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Finite Element Analysis Study of Box Culvert Jacking-Out Construction under Existing Railway Line

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Abstract

To shorten the existing box culvert demolition construction period and ensure the normal operation of the railway, the jacking-out construction method was adopted. The ABAQUS finite element software was used to establish a three-dimensional model of the box culvert and soil body of the relying project, and three excavation thickness (0 m, 1 m, 2 m) were used as the main variation parameters for numerical analysis and research, and the change law of the box culvert itself and soil body stress during the culvert jacking out process was obtained. The results show that the jacking force-displacement curves of the three working conditions can be divided into two stages, and the jacking force reaches the maximum value at the moment when the static friction turns into sliding friction at the end of the first stage. The stress distribution at the bottom slab of the box culvert in the jacking process is approximately normal, and the stress decreases with the increase of the roadbed excavation thickness. The increase of the roadbed excavation thickness can reduce the soil pressure on the side of the box culvert and effectively reduce the deformation of the roadbed in the jacking-out process. The deformation of the roadbed during the jacking process can be reduced by increasing the thickness of the roadbed excavation.

Keywords

Existing Box Culvert, Jacking-Out Construction, Excavation Thickness, Jacking Force

1. Introduction

With the development of the social economy, some transport infrastructure has been in use for a long time. As a result, many old roads, bridges, and culverts cannot meet the growing traffic demand. Existing bridge reinforcement or expansion is more common. Therefore, how to safely and reliably demolish bridges has become the focus of research. [1]. In the past, most bridges were demolished by mechanical violence, *i.e.* by mechanical breaking, rope sawing and other methods to dismantle the bridge structure and then lift it, while some bridges or special bridges were demolished by blasting and other methods. Mechanical breaking and demolition methods are dangerous and have a large impact on environmental pollution and residents' lives, and are often not applicable in urban areas and other areas with high safety and environmental requirements. Although the rope saw method can avoid the above problems, it often causes short ropes due to problems such as unleveled machines, rusted wire ropes and mismatched joint types, and construction safety is also difficult to guarantee [2] [3] [4].

The box culvert jacking construction method [5] [6] [7] can solve the problem of under-passing box culvert construction in the case of three-dimensional crossings with uninterrupted traffic, and realize the jacking construction of box culverts of larger spans. The method has the characteristics of convenient construction, small impact on the natural environment and saving natural resources. It is often used in the construction of new box culverts. This study combines the actual engineering conditions and introduces the jacking construction method into the demolition construction of existing box culverts, but the existing box culverts are subject to completely different loading, geological and hydrological engineering site conditions from the new ones, and with the passage of time, the box culvert structure itself may produce a series of problems such as uneven sinking, cracking, and material aging [8], so it is necessary to conduct finite element analysis on the box culvert structure before jacking out the construction.

2. Project Overview

This paper takes the renovation and expansion of an existing railway bridge as the research background and combines numerical analysis methods to carry out research on the stress distribution and deformation of the old box culvert itself and the surrounding soil during the jacking-out process under different working conditions. The existing bridge is a single box and single chamber box culvert, built in the 1990s, which consists of two box culverts of 5 m and 5.5 m in length respectively. The width of the box culvert is 9.2 m, the height is 6.2 m, the thickness of the box body side slab is 60 cm, the thickness of the top slab is 55 cm, the thickness of the bottom slab is 65 cm, the main reinforcement of the top and bottom slab are 25 mm diameter HRB335 grade reinforcement, the main body of the box culvert is made of C30 grade concrete, cross-sectional surface dimensions as shown in **Figure 1**. As the bridge section can no longer meet the requirements of flood control and drainage, the existing box culvert needs to be dismantled and expanded. At the same time, to ensure the normal operation of the upper railway, construction beams need to be erected at the same time as the old box culvert is jacked out. However, the existing box culvert will cause stress and deformation in the surrounding soil when jacking out, thus indirectly changing the support situation of the convenience beam, which will cause large deformation of the convenience beam under the action of the upper train load leading to engineering accidents. It is necessary to carry out finite element analysis before the jacking out of the existing box culvert construction. The preliminary engineering geological survey shows that the roadbed soil on the side of the existing box culvert is powdery clay and the bottom soil is clay. And the mechanical properties of the soil are obtained after taking samples and testing in the laboratory, which can be seen in **Table 1** in detail.

