Research on Risk Control Parameters of a Shielded-Tunnel-enlarged Station, based on Bearing Capacity of Pre-removed Segment

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Abstract: A pre-removed segment is a new structure segment applicable to enlarging shield tunnel technology. It can facilitate the removal of the excess partitioned segment, for an enlarged station, by shield tunnel, however, it may cause certain risk of enlarged excavation construction, when a certain construction control limit is exceeded. To study the risk control problem for the removed segment, applicable to the shielded-tunnel-enlarged station, a risk control method, based on the load critical curve of the pre-removed segment is proposed. In this paper, a three-dimensional stratum structure model of the shielded-tunnel-enlarged station is established and variations of forces on the interface of the pre-removed segment are analyzed, under the influences of buried depth and staggered distance, for different enlarged excavation construction stages, as well as different soil properties (elasticity modulus). Combined with the load critical curve of the contact surface concerning the pre-removed segment obtained from the test, the critical construction control surface of buried depth and staggered distance, was obtained to ensure the bearing capacity of the pre-removed segment in different soil properties and in all of the involved enlarged excavation stages. It provides the technical guidance and reference for the construction risk control of the application of pre-removed segment in the shielded-tunnel-enlarged station.

Keywords: pre-removed segment; buried depth; staggered distance; soil properties; enlarged excavation construction; the load critical curve; the critical construction control curve; risk control and shielded-tunnel-enlarged station

1 Introduction

It is a special construction method of underground engineering to enlarge subway station by shield tunnel[1-4]. The shield equipment passes first, and then the shield tunnel structure is used to enlarge the subway station in combination with other excavation methods[5-7]. Due to the complex process of segment removal during enlarging, the segment to be removed or cut can be set in the form of pre-removal in advance, which can reduce the difficulty of enlarged construction and shorten the enlarged construction period. Therefore, if the station enlarging plan is carried out in a certain section of shield tunnel in the future, the pre-removed segment can be installed in this section in advance, which can provide great convenience for the station expansion in the later period.

This leads to a question, of whether the internal force changes, of the pre-removed segment, can meet the requirements of the bearing capacity of the pre-removed segment during the shield tunnel, with the pre-removed segment still not enlarged. It is the key to control the construction risk to enlarge subway stations by shield tunnel, with the pre-removed segment, during this period. It should be said that this shielded-tunnel-enlarged station method, is not applicable to any operational stages, so the impact of subway train vibrations, on the shield tunnel structure, has not been considered[8]. In addition, this method is not suitable for staggered assembled segment tunnels in operation period [9].

At present, there are some cases concerning enlarged subway stations, with a shield tunnel: In Russia[10,11], the single-arch station structure was enlarged between two shield tunnels, in which some segments were partially removed and the interior space is poured into arch supports. In Saudi Arabia[12], open-cut method was used to remove part of large diameter shield tunnel, and the location where the tunnel was removed was enlarged into a station structure. In China, large-diameter shield segments were used to enlarge subway a station combined with a PBA method[13]. The segments at critical removal locations are also cut directly. In the above cases, segments are directly cut, which ensures the safety of the structure during the enlargement period, in which, segments are not removed. At the same time, it also increases the difficulty of partial demolition of segments during the enlarging of the subway station, especially for the underground construction.

If the segment to be removed is designed in a partitioned form, the construction difficulty of segment removal can be greatly reduced. At the same time, it also increases the safety risks of the structure, during the construction period. This partitioned segment is defined as a pre-removed segment, as shown in the Figure 1. In fact, this segment has been used in the discussion scheme for the shielded-tunnel-enlarged station of Beijing Metro Line 14. The bearing capacity test has also been done especially for this kind of segment[11]. Although it was not adopted in the final designing scheme, the experiments and related research are still valuable for similar projects. This paper is one research work, which based on the construction risk control of the shielded-tunnel-enlarged station with a pre-removed segment.

