loads on the top surface of rigid loading block. Considering geometric nonlinear effects the analysis step used Static General algorithm.

5.2.Parameter Analysis

In order to analyze the influence of wheel load location and pipe laying depth on PCC stress and deformation, 36 groups of finite element models were established as shown in Table 2.

Where, *b* represents the horizontal distance between the wheel load and the center point of PCC, and *h* represents the vertical distance from the top of PCC to the surface of the covering soil, as shown in Figure 8.

Table 2: Information on the specimens.

Specimen name	*b* (mm)	*h* (mm)	Wheel load (kN)
S0-0.5	0	0.5	17.5, 35.0, 52.5
S0-1.0	0	1.0	17.5, 35.0, 52.5
S0-2.0	0	2.0	17.5, 35.0, 52.5
S0.5-0.5	0.5	0.5	17.5, 35.0, 52.5
S0.5-1.0	0.5	1.0	17.5, 35.0, 52.5
S0.5-2.0	0.5	2.0	17.5, 35.0, 52.5
S1-0.5	1.0	0.5	17.5, 35.0, 52.5
S1-1.0	1.0	1.0	17.5, 35.0, 52.5
S1-2.0	1.0	2.0	17.5, 35.0, 52.5
S1.5-0.5	1.5	0.5	17.5, 35.0, 52.5
S1.5-1.0	1.5	1.0	17.5, 35.0, 52.5
S1.5-2.0	1.5	2.0	17.5, 35.0, 52.5

5.3.Results

It can be seen from the previous study that PCC bear bending deformation under the action of vertical pressure, and the lower edge of the top plate received tensile stress under the action of positive bending moment, while the ultimate tensile strength of concrete was low. Therefore, the lower edge of the top plate was the vulnerable part of PCC. Therefore, the concrete element stress at the midspan position of the lower edge of the top plate was extracted for analysis, as shown in Figure 9-Figure 11.

It can be seen from the figures that the tensile stress of the concrete at the lower edge of the top plate decreased with the increase of the wheel load distance when the covering soil thickness was fixed, and the corresponding tensile stress of the lower edge was the maximum when the wheel pressure acts on the top of PCC. When h = 0.5m and b = 0m, the tensile stress of the lower edge was 1.5MPa under the wheel load of 17.5kN. When the wheel load increased to 35kN, the tensile stress reached 2.1MPa, which was close to the ultimate tensile strength of concrete. Therefore, when the wheel load increased to 52.5kN, the top plate cracked and the concrete stress decreased, as shown in the figures. In addition, it can be seen from Figure 8, Figure 9 and Figure 10 that when the wheel load was constant, the tensile stress of the top plate gradually decreased with the increase of the wheel load distance. However, if the depth of covering soil was 0.5 m, the tensile stress caused by wheel load decreased greatly, at this time, the wheel loading area was not above the PCC.

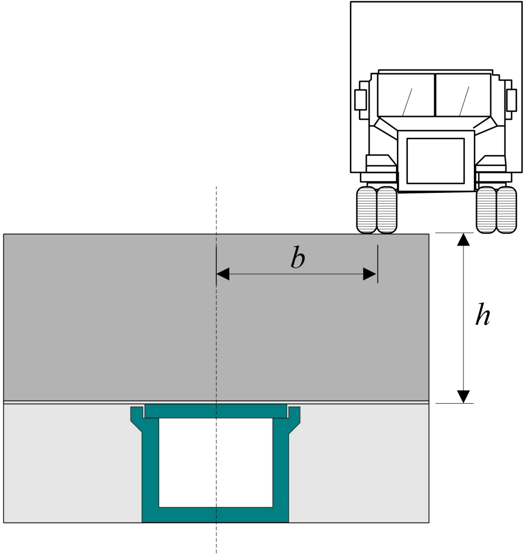


Figure 8: Stress curves of top plate lower edge.

