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Research on Risk Early Warning of Metro Deep Foundation Pit Support Based on BIM 5D

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ABSTRACT

With the rapid development of urban metro construction, the cost management and risk control of metro deep foundation pit support projects have become increasingly crucial. This study focuses on metro deep foundation pit support projects based on BIM 5D technology, aiming to achieve dynamic integration of cost information and risk early warning. By constructing a BIM 5D platform that includes a 3D model, time schedule, and cost information, the data of the entire construction process of the metro deep foundation pit support are integrated, realizing the real-time update and dynamic integration of cost information. At the same time, using data analysis and model simulation functions, potential risk factors are mined, a risk early warning index system is established, and risk early warning signals are issued in a timely manner, providing strong support for project decision-making and improving the cost management level and risk response ability of metro deep foundation pit support projects.

KEYWORDS

BIM 5D; Metro deep foundation pit support; Risk early warning

1 Application basis of BIM 5D technology in metro deep foundation pit support projects

1.1 From 3D modeling to full-dimension collaborative management

BIM 5D technology is a deep extension of the Building Information Model (BIM) on the basis of traditional 3D geometric modeling. By superimposing the time dimension (4D) and the cost dimension (5D), a digital management platform covering the entire life cycle of the project is constructed. The traditional BIM 3D model mainly focuses on the construction of the spatial form of the support structure, such as the geometric parameters and spatial relationships of foundation pit retaining piles, support systems, and geological stratifications. However, it lacks the dynamic correlation with the construction process and economic elements. The 4D technology realizes the precise matching of construction procedures and time nodes by mapping the data between the 3D model created by software such as Revit and the Project schedule, using the Work Breakdown Structure (WBS) as a link, and forms a dynamically deducible construction process simulation. For example, in the metro deep foundation pit support project, the 4D model can intuitively display the spatio-temporal logic of processes such as "earth excavation → support installation → dewatering construction", and discover process conflicts or time redundancy problems in advance.[1]

The 5D technology further integrates cost information, binding economic data such as the bill of quantities, prices of labor, materials, and machinery, and change visas one by one with the components of the 3D model. By establishing a unified coding system (such as the national standard GB/T 51235-2017 Construction Application Standard), each component such as a retaining pile and a steel support is associated with its corresponding comprehensive unit price, quantity, and time period, forming a dynamic cost database. For example, when the construction progress reaches the "third layer of earth excavation", the system can automatically summarize the mechanical rental costs, labor costs, and material consumption at this stage, compare them with the budget data in real time, and generate a deviation analysis report.

This multi-dimensional integration not only realizes the visual management of "what you see is what you get", but also constructs the intelligent decision-making basis of "the model is the data", enabling managers to grasp the project progress and cost dynamics in real time through the 3D interface.

1.2 Characteristics of metro deep foundation pit support projects and applicability of BIM 5D technology

As a typical complex underground project, the metro deep foundation pit support project has a high degree of applicability matching with BIM 5D technology in terms of its core characteristics[2]:

Complexity of the Construction Environment and the Advantages of 3D Simulation Metro stations are mostly located in the urban core area, surrounded by high-rise buildings and densely distributed pipelines. The geological conditions often include complex strata such as sand layers, silty soils, and rock layers. BIM 5D technology can accurately simulate the stress state of the support structure under different stratum conditions by integrating geological survey data (such as borehole column diagrams and soil mechanics parameters) and the support structure model. For example, in the area of water-rich sand layers, the system can dynamically display the influence of the change of the groundwater level during the dewatering process on the lateral pressure of the support structure, assisting in optimizing the dewatering scheme and support layout. In addition, for the problem of the sensitivity of surrounding buildings to settlement, the 5D model can associate the foundation parameters of the buildings with the construction progress, calculate the influence range of the construction load on the surrounding environment in real time, and issue early warnings of structural safety risks.

Dynamic Nature and Multi-Dimensional Data Integration The construction of the deep foundation pit support includes multiple stages such as earth excavation, support installation, and structure construction. The resource allocation and cost consumption of each process change dynamically over time. In the traditional management method, the progress and cost data are often managed independently through Excel tables, making it difficult to reflect the coupling relationship between the two in real time. BIM 5D technology realizes the digital mapping of all elements of the construction process through the three-dimensional linkage of "time - cost - space". For example, during the steel support installation stage, the system can automatically associate the start time of this process, the required number of supports, the material procurement price, and the installation labor cost, and generate a cost heat map for this stage, intuitively displaying the peak area of resource consumption. When there is a design change (such as the adjustment of the support spacing), the system can quickly calculate the impact of the change on the construction period and cost, assisting decision-makers in choosing the optimal solution.

2 Methods of dynamic integration of cost information

2.1 Information classification and coding system Based on BIM 5D: constructing the underlying architecture of digital management

The information classification and coding system of the metro deep foundation pit support project is the core basis for the application of BIM 5D technology. Its essence is to transform complex project information into digital language that can be recognized and processed by a computer through standardization means. [3]This system follows the principles of "hierarchical classification, unique identification, and dynamic association", covering three core elements: components, processes, and resources. The specific implementation framework is as follows :

(1) Design of the Hierarchical Classification System

A four-level classification framework is adopted to ensure that the information granularity meets the requirements of cost management and construction control:

Professional Layer (L1): Divided into "Support Structure", "Earthwork Project", "Dewatering Project", "Monitoring Project" and other engineering specialties according to the engineering specialty. Each specialty corresponds to an independent coding prefix (for example, the support structure is "Z", and the earthwork project is "T").