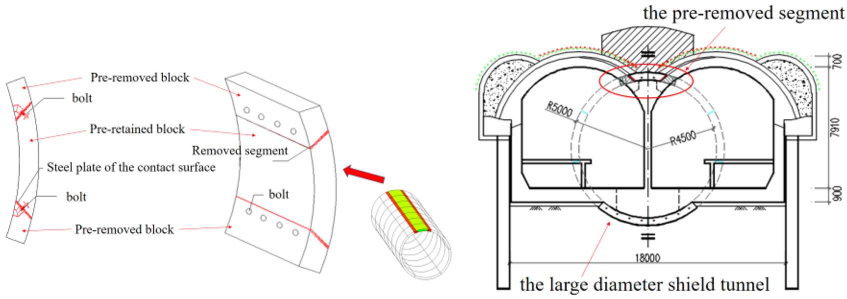


Figure 1
The pre-removed segment

The purpose of this research is to establish a method to analyze the reasonable construction risk control parameters of the shielded-tunnel-enlarged station with the bearing capacity of pre-removed segments, so that designers can quickly predict a reasonable risk range during the preliminary design phase.

In this paper, a three-dimensional stratum structure model for shielded-tunnel-enlarged stations is established to analyze the internal force changes of the pre-removed segment, under different key construction parameters with different soil properties. Based on the test results of the bearing capacity of the pre-removed segment, the reasonable construction key parameters are screened out, so the construction risk control index, of the shielded-tunnel-enlarged station, based on the bearing capacity of the pre-removed segment, was determined.

2 Risk Control Principle Based on Bearing Capacity of Pre-removed Segment

This paper is a research on construction risk control based on the completed bearing capacity test of pre-removed segment[14]. It was found through test analysis that there are many kinds of critical loading combinations on the contact surface of the same type of pre-removed segment, and these combinations will form the envelope of critical loading combinations, as shown in the Figure 2.

The critical state features of the pre-removed segment are as follows: When the internal force of the pre-removed segment is in a group of critical state combinations. The displacement of the contact surface of the pre-removed segment will increase suddenly. It will cause the bolts connecting the segments to be locked in place, so that the separation of the pre-removed segment cannot be successfully completed. At this time, the original cutting methods can only be adopted and the original intention of designing the pre-removed segment is invalid.

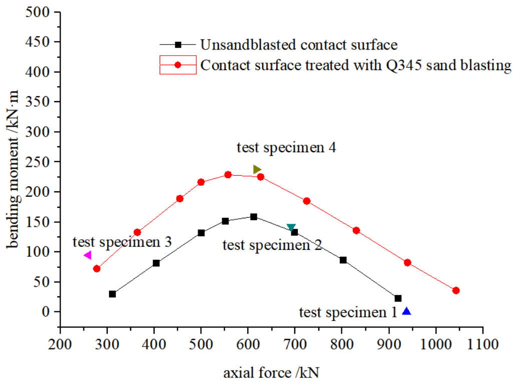


Figure 2
The load critical curve about the pre-removed segment

Therefore, in different enlarged excavation construction stages and under different soil properties (elasticity modulus), the internal force on the pre-removed segment changes with the variation of construction parameters. When the internal force combination value of the removed segment corresponding different construction conditions is within the range of critical curve, the removed segment is in normal condition. Otherwise, the pre-removed segment cannot be removed successfully and it may cause structural safety and stability risks. Therefore, the reasonable risk control parameters can be found through the load-bearing critical curve of the pre-removed segment.

3 Analysis of Major Risk Factors

This paper analyzes the risk factors of the enlarged subway station by the large-diameter shield tunnel combined with the PBA method. From the perspective of the enlarged construction process, the stages in which the pre-removed segment is still in a working state include, as shown in the Table 1:

(1) Initial state of tunnel segment

(2) Pilot tunnel excavation

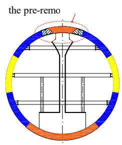
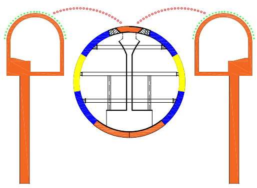
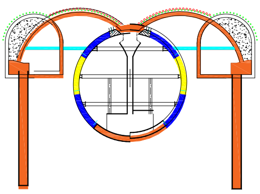
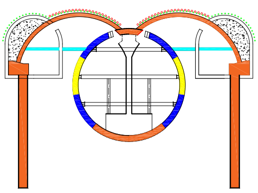
(3) Supporting arch excavation