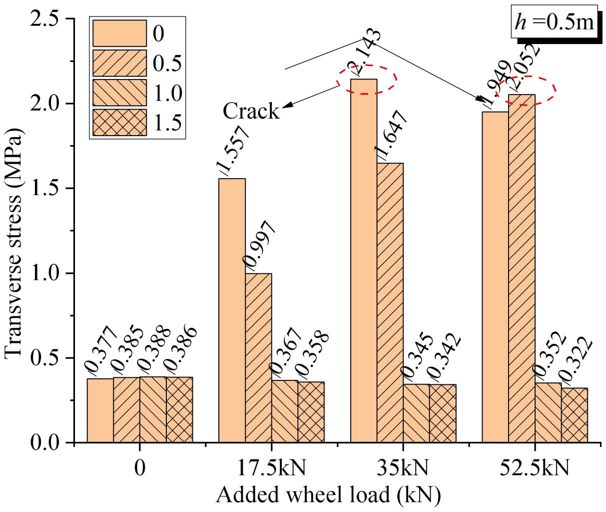


Figure 9: Stress curves of top plate lower edge.

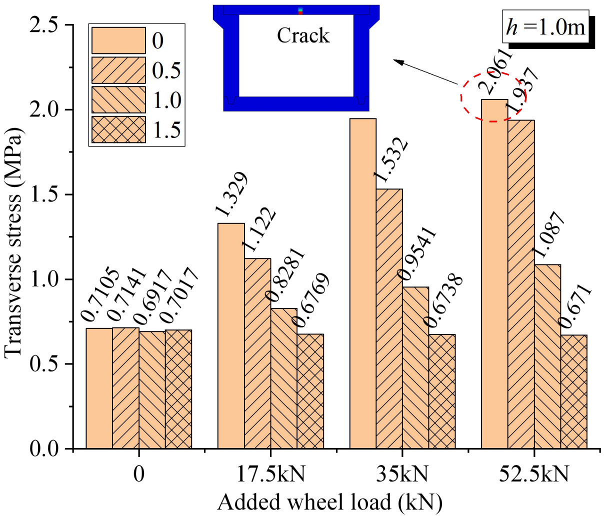


Figure 10: Stress curves of top plate lower edge.

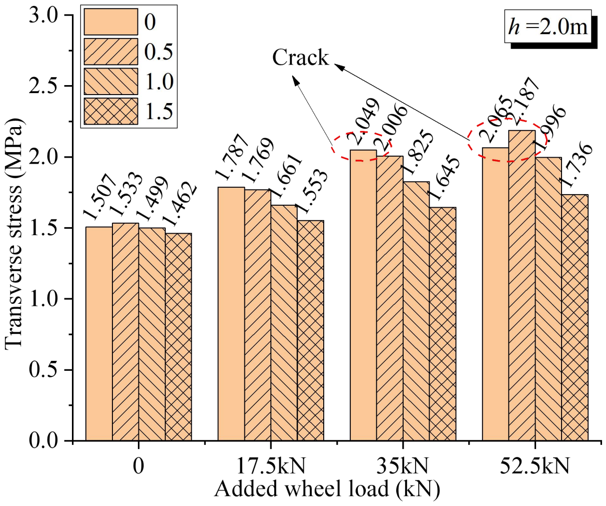


Figure 11: Stress curves of top plate lower edge.

It also can analyze the influence of the depth of covering soil and the distance of wheel load on the stress of the top plate in PCC, when *b* = 0m, the wheel load of 35kN caused the cracking of the concrete at the lower edge, and the tensile stress of the lower edge further increased by increasing the thickness of the covering soil. When b = 0.5m, the increase of overburden thickness from 0.5m to 1.0m can disperse the local wheel pressure to a certain extent and reduce the tensile stress of the lower edge, but above figures shown that when the thickness of covering soil increased to 2.0 m from 1.0m, the proportion of tensile stress at the lower edge caused by gravity action of covering soil increased, and at this time, increasing the thickness of covering soil will be unfavorable to the stress of PCC. When b = 1.0 and 1.5, the wheel load did not directly act on the upper surface of PCC, and the tensile stress proportion of the lower edge caused by the wheel load decreased. The load on PCC mainly came from the gravity action of the covering soil.

6. Conclusions

1. The performance of the prefabricated cable conduit could meet the requirements of the stress and deformation under construction and utilizing conditions, and there is enough safety reservation.

2. The position of vehicle wheel load and the thickness of soil cover have significant influence on the vertical displacement and concrete stress of PCC. The PCC wall is the control component of the main compressive stress of the structure, and top plate is the control component of the tensile stress.

3. When the thickness of covering is too thick, the earth pressure is also a load that can not be ignored, which will make PCC and internal cables still have potential damage. The design of PCC should consider the influence of soil load and vehicle load.

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