3. Finite Element Modeling

Abaqus 6.14 is adopted to carry out numerical analysis of box culvert jacking construction. In order to ensure the accuracy of the finite element simulation results, the three-dimensional model of box culvert jacking construction is established by referring to the previous finite element modeling method of box culvert jacking construction [9] [10] and summarizing the structural form of the actual project box culvert and the surrounding soil parameters. The analysis of soil stress distribution, soil deformation and box culvert structure stress distribution is carried out through the post-processing function of the program, and the corresponding change laws are obtained to provide theoretical support for the actual box culvert jacking-out construction.

Considering that the force and deformation of the culvert structure and the surrounding soil in the construction is no longer a simple planar problem, the

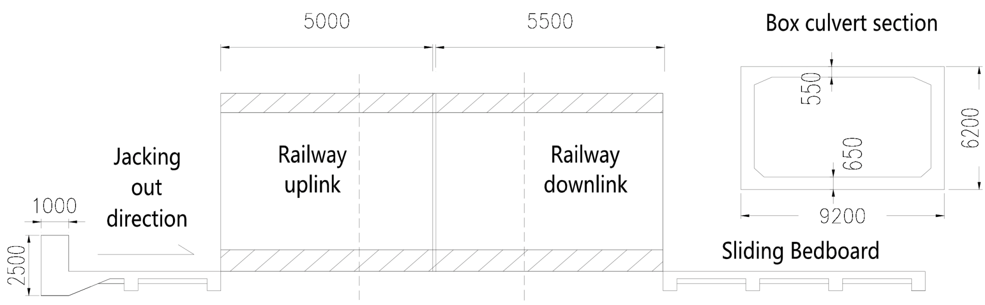

Figure 1. Box culvert dimensions (Unit: mm).

Table 1. Soil material parameters.

Location and type of soil	Weight capacity r/ (kg·m^3)	Elastic modulus E/ (MPa)	Poisson's ratio v	Angle of internal friction φ/(°)	Cohesion c/(KPa)
Side of box culvert (Powdery clay)	1990	32,000	0.31	15.2	10.0
Bottom of box culvert (clay)	1700	24,000	0.30	8	25.0

three-dimensional model is chosen for finite element simulation analysis, see Figure 2(a). Considering the efficiency of finite element calculation, the size of the bottom soil is set to 20 m (X) × 5 m (Y) × 30 m (Z). A fixed restraint is applied to the bottom soil base, and to the side of the roadbed respectively. The main consideration in the finite element analysis is the contact analysis between the soil and the existing box culvert, where the two transmit tangential and normal stresses mainly through the contact pairs. Therefore, the contact between the two adopts the general contact, the tangential direction adopts the penalty function calculation, the friction coefficient according to the data provided by the site survey report, the friction coefficient between the bottom of the box culvert and the soil body is taken as 0.36, the friction coefficient between the side of the box culvert and the soil body is taken as 0.24. In order not to allow the penetration behavior between the box culvert and the soil body, the normal direction adopts the hard contact.

The concrete principal model was simulated using "concrete damage plasticity" provided in the finite element software, while the compressive test results of the actual drilled core sampling specimens were used for the concrete strength, and the other parameters were selected regarding the Code for the Design of Concrete Structures (GB50010-2010) [11]. The Mohr-Coulomb yielding criterion [12] [13], which is more applicable to Geotechnical analysis, is adopted for the present constitution to track the full amount of displacement, strain, and stress during the deformation process [14], and other parameters were selected according to the preliminary engineering geological investigation report, see Table 1 [15] [16] [17]. The mesh division is shown in Figure 2(b).

