Construction risk prediction and dynamic control method of water supply and drainage pipe network for complex urban environment

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Abstract: In order to cope with the multiple challenges faced by water supply and drainage pipe network construction in complex urban environment, such as complex geology and dense underground space, and to solve the shortcomings of traditional methods in data fusion, dynamic response and multi-objective coordination, this paper puts forward a risk prediction and dynamic regulation method for water supply and drainage pipe network construction in complex urban environment. This method constructs a multi-source heterogeneous data fusion layer, integrates geological and underground space, environment and society, real-time monitoring and construction process data to form a standardized data set; Building a dynamic risk knowledge graph (KG) based on fused data to achieve formal expression and dynamic updates of construction related entities and relationships; Adopting a hybrid intelligent prediction model that integrates finite element method physical model and physical information neural network (PINN) deep learning model to improve the accuracy of risk prediction. At the same time, a three-level hierarchical control system of "on-site edge cloud" is designed, combined with NSGA-III algorithm to achieve multi-objective collaborative optimization, and integrated to build an intelligent decision support system. The engineering application case shows that this method can significantly reduce the maximum settlement by 33%, avoid the alarm of settlement overrun and delay in construction period, increase the average daily driving speed by 20%, effectively realize the accurate prediction and dynamic regulation of construction risk, and provide intelligent solutions for similar projects.

1. Introduction

With the acceleration of urbanization, the water supply and drainage pipe network, as a key part of the city's lifeline, faces multiple challenges such as complex geology, dense underground space, dynamic environmental interference and social sensitivity. The traditional methods relying on static norms and experience are difficult to cope with, resulting in frequent accidents and delays in construction period. It is urgent to establish an intelligent risk prediction and dynamic control system to improve construction safety and urban resilience [1-2]. This study proposes innovative solutions to address the bottlenecks in current research, such as insufficient data fusion, delayed dynamic response, and difficulties in multi-objective collaboration. This includes building a dynamic risk knowledge graph (KG) that integrates geological, monitoring, and urban data, using a hybrid prediction method combining physical models and deep learning to improve accuracy, designing a three-level hierarchical control system of "on-site edge cloud" to achieve real-time optimization of construction parameters and intelligent emergency response, and introducing the NSGA-III algorithm to achieve multi-objective collaborative optimization of construction period, cost, and environmental risks.

2. Multi-source data-driven construction risk prediction model

2.1 Multi-source heterogeneous data fusion layer

Multi-source heterogeneous data fusion layer is responsible for integrating four types of data from different sources [3-4]. Geological and underground spatial data including engineering

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geological survey report, underground pipeline BIM/GIS model and geological radar data; Environmental and social data covering real-time meteorology, traffic flow, surrounding building information and social public opinion; Real-time monitoring data of foundation pit displacement, stress, settlement, vibration, water level and gas concentration from IoT sensors on site [5]; And construction process data such as equipment operation parameters and construction progress; By constructing a unified data lake, these heterogeneous data are cleaned, aligned in time and space and processed by feature engineering to form a high-quality and standardized data set, which provides reliable input for the upper analysis model [6].

2.2 Dynamic risk KG construction

Based on the fused multi-source heterogeneous data, KG is built around the core of "construction risk", and the complex relationships among geological entities, environmental entities, construction activities and risk events, such as "location", "initiation" and "influence" are formally expressed [7]; The atlas has the ability of dynamic evolution, which can continuously update with the continuous access of real-time monitoring data and the progress of construction, reflect the changes of urban environment and construction state in real time, and provide timely and accurate contextual information support for subsequent risk identification and reasoning.

2.3 Hybrid (physical-data-driven) intelligent prediction model

In order to improve the accuracy and reliability of construction risk prediction, a hybrid intelligent prediction model is proposed, which combines the advantages of physical mechanism model and deep learning model. Specifically, the physical mechanism model is based on the finite element method, which can simulate key physical processes such as soil deformation, pipeline stress and groundwater seepage, thus providing the mechanism explanation and preliminary prediction of potential risk evolution [8]. This model provides a solid theoretical foundation and prior knowledge under extreme working conditions, ensuring the rationality and scientificity of the predicted results. At the same time, deep learning models use Physical Information Neural Network (PINN) as the core algorithm (as shown in Figure 1), embedding the constraints of physical equations into the loss function of the neural network, so that the prediction results not only conform to the data rules, but also strictly follow the laws of physics.