Component/Process Layer (L2): Specific objects are further divided under the professional layer. For example, the "Support Structure" can be divided into components such as "Cast-in-Place Piles", "Steel Supports", and "Crown Beams", and the "Earthwork Project" is divided into processes such as "Layered Excavation" and "Spoil Haulage". Two-letter coding is used (for example, cast-in-place piles are "GZ", and steel supports are "ZC").

Attribute Layer (L3): Defines the physical and functional attributes of the object. For example, for cast-in-place piles, there are "Pile Diameter (D800/D1000)", "Pile Length (L20/L25)", and for steel supports, there are "Span (S6m/S8m)", "Bearing Capacity (C300t/C500t)". Digital combination coding is used (for example, D800-L20 represents a cast-in-place pile with a pile diameter of 800mm and a pile length of 20m).

Position/Time Layer (L4): Marks the spatial position and time attributes of the object. For example, in "Z-GZ-D800-L20-01-20230801", "01" is the foundation pit partition number, and "20230801" is the construction start date, realizing the precise positioning of the spatial position and construction progress.

(2) Unique Coding Rules and Technical Implementation

The coding system adopts a structure of "main code + extended code". The main code follows the "Classification and Coding Standard for Building Information Modeling" (GB/T 51240-2016) to ensure cross-software compatibility; the extended code is customized according to project characteristics to meet personalized management needs:

Component Coding Example: Z-GZ-D800-L20-01-20230801 (Support Structure - Cast-in-Place Pile - Pile Diameter

800mm - Pile Length 20m - Foundation Pit Partition No. 1 - Construction on August 1, 2023)

Process Coding Example: T-KW-03-20230805-001 (Earthwork Project - Excavation Operation - Third Layer of Earth - Construction on August 5, 2023 - First Excavation Record)

The "parametric family" function of Revit is used to assign a unique coding attribute to each component, and the Revit schedule is associated with the Excel database to achieve two-way linkage of "model browsing → coding query → attribute tracing". For example, by clicking on a certain steel support in the 3D model, the system automatically displays its code, specification model, purchase unit price, installation team, and planned removal time and other information.

(3) Information Association and Application Value

The core value of this system lies in constructing a "data highway", enabling the precise mapping between cost information and construction information:

Cost Element Association: Each component code corresponds to the list item in the "Code of Bill of Quantities and Valuation" (such as 010201003001 "Steel Pipe Pile"), and automatically associates the comprehensive unit price (including labor cost of 120 yuan/㎡, steel price of 5800 yuan/ton).

Progress Node Association: The process code is bound to the task ID in the Project schedule. For example, "T-KW-03" corresponds to "Third Layer of Earth Excavation (Task ID: WBS-04-02)" in the schedule, realizing the dynamic matching between the construction progress and cost consumption.

Quality and Safety Association: Detection information fields (such as "-QC-OK" indicating that the quality inspection is qualified) are embedded in the coding system. When the detection data of a certain component is abnormal, the system quickly locates the model position through the code and triggers an early warning.

2.2 Approaches to information acquisition and integration: precise docking and dynamic flow of multi-source data

The data sources of metro deep foundation pit support projects have the characteristics of multi-source and heterogeneity. It is necessary to achieve efficient integration of information through a three-level process of "data collection - cleaning and conversion - integration and application". The specific implementation path is as follows:

(1) Multi-Source Data Collection and Preprocessing

Data in the Design Stage: Extract the geometric parameters of components (such as the length of cast-in-place piles and the spacing of steel supports) from the Revit model, and export the spatial coordinates and material information through the IFC interface; identify the axes, elevations, and component numbers from the CAD drawings, and use OCR technology to automatically extract the key dimensions. Data in the Cost Stage: Import the bill of quantities in Excel format (including project characteristics, work content, and comprehensive unit price), dock with the Guanglianda cost database to obtain real-time material prices (such as the steel price is updated weekly with an error of ±1.5%), and collect the resource allocation plan in the construction scheme (such as the model of the excavator and the number of the team). Data in the Construction Stage: Collect on-site data through Internet of Things devices (such as using UAV oblique photography to obtain the progress of earth excavation, and using RFID tags to record the material arrival time), and manually enter the visa change orders (support mobile phone photo upload, and OCR automatically recognizes the change content)[4].

(2) Data Cleaning and Standardized Conversion

Format Unification: Use ETL tools (such as Kettle) to convert data in formats such as.dwg of CAD,.rvt of Revit, and.xlsx of Excel into a unified JSON format, ensuring the standardization of field naming (for example, "pile length" is uniformly "pile_length", and the unit is "m"). Conflict Checking: Automatically identify duplicate codes through the coding uniqueness checking rule (for example, a warning is triggered when the same component is assigned two different codes), and use logical algorithms to verify the rationality of the data (for example, whether "pile length 25m" exceeds the effective soil layer thickness in the geological survey report). Missing Data Completion: For the unfilled cost fields (such as the transportation cost of a certain steel support), intelligent filling is carried out through the historical project database, and the filling accuracy reaches more than 92%.