(4) The pre-removed segment removed

The main influence of each risk factor on internal force of pre-removed segment is as follows:

(1) **The buried depth of tunnel:** With the change of buried depth, the ground stress in surrounding rock changes correspondingly, and the internal force on the pre-removed segment also adjusts accordingly.

Table 1
Main factors affecting internal force of pre-removed segment in different construction stages

Enlarged excavation construction stages	Enlarged construction diagram	Main factors affecting the pre-removed segment
Stages 1: Tunnel segment ring		buried depth of tunnel; the soil properties
Stages 2: pilot tunnel excavation		buried depth of tunnel; asymmetric excavation; the soil properties
Stages 3: Supporting arch excavation		buried depth of tunnel; asymmetric excavation; the soil properties
Stages 4: The pre-removed segment removed		The pre-removed segment has been removed and this stage is beyond the analysis scope of this paper

(2) **Enlarged excavation construction stage:** The construction stages before the pre-removed segment is removed mainly include tunnel segment ring (Stages 1), pilot tunnel excavation (Stages 2) and supporting arch excavation (Stages 3), Shown in table 1. The internal forces on the contact surface of the pre-removed segment will be constantly adjusted in the three main construction stages. Each construction stage has different influence on the internal force of pre-removed segment.

(3) **Asymmetric excavation:** In fact, it is difficult to complete the synchronous construction of the left and right sides in the pilot tunnel excavation stage and supporting arch excavation stage. When the two sides of the driving length are different, the partial load will be formed on the pre-removed segment, which will cause the change of the internal force of the pre-removed segment.

(4) **Soil properties:** Numerical analysis shows that the soil properties have a great influence on the internal force of the structure, the influence of elastic modulus of soil is particularly obvious. Considering that this kind of engineering may occur in different soil environments, this paper considers the influence of different elastic modulus of soil on the internal force of the contact surface of pre-removed segment based on the combination of the first three analyses.

These four risk factors are correlated. buried depth is a key factor affecting structural mechanics. The internal force of pre-removed segment is also affected by different enlarged excavation construction stages, which also affect the allowable range of asymmetric excavation at each enlarged excavation construction stage. At the same time, the elastic modulus of soil has a further superposition effect on the internal force of the pre-removed segment. And the value range of internal force is limited by the bearing capacity of the enlarged segment which determines the reasonable range of the four main factors mentioned above.

Therefore, three-dimensional numerical analysis can be used to grasp the influence of different buried depth, enlarged excavation construction stages and asymmetric excavation in different soil environments on the internal force of the pre-removed segment. And the critical line of bearing capacity of pre-removed segment is taken as the control standard. A reasonable parameter selection scheme, for risk control of enlarged subway station, is proposed based on the bearing capacity of the pre-removed segment, as a control standard.

4 Model Analysis

4.1 Establishment of Numerical Model

The ABAQUS software is used to analyze the influence of enlarged excavation construction stages and asymmetric excavation on the internal force of the pre-removed segment, in different buried depths and for different elastic modulus of soil. The simulation is carried out for the shielded-tunnel-enlarged station with the PBA method, which involves a construction process before the pre-removed segment is removed. The models transverse length is 130 m and longitudinal length is 36 m. The width of each tunnel segment is 1.8 m, the thickness is 0.5 m. The model contains 20 tunnel segment rings. The 20 pre-removed segments will be removed in the model. Main parameters of the model are shown in Table 2.