The numerical analysis of the box culvert jacking out is mainly divided into two steps: 1) the box culvert self-weight on the lower soil extrusion, that is, in the simulation by specifying the density of reinforced concrete, defining the static loading step and applying gravitational acceleration to impose. 2) Jacking out the box culvert, that is, by specifying the box culvert bottom slab Z-axis direction 10.5 m boundary conditions to impose. The finite element analysis considers the actual roadbed excavation situation on site and considers three different working conditions: working condition 1 is no excavation on the side of the

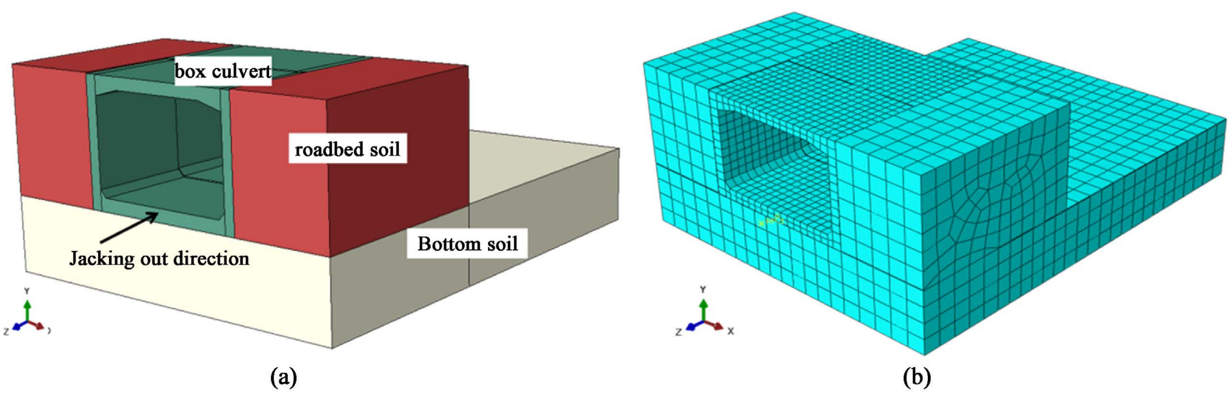

Figure 2. Finite element 3D model and meshing. (a) 3D finite element models; (b) Mesh division.

box culvert, working condition 2 is the box culvert side roadbed excavation thickness of 1 m, working condition 3 is the box culvert side roadbed excavation thickness of 2 m.

4. Results of Finite Element Analysis

The jacking force-displacement curves for the three working conditions are similar, and the whole ejecting process is divided into two stages, the first stage is from the beginning of the jacking force to the beginning of the movement of the box culvert, and the second stage is from the beginning of the movement of the box culvert to the completion of the jacking out of the box culvert, see **Figure 3**. At the beginning of the first stage, as the jacking force increased, there was no significant displacement of the box culvert, and the smaller displacement was probably due to the elastic deformation of the box culvert concrete during the application of the force. It is not until the end of the first stage that the jacking force-displacement curve shows a peak point, followed by a sharply declining section of the curve, but the decline is not very large, see **Figure 3**. The reason for this phenomenon is that at the beginning of the jacking out of the box culvert, there is only static friction between it and the surface of the soil when the jacking force overcomes the static friction, the static friction becomes sliding friction, the box culvert will suddenly move forward, and because the sliding friction is smaller than the static friction, the value of the jacking force then decreases, and the speed of the box culvert moving forward will also slow down. The maximum jacking force of the three working conditions is selected for comparison and it was found that the jacking force value of working condition 1 (2811.81 kN) was greater than that of working condition 2 (2577.51 kN) and the jacking force value of working condition 2 was greater than that of working condition 3 (2361.03 kN), which indicated that the greater the thickness of the roadbed excavation, the smaller the jacking force required. In the second stage, the variation of the jacking force stabilizes and the sliding friction to be overcome by the jacking force consists of two components, the sliding friction between the box culvert and the bottom and side soils respectively. The small decrease in jacking force may be because as the box culvert is jacked out, the contact

