Application of BIM Technology in Freezing Design of Metro Section Lateral Pump House

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Abstract. With such characteristics as deep buried, complex geological conditions and sensitive surrounding environment, a metro section lateral pump house in Zhengzhou is conducted using horizontal ground freezing reinforcement method within metro tunnel, combined with mine excavation and lining. In order to ensure the expected effect of freezing reinforcement, BIM technology is applied in layout test of freezing holes. A 3D parameterized freezing pipe model adapted to stakeout data is build, and mathematical relationship of main model parameters is obtained. The rationality of freezing hole layout is verified through collision detection analysis and formation prediction analysis of frozen soil wall, providing reference for application of BIM technology in freezing design of complex cross passage.

1. Introduction
The method of artificial stratum freezing has been widely used in the underground engineering of water-rich soft stratum for its good water resistance, flexible hole arrangement and strength of freezing curtain [1]. Due to the short-board effect, a leak in the frozen curtain may result in the whole failure, and then in the safety accident. In addition to the operation and management of the freezing system, the waterproof performance of the freezing curtain mainly depends on the arrangement of the freezing pipes. Whether the layout of the freezing pipes is reasonable or not is a factor that must be considered in the design. Once the spacing between the final holes is too large, which may exceed the expansion limit of the frozen soil, the freezing curtain cannot be enclosed [2]; Too large spacing of the final holes may lead to a collision of the freezing pipes, a failure in the freezing holes construction, or leave no space for hole filling or pipe breaking. BIM is a kind of technology which can check the collision problem of freezing pipe layout and predict the intersection in the early stage. Its efficient parameterization and visualized collaboration [3] can guide the design of freezing curtain without errors.

Based on a real project case, this paper uses BIM technology [4] to establish a three-dimensional (3D) parametric model of frozen pipe. Through collision inspection [5] and prediction of the freezing curtain formation, the layout of freezing holes can be inspected [6] to realize the 3D visualization, so as to eliminate the hidden dangers including error, leakage, collision and lack [7] in the initial design.

2. Project Overview and Construction Difficulties
A subway section in Zhengzhou passes through the downtown area, with 6.2 m of its outer diameter of the tunnel and 350mm of the segment thickness. An external wastewater pump station is installed at the left line mileage of DK15+066.276. In order to reduce the impact of shield tunneling on the surrounding...
environment, the distance between the center lines of the left and right line tunnels in the middle section is gradually reduced and overlapped up and down in the environmentally sensitive section. The distance between the center lines of the left and right tunnels is only 6.950 m at the mileage where the external pumping house is located. The left line tunnel is located under the right line tunnel, and the net distance of the vertical tunnel is only 6.91m.

The external pumping house is designed to be reinforced by horizontal freezing method in tunnel and excavated by understratum excavation method. The lining adopts secondary lining. The initial lining is 250mm thick C25 early strength shotcrete. The secondary lining structure is 400mm thick (500mm thick at the water collecting well) C35 formwork reinforced concrete. A 1.5mm-thick PVC board full-thickness waterproof layer is set between the primary lining and the secondary lining. The upper channel section is a straight wall circular arch structure with a clear width of 3m and a clear height of 3.5m. The lower catch pit is a box structure with a net width of 2.8m, a net length of 3.25m and a net height of 3.65m. The buried depth of the vault of the external pumping house is 26.992m. The upper channel is mainly located in the silty clay layer of ③24, and the lower part of the water collecting well is located in the silty clay layer of ③25. The water content is as high as 30%. The lower part of the main body of the tunnel at the corresponding mileage of the right line tunnel is in the fine sand layer of ②51, and the permeability coefficient is as high as 1.0×10-2 cm/s. The stratum and surrounding environment of the external pumping house are shown in Fig. 1.

![Fig.1 schematic diagram of stratum and surrounding environment of the external pumping house](image)

The main difficulties in the construction of the external pumping house are as follows: (1) The buried depth is large. The buried depth of the vault of the external pumping house is 26.992m, and the bottom of the water collecting well is 35.142m, with pressure of water and soil and high risk of water and sand gushing during drilling and excavation. (2) The geological conditions are complex. There is a thick permeable sand layer in the upper part of the influence area of construction, and there is potential water permeability risk under the disturbance of shield driving and late grouting construction. (3) The surrounding environment is sensitive. The stratum above the external pumping house is a busy road with large traffic flow and complicated understratum pipelines. There are 7 important pipelines in the construction affected area, so the control requirements of soil erosion and frost heaving thawing settlement are high.