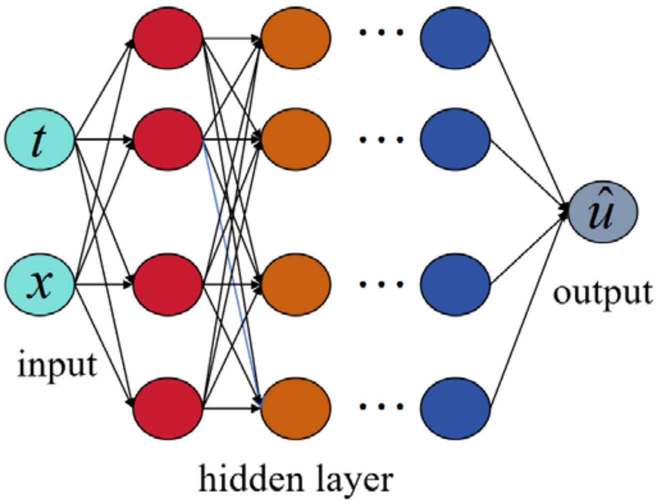

Figure 1 PINN network schematic

In the aspect of hybrid mechanism, firstly, a general framework is constructed by physical model and necessary prior knowledge is provided, and then real-time monitoring data are processed by deep learning model for online calibration and deviation correction. This combination method not only retains the reliability of the physical model, but also gives full play to the high precision advantage of the data-driven model, and finally forms a comprehensive prediction model. The model can output the probability and expected scale of risk events such as settlement overrun, piping and collapse, which provides strong support for construction risk management. In this way, the hybrid intelligent prediction model effectively solves the problem of insufficient generalization ability of pure data-driven model under extreme working conditions, and realizes accurate prediction and effective management of construction risks.

3. Dynamic control method and decision support system (DSS)

3.1 "Site-Edge-Cloud" three-level hierarchical control system

An efficient and collaborative intelligent decision-making and response architecture is shown in Figure 2. The field layer is deployed in the industrial computer or gateway of the construction site, and the real-time data of the sensor is processed from millisecond to second level through the lightweight AI model, so as to realize autonomous closed-loop regulation and immediate alarm for local low-level risks such as abnormal equipment parameters [9]; The edge layer is located in the project headquarters or regional server, which gathers data from multiple working faces, runs complex models to carry out cross-regional risk correlation analysis, and supports the optimization of construction sequence from hours to days and the dynamic allocation of resources; The cloud layer relies on powerful computing power and total data to judge the macro situation and update the global KG, and through multi-objective optimization algorithms such as NSGA-III, it seeks Pareto optimality among construction period, cost and safety risks, provides strategic construction scheme adjustment strategies, and realizes multi-level intelligent regulation from quick response to global optimization.