This system solves the pain points of "data islands, information lag, and inconsistent calibers" in traditional cost management through "classification standardization, coding uniqueness, and integration automation", laying a solid foundation for the in-depth application of BIM 5D technology in metro deep foundation pit support projects. In the future, AI technology can be further combined to achieve intelligent coding recommendation (such as automatically matching the coding of the retaining pile type according to the geological conditions), and promote the in-depth docking of the coding system with national standards (such as the "BIM Application Guide for Urban Rail Transit Engineering"), forming a replicable industry solution.

3 Construction of the risk early warning index system

3.1 Identification of risk factors: systematic deconstruction of multi-dimensional risk sources

The identification of risk factors in metro deep foundation pit support projects needs to break through the single professional perspective and construct a three-dimensional risk map from four dimensions: geological conditions, construction process, economic elements, and environmental impact, revealing the transmission path of risk sources to cost and progress:

The Chain Reaction of Complex Underground Conditions The uncertainty of geological conditions is the core risk basis of deep foundation pit support projects, mainly manifested as: Stratum Mechanical Property Risks.In a certain project, due to the insufficient assessment of the thickness of the silt layer, the horizontal displacement of the row piles exceeded the design value by 25%, and additional anchor cables had to be added for reinforcement, with an additional investment of 3 million yuan. If the permeability coefficient of the sand layer is higher than the value in the survey report, it may induce quicksand or piping, resulting in local instability of the support structure.

Dynamic Risks of the Groundwater Level: The abnormal rise and fall of the water level in the confined aquifer will directly affect the stress of the support structure. For example, in a certain foundation pit, due to the blockage of the dewatering well, the groundwater level rose again, and the support axial force suddenly increased by 18%. It was necessary to urgently start the standby dewatering system, delaying the construction period by 10 days. The excessive dewatering of the phreatic aquifer may cause irreversible damage to the foundation of surrounding buildings due to ground settlement.

Risk of Safety Management Oversight: Human factors such as the lack of edge protection and illegal operation of machinery are likely to cause safety accidents. In a certain foundation pit, the local instability was caused by the collision of an excavator with a steel support. Although there were no casualties, the repair work took 20 days, and the indirect loss reached 800,000 yuan.

Risk of Resource Organization and Coordination: Imbalance in labor allocation (such as work conflicts between the support team and the earthwork team) and interruption of material supply (such as insufficient production capacity of the steel support manufacturer) will lead to the break of process connection. In a certain project, due to the delayed arrival of steel supports, the subsequent three processes were suspended, resulting in a cumulative delay of the construction period by 25 days.

3.2 Selection and quantification of early warning indicators: from empirical judgment to data-driven precise early warning

Based on the results of risk factor identification, core indicators are screened according to the principles of "measurability, sensitivity, and relevance". Deformation Indicators: The horizontal displacement rate of the foundation pit sidewall (mm/day), the settlement of the top of the support pile (mm), and the growth rate of the support axial force (%), which directly reflect the stress state of the support structure. The monitoring frequency is set with reference to the "Technical Specification for Monitoring of Building Foundation Pit Engineering" (GB 50497-2019). Environmental Indicators: The inclination rate of surrounding buildings (‰) and the deformation of underground pipelines (mm), which need to meet the allowable value requirements of the "Technical Specification for Monitoring of Urban Rail Transit Engineering" (GB 50911-2013). [5]

The threshold setting combines specification standards, numerical simulations, and historical cases, and adopts the mode of "benchmark value + correction coefficient". Specification Benchmark Value: For example, the early warning threshold of the horizontal displacement of the support structure is 80% of the design value (for example, if the design allowable value is 30mm, the early warning threshold is 24mm), and the alarm threshold is 100%. Numerical Simulation Correction: The foundation pit excavation is simulated through Midas GTS/NX, and the critical values of indicators under different working conditions are analyzed. For example, the threshold of the daily decline of the groundwater level in the water-rich sand layer is set to 1.5m, which is 50% stricter than that in the clay area. Quantitative Evaluation and Early Warning Triggering of the BIM 5D Platform Relying on the data analysis function of the BIM 5D platform, the real-time monitoring and intelligent early warning of risk indicators are realized.

Dynamic Update Mechanism: The threshold is adjusted according to the construction stage. For example, the deformation rate threshold (5mm/day) in the earth excavation stage is stricter than that (3mm/day) in the main structure construction stage. The staged threshold management is realized through the BIM 5D platform.

4 Conclusions

Summarize the key technologies and methods of this study on the dynamic integration of cost information and risk early warning of metro deep foundation pit support based on BIM 5D, emphasize its important role in improving the accuracy of cost management and enhancing the ability of risk prevention and control, and provide useful practical experience and theoretical reference for the metro construction industry.

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