Table 2
Main parameters of the model

buried depth (m)	Model height (m)	Length difference of asymmetric excavation		
		Pilot tunnel excavation	Supporting arch excavation	Elastic modulus of soil
10	50	The staggered distance is divided into 6 stages, with each stage increasing by 3.6 m and the range is 0-18 m	The staggered distance is divided into 6 stages, with each stage increasing by 3.6 m and the range is 0-18 m	The elastic modulus of soil is divided into three categories: 6 MPa, 30 MPa and 150 MPa
18.5	60			
30	70			
40	80			
50	90			

Note: Because the numerical calculation uses the stratum structure model, the height of the calculation model will be adjusted accordingly with the change of the buried depth of the station roof structure in keeping the thickness of the soil at the bottom of the station constant.

Table 3
Physical and mechanical parameters of materials

Model components	Materials	Density kg/m^3	Elastic modulus /GPa	Poisson's ratio
tunnel segment	toncrete C50	2450	34.5	0.2
bolt	steel	7800	210	0.2
temporary support	steel	7800	210	0.2
Beam, column, primary lining	toncrete C30	2500	30	0.2
Grouting layer	grouting material	2150	0.06	0.3
Soil layer (all soil parameters are considered as a single homogeneous material by weighted average method)	soil	1950	The values of elastic modulus are shown in Table 2. And the cohesion of the soil is 20kPa and the angle of internal friction is 15°.	0.3

Hypothetical conditions: To study the main risk factors, material parameters such as all soil parameters are considered as a single homogeneous material by weighted average method. The cohesion of the soil is 20 kPa and the angle of internal friction is 15°. The cohesion of the grouting material is 50 kPa and the angle of internal friction is 35°. Each stage of the enlarged construction was completed before the next enlarged construction begins. Pre-removed segment structure is simulated according to actual size. The pre-removed segment consists of three component blocks that are bolted together. These are all solid units. A contact unit is arranged between the blocks. Rigid contact is set in the normal direction of the block contact surface and frictional contact is set in the tangential direction. A binding connection is set between the two surfaces of the bolt and the inner surface of the bolt hole on the corresponding pre-removed segment, and the bolt is set up with a prestressing force of 100 kN. The temporary supports are used for beam units. The physical and mechanical parameters of the materials[15,16] involved in the calculations for the model, are shown in Table 3.

The 3D model mesh division schematic and the bolt and contact surface detail schematic is shown in Figure 3.

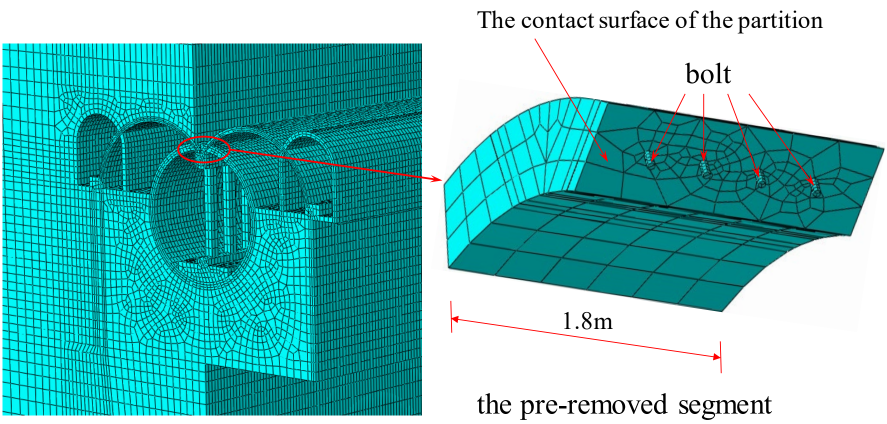


Figure 3
3D model and bolt connection of pre-removed segment

4.2 Analysis of Computing Results

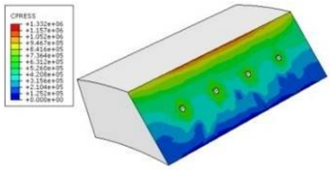
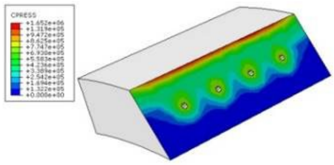
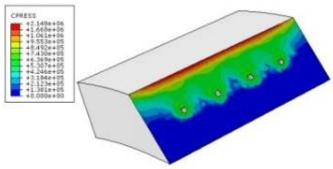
ABAQUS calculation software is used to analyze the influence of enlarged excavation construction stages and asymmetric excavation on the internal force of the pre-removed segment in different buried depths.