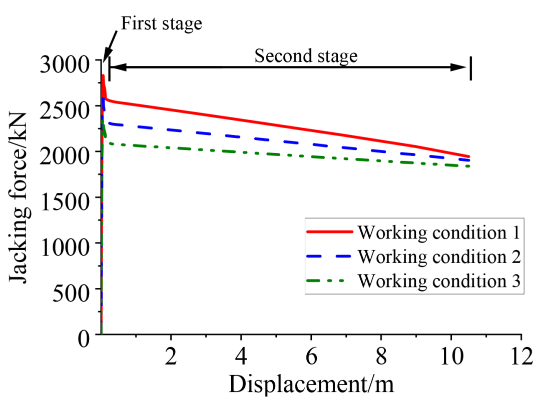

Figure 3. Jacking force-displacement relationship.

area between its sides and the soil gradually decreases, and therefore the jacking force required decreases.

Figure 4 shows the Mises stress cloud for the box culvert at the end of the first stage for the three different working conditions. It can be seen that the stress in the top and bottom slabs of the box culvert are greater than those in the side slabs when the combined effect of gravity and jacking force is considered, but at this point, none of the maximum stresses in the box culvert exceed 3 MPa, which is much less than the measured strength of the concrete, and therefore no damage to the concrete will occur. In addition, Figure 4 shows that the stresses in the top and bottom slab of the box culvert are large in the middle and small on both sides, and this phenomenon is particularly evident in the bottom slab as the jacking force is applied to the bottom slab. To study the stress distribution of the box culvert in more detail, the stresses in the middle of the box culvert floor along the width direction were extracted for the three working conditions, see Figure 5. The stress distribution at the bottom of the box culvert under the three working conditions is approximately normal, and the stress of the bottom slab of the box culvert in working condition 2 and working condition 3 is slightly less than that in working condition 1, which indicates that with the increase of the thickness of the roadbed excavation on both sides of the box culvert, the stress of the bottom slab of the box culvert will be reduced when the maximum jacking force is reached, and the concrete is less prone to cracking.

During the jacking-out process, the stresses in the soil do not change very much, so the soil stress cloud (see Figure 6) when the box culvert is jacked to the