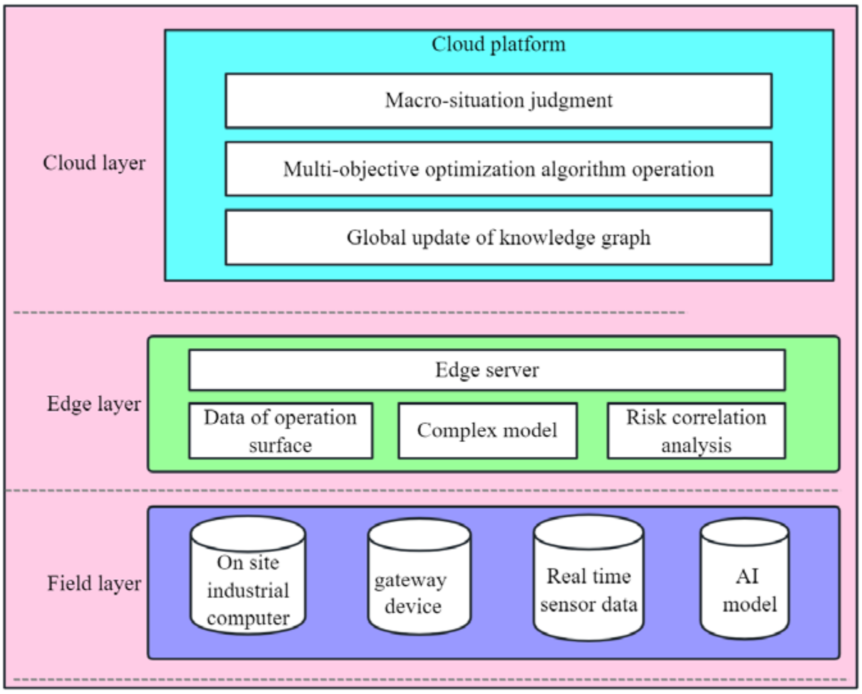

Figure 2 Intelligent decision-making and response architecture

3.2 Intelligent DSS

Intelligent DSS integrates multi-source data fusion, dynamic KG, hybrid forecasting model and three-level control system into a unified visualization platform, and constructs a digital twin environment through BIM+GIS to realize three-dimensional dynamic display of monitoring data, risk prediction heat map and control simulation effect; The system supports scenario deduction and scenario simulation, allows decision makers to adjust parameters and preview the risk evolution trend in real time, and realizes interactive decision-making of "what you see is what you get"; At the same time, it has built-in emergency response plan database, which can automatically match and recommend disposal schemes when high-risk early warning or incidents occur, and jointly dispatch emergency resources to comprehensively improve the intelligence, visualization and emergency response capabilities of construction management.

4. Case analysis of engineering application

This case focuses on the pipe jacking project of deep buried sewage main pipe in a downtown area. The construction route needs to cross the high-sensitivity soft soil layer, and a historical protection building and a traffic main road are flanked, which faces extremely high construction risk and great social impact. The main challenge is that soil disturbance caused by pipe jacking operation may lead to uneven settlement of historical buildings (warning value is 5mm) and pavement collapse. However, traditional construction management relies on manual regular monitoring, which is lagging behind, and the control means are passive, so it is difficult to realize early warning and active intervention of risks. Moreover, there is a lack of scientific and effective trade-off mechanism between multiple objectives such as time limit, cost and settlement control, and intelligent technical support is urgently needed to realize accurate prediction and collaborative control.

In this study, the "risk prediction-dynamic regulation" system is applied to the pipe jacking project of deep buried sewage main pipe in the city center. Firstly, the dynamic risk KG is constructed by integrating multi-source data such as geological exploration, BIM of historical buildings, real-time parameters of pipe jacking machine and settlement monitoring. Then, the PINN mixed model is used to predict the settlement trend of historical building foundation and surface in the next 12 hours based on real-time excavation parameters. On this basis, the "site-edge-cloud" three-level regulation is implemented: the site layer automatically fine-tunes the excavation parameters for short-term overrun to maintain the earth pressure balance, the edge layer optimizes the grouting pressure and grouting quantity to compensate when the accumulated settlement approaches the warning value, and the cloud layer coordinates the construction progress, material cost and settlement risk through NSGA-III multi-objective algorithm to generate the globally optimal excavation speed scheme, so as to realize accurate risk prediction and hierarchical coordinated regulation.

By comparing with the data of traditional construction section, the effectiveness of this method is verified (Table 1 and Figure 3 for false cases).

Table 1 Key indicators comparison table

Performance index	Traditional method construction section	The construction section adopt that method	Lifting effect
Maximum settlement (mm)	7.2	4.8	33%(↓)
Number of settlement overrun alarms	3	0	100%(↓)
Average daily driving speed (m/ day)	8.5	10.2	20%(↑)
Time delay caused by settlement problem	5 days	0 days	100%(↓)

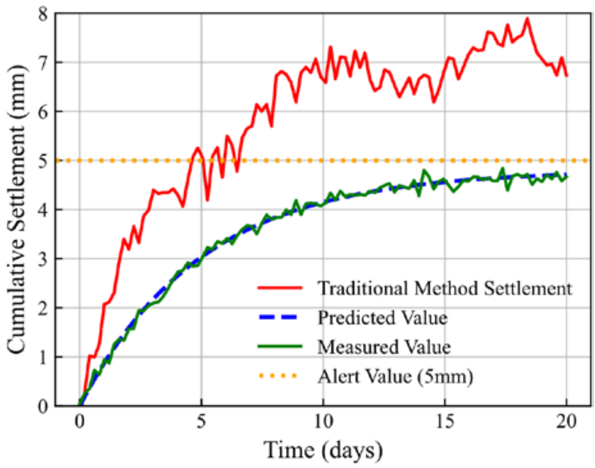

Figure 3 Curve of foundation settlement of historical buildings with time

The application results show that compared with the traditional construction methods, the intelligent prediction and control system has made significant progress in key construction indicators. In terms of the maximum settlement, the construction section of this method is controlled at 4.8mm, which is 33% lower than the traditional method's 7.2mm, and the settlement process is always below the warning value of 5mm, which realizes that the alarm times of settlement overrun and the construction period delay caused by settlement are both zero; At the same time, the average daily tunneling speed has been increased from 8.5 meters to 10.2 meters, which has increased by 20%, effectively ensuring the construction efficiency.