3. Freezing Design

According to the bearing capacity calculation of the frozen wall curtain, the frozen soil mechanical parameter index corresponding to the average temperature of -10℃ is selected, and the design frozen wall thickness is determined to be 2.3m, and the active freezing time is expected to be about 50 days. A total of 95 freezing holes, 8 temperature measuring holes and 4 pressure relief holes are arranged. The
The deflection of single hole shall not exceed 150mm. The freezing pipe is made of φ89×8 mm low carbon steel seamless steel pipe. The arrangement of freezing holes is shown in Fig. 2.

4. Parameter Analysis of Freezing Pipe Modeling

In order to check whether the arrangement of freezing holes can achieve the expected freezing effect according to the expected active freezing time and ensure the safety of excavation construction, the parameterized three-dimensional visible frozen pipe model and freezing curtain intersection model are established by using BIM technology.

The external pumping house is different from the connecting channel, so it is impossible to arrange holes on both sides. The end freezing curtain needs to be realized through the large horizontal angle oblique end freezing hole, so the construction is difficult. The parameters and steps are very important when lofting the drilling holes in the external pumping house. Firstly, the opening position is determined according to the positioning angle and the opening position map, then the horizontal angle of the hole position is determined through the back view point, and finally the vertical inclination angle is determined on the vertical plane where the horizontal angle is located.

In order to adapt to the lofting steps, the parametric 3D freezing pipe model should also be built according to the lofting steps. Firstly, a reference line W with an angle of a to the X-axis is established on the XY plane; secondly, the lofting path is drawn on the plane that passes through the reference line and is perpendicular to the XY plane (called WY plane). The length of the lofting path is L, and the included angle with the reference line W is b. Finally, the lofting profile is drawn to form a 3D entity.

Since the two-dimensional elevation (Fig. 2a) represents the projection of a 3D solid on the XZ plane, the vertical inclination angle (c) of the frozen pipe on the projection plane is directly related to a and b. Qualitatively, c is not less than b in absolute value. If the influence is ignored during construction, the setting out is carried out directly according to the value of c on the two-dimensional elevation. The error is small in case the value of a is small, and the deviation slope of the freezing hole after hole forming may not exceed the allowable value. In case the value of a is large, the inclination angle of the freezing hole will be too large to meet the control requirements of the deviation rate and the maximum spacing of the final holes. Supposing the difference cannot be found in the deflection measurement stage and the b and a values of the rechecked holes are consistent with the values of c and a in the two-dimensional drawing, the final hole spacing may be too large, which make it unable to enclose the circle as scheduled, or even to form a closed reinforced body.

In order to deduce the mathematical relationship among the main lofting parameters a, b and c of the freezing hole, the 3D decomposition of the freezing hole is shown in Fig. 3. The following equation can be obtained.

\[
\tan(c) = \frac{h}{x} = \frac{\tan(b)\times w}{\cos(a)\times w} = \frac{\tan(b)}{\cos(a)}
\]
The space length of frozen pipe is \( L \), and its projection length on XZ plane is \( S \). It can be concluded that both satisfy equation (5).

\[
S = \frac{x}{\cos (c)} = \frac{\cos(a) \times w}{\cos (c)} = \frac{\cos(a) \times L \times \cos(b)}{\cos (c)}
\] (2)

Taking the freezing hole at the oblique-sealing end as an example, according to equation (1) and equation (2), the lofting parameters are obtained.

The difference between hole depth \( L \) and \( S \) varies with the change of \( a \), \( b \) and \( c \) values, and the difference is between 1.110 ~ 3.055m, which is far beyond the allowable range of error. The difference between the inclination angle \( b \) and \( c \) varies with the change of \( a \) value, and the difference is 0.1~7.4° and the relationship between the main lofting parameters of the end freezing hole is shown in Fig. 3.

![Fig.3 3D decomposition diagram of freezing hole and curve of inclination b and c of freezing hole at the oblique-sealing end with the change of horizontal angle a](image)

It can be seen from Fig. 3 that when the difference between the inclination angles \( b \) and \( c \) is small (< -10°), the difference is small in the range of 1°. With the increase of \( a \), \( b \) and \( c \) at the same time, the difference between \( b \) and \( c \) develops rapidly. Among them, the difference of setting out parameters of E28 freezing hole is 7.4° and the difference of hole depth \( L \) and \( S \) is more than 3m. Therefore, due to the large horizontal angle of the freezing hole at the oblique-sealing end of the external pumping house, special attention should be paid to the difference between the actual setting out parameters and the parameters shown in the two-dimensional elevation drawing. Once the difference is ignored, the final hole spacing may be too large, leading to the failure of intersection.