Table 4 shows the distribution of CPRESS (compressive stress) on the contact surface of the pre-removed segment in different enlarged excavation construction stages under the condition of 18.5m buried depth and 0m staggered excavation (i.e. symmetrical excavation) which in the elastic modulus of soil is 30 MPa.

As can be seen from Table 4, when the buried depth of the structure is 18.5 m, the staggered distance is 0 m and the elastic modulus of soil is 30 MPa, the characteristics of the contact surface of the pre-removed segment change as follows:

Table 4

Variation of CPRESS on the contact surface at different construction stages

Enlarged excavation construction stages	CPRESS diagram on the contact surface of the pre-removed segment
Stages 1: Tunnel segment ring	
Stages 2: Pilot tunnel excavation	
Stages 3: Supporting arch excavation	

(1) **Tunnel segment ring (Stages 1):** The CPRESS (compressive stress) distribution on the contact surface of the pre-removed segment is relatively uniform. and the area near the bolt hole of the contact surface is in compressed state. and only the lower edge of the pre- removed segment is in open state.

(2) **Pilot tunnel excavation (Stages 2):** The CPRESS distribution is basically the same as in the previous stage. However, the degree of pressure on the upper edge area and the degree of opening of the lower edge seam have increased, and the contact surface in the vicinity of the bolt is still under pressure. It indicates that in the pilot tunnel excavation stage, the tension of the lower edge of the contact surface of the pre-removed segment has a gradually increasing trend.

(3) **Supporting arch excavation (Stages 3):** The CPRESS distribution is basically the same as in the first two stages. The compression degree of the upper edge and the opening degree of the lower edge increase further. Although the contact surface near the bolt is still under pressure, the upper part of the area near the bolt begins to open trend. It is obvious that the largest opening range of the pre-removed segment in this stage which among the previous several stages.

In the same enlarged excavation construction stage, which the elastic modulus of the soil is 30 MPa, the converted axial force and bending moment on the contact surface with different burial depth conditions and different staggered distances are obtained, as shown in Figure 4 and Figure 5.

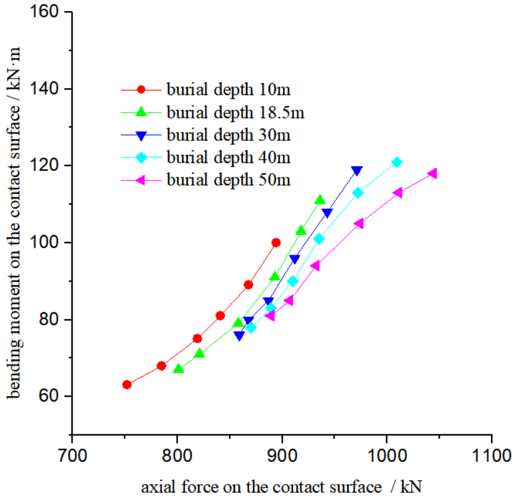


Figure 4
The relationship about the internal force of contact surface of the pre-removed segment in pilot tunnel excavation stage

Note: The calculation points of each burial depth in the figure are calculated in order of the staggered distance 0 m, 3.6 m, 7.2 m, 10.8 m, 14.4 m and 18 m, which the elastic modulus of the soil is 30 MPa.