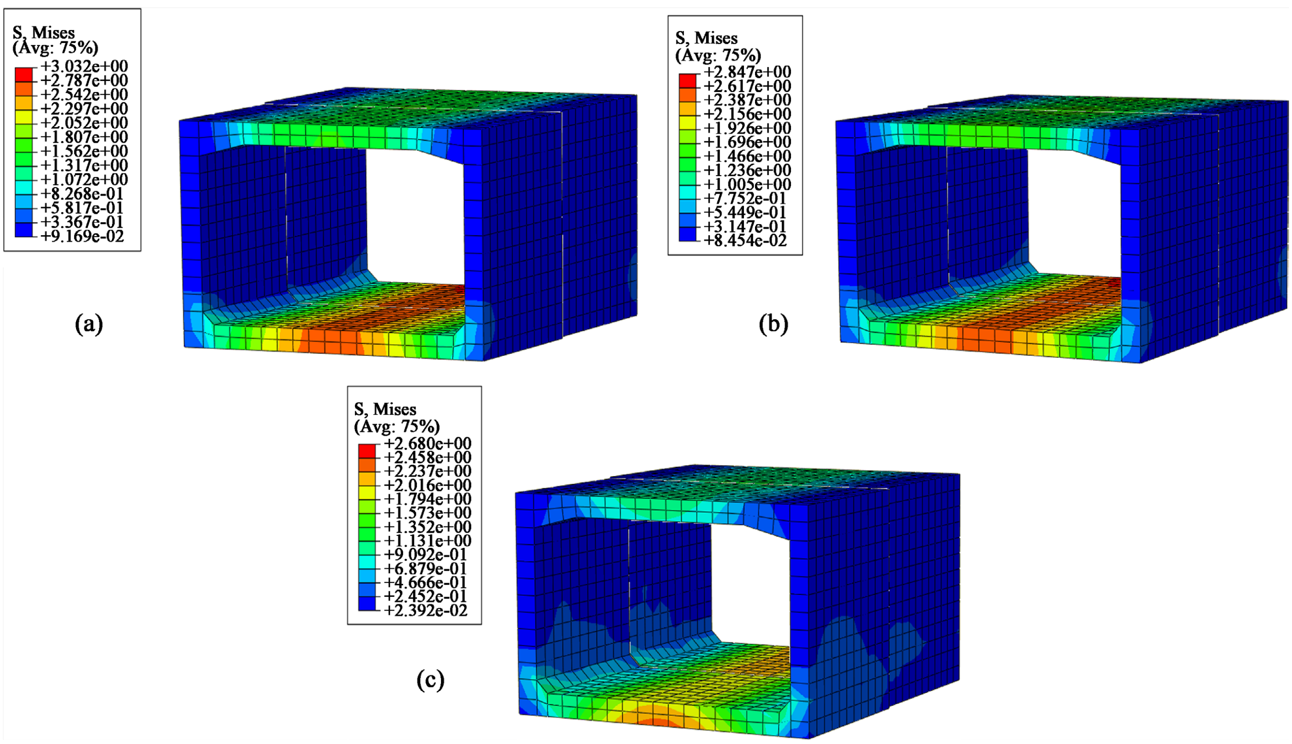

Figure 4. Box culvert stress clouds. (a) Working condition 1; (b) Working condition 2; (c) Working condition 3.

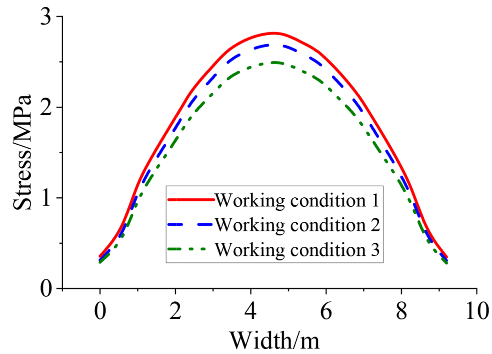

Figure 5. Stress distribution along the width of the box culvert bottom slab.