In addition, in the freezing design stage, due to various reasons (such as the shield has not been pushed through the connecting channel, the through survey has not been carried out, or the management is not paid attention to, etc.), the survey deviation data of the reserved openings of the left and right tunnel connecting channels are not obtained, which leads to the discrepancy between the setting out parameters of the freezing hole design and the actual project. In case the setting out parameters differ greatly, this kind of problem is also easy to occur.

5. To Establish the 3D Visualized Model of Freezing Pipe

Based on the lofting parameters, the adjustable parametric model of a single freezing pipe can be established first, and then it can be placed in the corresponding position of tunnel segment according to the location of the opening to complete the establishment of the freezing pipe model of the whole external pumping house.

The modeling steps of a single frozen pipe are as follows: first, draw a line with reference to the elevation plane, and fix one end of the line to the original point, and add the instance parameter of horizontal angle represented by \( a \). Secondly, select the work plane perpendicular to the reference-level plane on the reference line and set it as the current mode; then draw the lofting path, fix it to the original point, and add inclination angle and hole depth instance parameters \( b \) and \( L \) respectively; finally, the lofting profile is drawn to generate the 3D solid model. In order to test whether it is parameterized, the
expected entity model is generated by changing the parameters a, b and L in its attributes. Load the parameterized model, and modify the lofting parameters after placing according to the opening position to form the freezing pipe model of external pumping house, as shown in Fig. 4.

![Fig.4 parametric 3D freezing pipe model drawing of external pumping house](image)

6. Analysis of Collision Detection and Prediction of Freezing Curtain Formation

In order to detect whether the freezing pipe has collision, it is necessary to consider the allowable deflection of 150 mm for the designed single hole. In addition, there are errors in the positioning and lofting of the freezing hole and the drilling construction of the freezing hole. The collision threshold can be determined within 200 mm outside the axis of freezing hole. In other words, the outer diameter parameters of the freezing pipe are changed to 200 mm, and then the collision detection method is used. The collision detection results show that there is no conflict, which indicates that the freezing hole layout of the external pumping house will not produce collision after considering the construction error.

In order to ensure that the thickness of the freezing curtain reaches the expected value within the designed active freezing time, the formation of the freezing curtain is predicted. According to the characteristics of Zhengzhou stratum, in order to be conservative, the average spreading speed of frozen soil is 25 mm/d, the active freezing is 50d, and the development thickness of frozen soil cylinder on one side is 1250mm. The freezing curtain model is formed by modifying the external diameter parameters of the freezing pipe to 2500mm, as shown in Fig. 5.

![Fig.5 forecast diagram of freezing curtain formation of external pumping house](image)

It can be seen that in case the freezing curtain is actively frozen for 50d, the freezing curtain can achieve the expected effect and good uniformity, which verifies the rationality of the arrangement of freezing holes. The drilling construction of the external pumping house started on September 12, and the active freezing started on October 9 for 45 days. According to the temperature calculation of the temperature measuring hole, the actual average expansion speed of frozen soil is 28.2mm/d, and all parameters of the freezing curtain meet the design requirements [8]. The excavation started on November 27, and the construction of the secondary lining structure of the water collecting well was completed on December 25.
7. Conclusion
BIM technology is used to verify the design of freezing hole in the external pumping house, the possible collision of freezing pipe and the formation of freezing curtain are analyzed, the rationality of freezing hole arrangement is verified, and the superiority of visual parameterization of BIM technology is highlighted, which can provide experience for the design and construction of freezing method for complex connecting channel in the future. The main conclusions are as follows.

Special attention should be paid to the difference between the actual lofting parameters and the parameters shown in the two-dimensional elevation drawing in case the horizontal angle of the inclined end sealing hole of the external pumping house is large. Once the difference is overlooked, the final hole spacing may be too large, resulting in the failure of intersection.

The difference of setting out parameters will also occur in case the position deviation of reserved opening of two tunnel connecting channels is too large due to the assembly of shield segments.

The BIM technology is applied to realize parameterization for the complex connecting channel constructed by freezing method. As long as one part is adjusted, the model can be changed accordingly. Forecasting the formation of freezing curtain in advance can effectively coordinate the design and construction, prevent problems such as errors, omissions, collisions and shortages, thus improving efficiency and reducing risks.

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