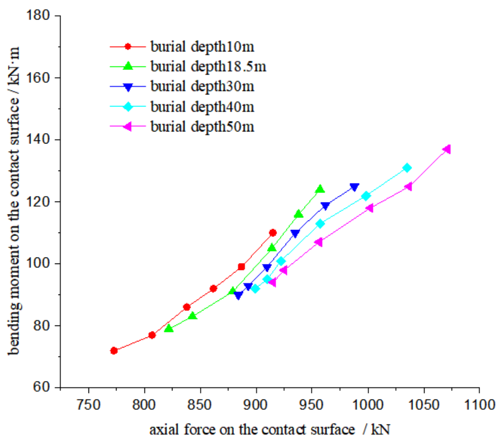


Figure 5
The relationship about the internal force on contact surface of the pre-removed segment in supporting arch excavation stage

Note: The calculation points of each burial depth in the Figure are calculated in order of the staggered distance 0 m, 3.6 m, 7.2 m, 10.8 m, 14.4 m and 18 m, which the elastic modulus of the soil is 30 MPa.

According to Figure 4 and Figure 5, the following rules can be seen.

(1) In the same buried depth and enlarged construction condition, the internal forces on the contact surface of the pre-removed segment are different due to different staggered distances. The axial force and bending moment of the contact surface gradually increase with the increase of the staggered distance.

(2) The influence range of the internal force of the contact surface caused by the excavation with the staggered distance of the buckle is greater than that of the excavation with the staggered distance of the small guide tunnel.

(3) The internal force of the contact surface will increase gradually with the increase of the buried depth under the condition of the same staggered excavation.

5 Construction Risk Control Based on Pre-removed Segment in Normal Service Conditions

5.1 Risk Control in Pilot Tunnel Excavation Stage

The internal force of the contact surface of the pre-removed segment obtained from the previous numerical analysis in pilot tunnel excavation stage was compared with the critical curve of the contact surface internal force obtained by the previous test, the following characteristics can be found, as shown in Figure 6.

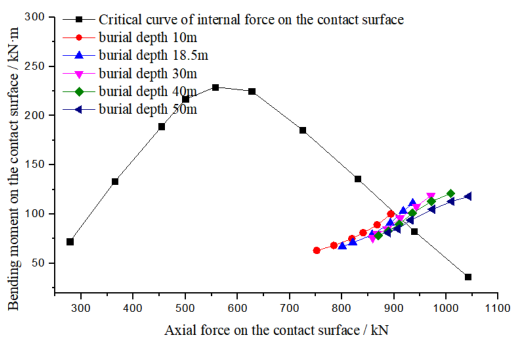


Figure 6

The relationship between internal force of contact surface and critical curve of internal force of contact surface in different buried depth and staggered distance in pilot tunnel excavation stage

As shown in the Figure 6. In the condition of different buried depth and staggered distance and the elastic modulus of the 30 MPa soil layer, the internal force produced by pilot tunnel excavation on the contact surface of pre-removed segment is not all within the critical curve of internal force of contact surface. Therefore, when the combination of parameters beyond a certain burial depth and staggered distance is exceeded, no matter how the excavation is done, it cannot meet the normal use requirements of the pre-removed segment. According to the critical curve of internal force on the contact surface, the critical buried depth and staggered distance that meet the requirements of pre-removed segment should be determined. The analysis results are shown in Table 5.

Table 5

Critical staggered distance of different buried depths

Buried depth (m)	Axial force (kN)	Bending Moment (kN·m)	Conv. of staggered distance / m
10	--	--	--
18.5	907.7	98.1	10.8
30	912.9	95.6	8.3
40	917.6	93.3	6.9
50	921.9	91.1	5.7

According to Table 5, the relationship in pilot tunnel excavation stage between critical burial depth and critical staggered distance excavation in normal use of pre-removed segment is calculated, as shown in Figure 7.

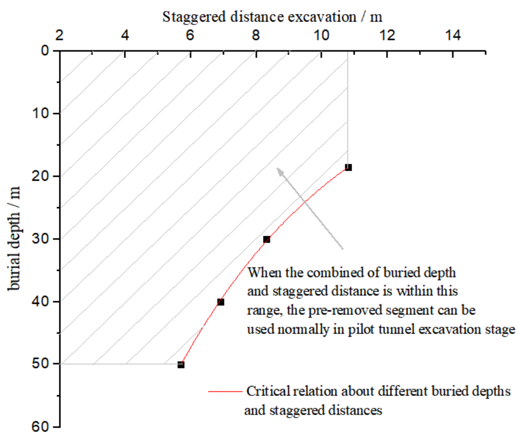


Figure 7

The critical relation about different buried depths and staggered distances in the pilot tunnel excavation stage

In the soil, the elastic modulus of which is 30 MPa, when the combination of the buried depth and staggered distance is within the envelope of the critical curve, the pre-removed segment can meet the requirements of its bearing capacity.