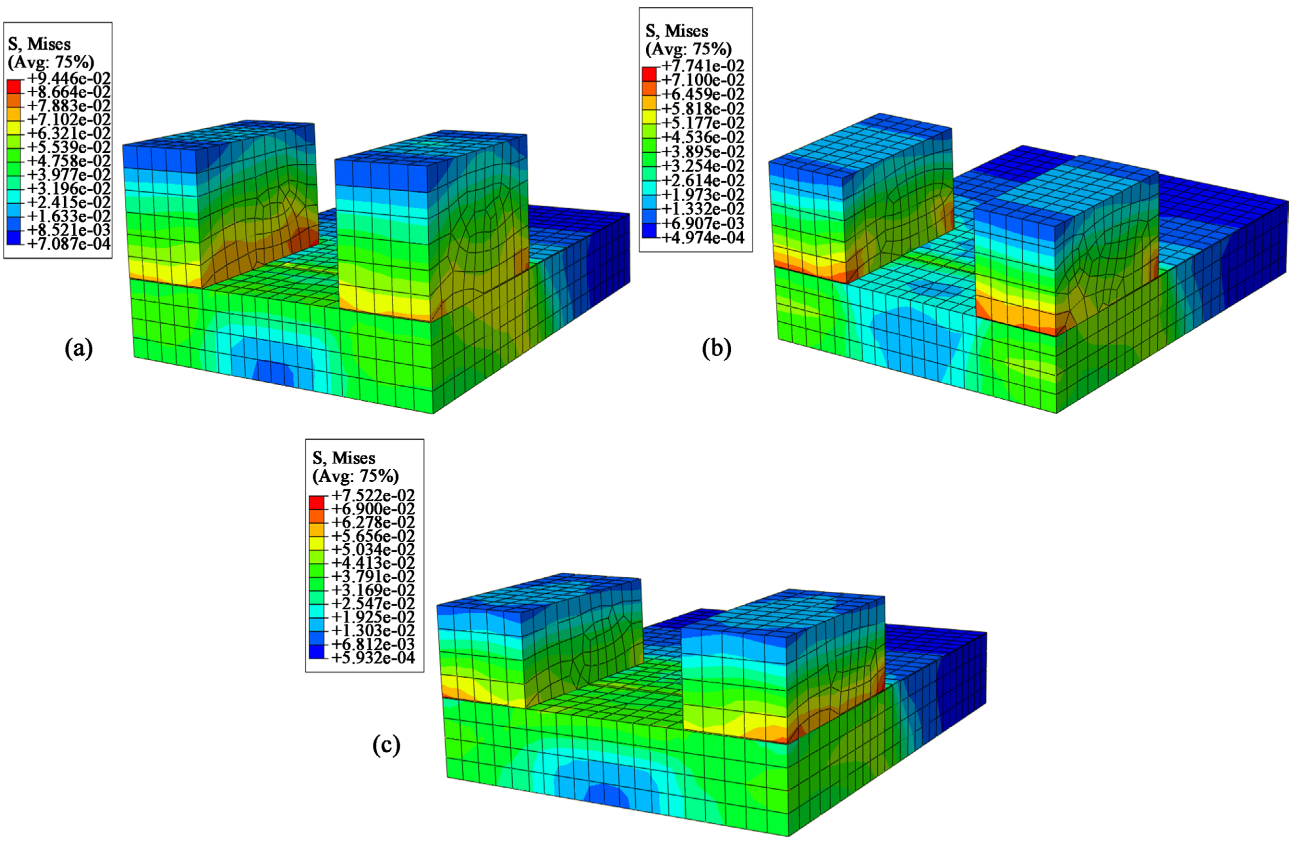

Figure 6. Soil stress clouds. (a) Working condition 1; (b) Working condition 2; (c) Working condition 3.

middle of the roadbed is selected for analysis. The stresses in the lower soil are increased due to the large sliding friction between the box culvert floor and the lower soil. The soil stresses in the roadbed on both sides are relatively high and show a progressive top-down change, with a maximum value occurring at the lower end of the roadbed. In the jacking out direction, the soil at the front, middle, and end of the roadbed width direction was selected, and some points were selected along the height of the soil from the bottom to the top on the contact surface of the box culvert and the roadbed soil at the corresponding location, and points at 0, 1, 2, 3, 4, 5 and 6m height were selected in working condition 1, points at 0, 1, 2, 3, 4 and 5m height were selected in working condition 2, and points at 0, 1, 2, 3 and 4 m were selected in working condition 3, see Figure 7. Figure 8 shows the stress of the soil in the three working conditions at the three locations selected points, it can be seen that the stress of the lateral roadbed soil in the three working conditions are gradually smaller with the increase in height, and with the increase in the thickness of the roadbed excavation, the stress of the same height point in the three parts have been reduced. It can be seen that the increase in the thickness of the roadbed excavation can effectively reduce the soil pressure on the side of the box culvert, and accordingly the friction between the side of the box culvert and the soil is reduced during the jacking-out process.

From the calculation results it is known that the maximum deformation of the roadbed soil occurs at the jacking out of the box culvert to the end, for this reason, the deformation of the soil at this moment in the front, middle, and end is extracted, see Figure 9. From the deformation of the three parts, it can be seen that the deformation of the upper soil is greater than that of the lower soil, and the soil may collapse first in the upper part, so the upper soil should be reinforced. Comparing the soil deformation of the three working conditions, it can be found that the maximum deformation of working condition 1 reaches 119.22 mm, which is significantly larger than the other two working conditions, which indicates that the roadbed excavation can significantly reduce the deformation of