It can be seen from the settlement change curve in Figure 3 above that the predicted value is highly consistent with the measured value, which verifies the accuracy and reliability of the hybrid prediction model. Through dynamic KG and three-level regulation mechanism, the system realizes accurate prediction and active intervention of foundation settlement of historical buildings, and avoids the disadvantages of large settlement fluctuation and lagging response in traditional methods.

The case verifies the effectiveness of the proposed "multi-source data-driven construction risk prediction and dynamic control method" in complex urban environment, which can realize accurate advance prediction of construction risk and change the traditional passive response into active intervention. Significantly reduce the impact on the surrounding environment and effectively ensure the safety of sensitive structures such as adjacent historical buildings; Through multi-objective optimization, the construction efficiency is improved while controlling the settlement risk, and the collaborative optimization of safety, construction period and cost is realized, which provides an efficient and reliable intelligent construction solution for similar urban underground pipe network projects.

5. Conclusion

Aiming at the multiple challenges faced by the construction of water supply and drainage pipe network in complex urban environment, this study puts forward an innovative multi-source data-driven construction risk prediction and dynamic regulation method. By constructing a dynamic risk KG that integrates geological, monitoring and urban data, and combining the hybrid prediction method of physical model and deep learning, the accurate prediction of construction risk is realized. At the same time, a "site-edge-cloud" three-level hierarchical control system is designed, which realizes real-time optimization of construction parameters and intelligent emergency response, and realizes multi-objective collaborative optimization of construction period, cost and environmental risk through NSGA-III algorithm. In an engineering application case, this method was successfully applied to the pipe jacking project of deep buried sewage main pipe in a downtown area, which significantly reduced the maximum settlement, avoided the alarm of settlement overrun and the delay of construction period, and improved the average daily driving speed. The experimental results show that the key indexes of the construction section using this method are significantly improved compared with the traditional method, which verifies the effectiveness of this method.

To sum up, the multi-source data-driven construction risk prediction and dynamic control method proposed in this study can realize the accurate advance prediction of construction risk, change the traditional passive response into active intervention, significantly reduce the impact on the surrounding environment, and effectively ensure the safety of sensitive structures such as nearby historical buildings. At the same time, through multi-objective optimization, the collaborative optimization of safety, construction period and cost is realized, which provides an efficient and reliable intelligent construction solution for similar urban underground pipe network projects.

References

[1] Bai Jianhua. Quality Control of Concrete Structure Construction in Municipal Pipeline Water Supply and Drainage Engineering[J]. Product Reliability Report, 2025, (06): 117-118.

[2] Xie Long. Research on Construction Technology and Countermeasures of Municipal Water Supply and Drainage Pipeline System Engineering[J]. Chinese Construction, 2025, (06): 180-182.

[3] Zhao Manman, Li Mengya. Application Research of BIM in Urban Water Supply and Drainage Engineering[J]. Construction Machinery & Maintenance, 2025, (05): 136-138.

[4] Cao Bei, Guan Xiao. Ultra-Large Diameter Steel Pipe Jacking Construction Technology for Municipal Water Supply and Drainage Pipeline[J]. Northern Architecture, 2024, 9(06): 106-110.

[5] Zhang Kao. Analysis of Construction Key Points of Concrete Structure in Municipal Pipeline Water Supply and Drainage Engineering[J]. China Cement, 2024, (10): 85-87.

[6] Shi Xingna, Wang Yadong. Research on Optimization of Building Water Supply and Drainage Pipeline Construction Based on BIM Technology[J]. Jiangxi Building Materials, 2024, (09): 374-377.

[7] Jiang Feng. Research on Optimal Configuration and Management of Municipal Water Supply and Drainage Pipeline[J]. New Urban Construction Science and Technology, 2024, 33(09): 122-124.

[8] Wang Ruirui. Exploration of Safe, Rational, and Stable Operation of Water Supply and Drainage Pipeline System within Industrial Parks[J]. China Metal Bulletin, 2024, (05): 140-142.

[9] Chen Bing. Application of Long-Distance Pipe Jacking Construction Technology in Municipal Water Supply and Drainage Pipeline Construction[J]. Bulk Cement, 2024, (02): 141-143.