Otherwise, the staggered distance needs to be adjusted to a reasonable range to ensure that the pre-removed segment can be used properly in the pilot tunnel excavation stage.

Furthermore, the corresponding critical burial depth and staggered distance relationship can also be obtained in the pilot tunnel excavation stage for the different elastic modulus (6 MPa, 30 MPa, 150 MPa) of the soil. As shown in Figure 8, the critical relation surface in the pilot tunnel excavation stage can be obtained by combining these critical relationships, which are determined by different buried depths, staggered distances, and elastic modulus of the soil.

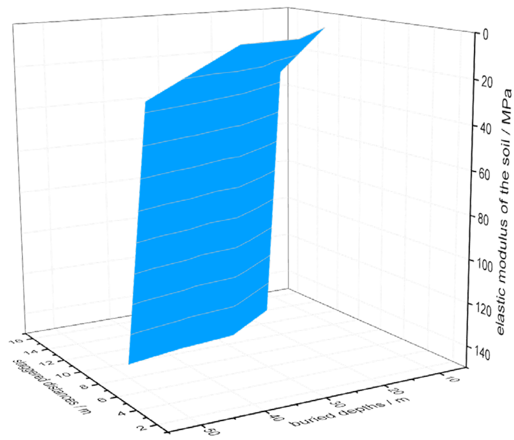


Figure 8

The critical surface about different buried depths, staggered distances, and the elastic modulus of soil in the pilot tunnel excavation stage

In the soil, the elastic modulus of which is 6 MPa, 30 MPa, and 150 MPa, when the combination of the buried depth and staggered distance is within the envelope of the critical surface, the pre-removed segment can meet the requirements of its bearing capacity. Otherwise, the staggered distance needs to be adjusted to a reasonable range to ensure that the pre-removed segment can be used properly in the pilot tunnel excavation stage.

5.2 Risk Control in Supporting Arch Excavation Stage

The internal force of the contact surface of the pre-removed segment obtained from the previous numerical analysis in the supporting arch excavation stage was compared with the critical curve of the contact surface internal force obtained by the previous test, the following characteristics can be found, as shown in Figure 9.

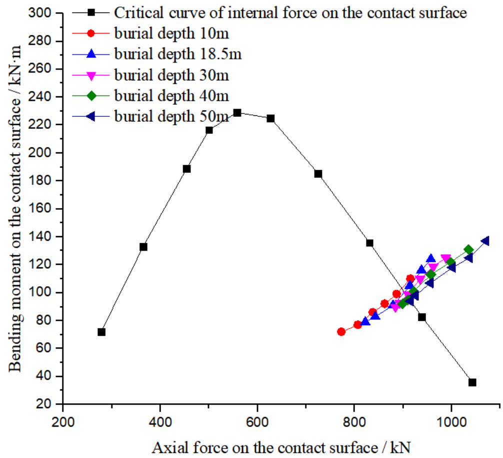


Figure 9

The relation between internal force of contact surface and critical curve of internal force of contact surface under different buried depth and staggered distance in supporting arch excavation stage

As the same data analysis process as 5.1, the corresponding critical burial depth and staggered distance relationship can also be obtained in supporting arch excavation stage for the different elastic modulus (6 MPa, 30 MPa, 150 MPa) of the soil. As shown in Figure 10, the critical relation surface in the pilot tunnel excavation stage can be obtained in supporting arch excavation stage by combining these critical relationships, which are determined by different buried depths, staggered distances, and elastic modulus of the soil.