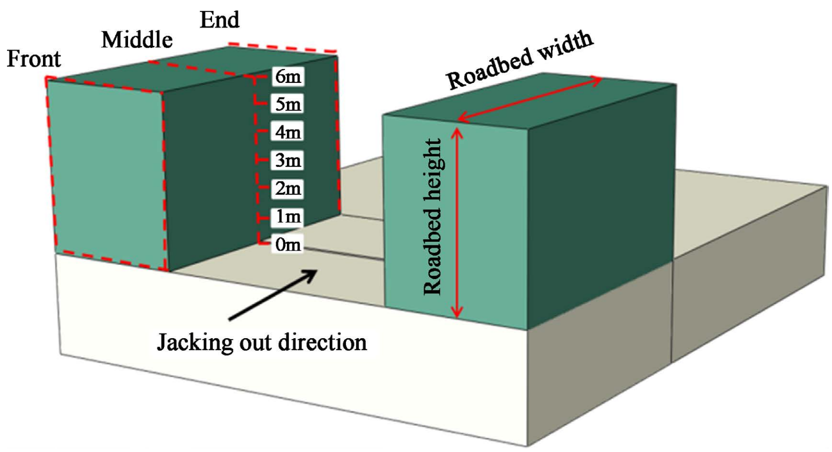

Figure 7. Location of sampling points.

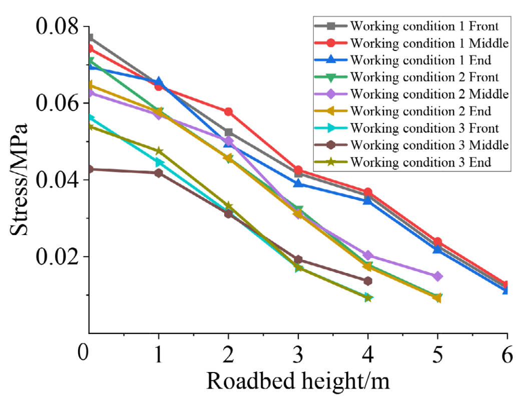

Figure 8. Soil stress.

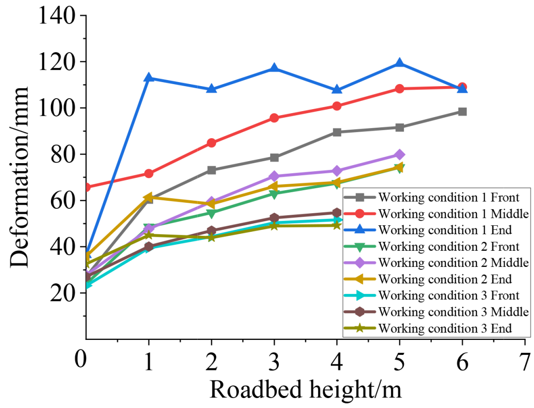

Figure 9. Soil deformation.

the roadbed in the process of jacking.

5. Conclusions

In this paper, a three-dimensional finite element model of the soil and box culvert is established based on ABAQUS, and the actual geological survey and material test results are applied to the finite element contact pairs and material property definitions to ensure the feasibility and rationality of the finite element simulation. The following conclusions were obtained from the finite element analysis of the jacking force-displacement relationship curve, the box culvert stress cloud, the soil stress cloud, etc.

1) The jacking force-displacement curves for the three working conditions follow approximately the same trend, with the whole jacking process divided into two stages, with the maximum jacking force occurring at the moment when the static friction is transformed into sliding friction.

2) During the whole process of jacking out, the stress distribution at the bottom of the box culvert is approximately normal. With the increase of excavation thickness on both sides of the box culvert, the stress on the bottom slab of the box culvert will be reduced when the jacking force reaches the peak point, and the possibility of concrete cracking is reduced.

3) The stresses in the lateral roadbed soil under all three working conditions are gradually smaller as the height increases, and as the thickness of the roadbed excavation increases, the stresses and deformations at the same height in all three parts decrease.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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