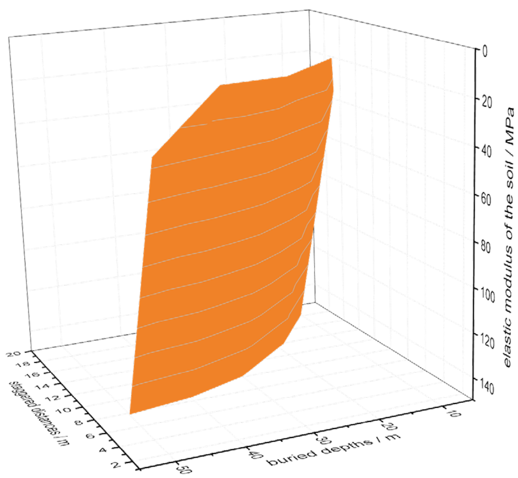


Figure 10

The critical surface about different buried depths, staggered distances, and the elastic modulus of soil in supporting arch excavation stage

In the soil, the elastic modulus of which is 6 MPa, 30 MPa, and 150 MPa, when the combination of the buried depth and staggered distance is within the envelope of the critical surface, the pre-removed segment can meet the requirements of its bearing capacity. Otherwise, the staggered distance needs to be adjusted to a reasonable range to ensure that the pre-removed segment can be used properly in supporting arch excavation stage.

5.3 The Envelope Surface, for a Reasonable Risk Control Range

Considering the actual construction requirements, the new envelope surface can be obtained by superimposing the critical surface of the two construction stages, as shown in Figure 11.

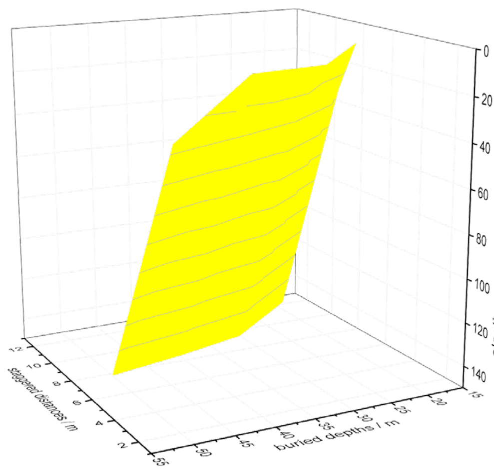


Figure 11
The envelope surface about different buried depths, staggered distances, and the elastic modulus of soil in all enlarged excavation stages

The new envelope surface indicates when the construction parameter combination meets the combination of the station buried depth, staggered distance and elastic modulus of soil corresponding to the critical surface, the pre-removed segment can meet the requirements of its bearing capacity in all enlarged excavation stages prior to the pre-removed segment removed stage.

Conclusions

A risk control method of enlarged subway station construction, using a shield tunnel was proposed, using the bearing capacity of pre-removed segment. In this paper, a three-dimensional stratum structure model of the shielded-tunnel-enlarged station is established and the internal forces of contact surface are screened in various enlarged construction conditions, different buried depths, staggered distances, and the elastic modulus of the soil. Combined with the critical internal force curve of the contact surface around the pre-removed segment, obtained from the test, the construction control surface of critical buried depth and staggered distance was obtained, to ensure the bearing capacity of the pre-removed segment. This provides a technical reference for the construction risk control of the application of pre-removed segment, in the shielded-tunnel-enlarged station.

The results show that the internal force of the contact surface is largest in the supporting arch excavation stage, followed by the pilot tunnel excavation stage. The compression surface on the contact surface of the pre-removed segment gradually concentrates on the upper region and gradually detaches on the lower region.

With the increase of buried depth, the internal force of the contact surface presents a nonlinear growth and the internal force growth, tends to slow, below 30 m.

In the scenario of equal buried depth and the equal enlarged constructions, the internal force of the contact surface gradually increases with the increase of staggered distance. And the influence range of the internal force of the contact surface, caused by the enlarged excavation with staggered distance in supporting arch excavation stage, is greater than in the pilot tunnel excavation stage.

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