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Research on Reinforcement and Anti-Seepage Construction Methods of Hydraulic Engineering Embankments Based on Digital Twin Technology

Ahmat Hasim*

Tarim River Basin Mainstream Authority, Korla 841000, China

**Author to whom correspondence should be addressed.*

Abstract: In recent years, digital twin technology has gained significant attention and application in the engineering construction field in China. Its real-time feedback function has brought more standardized construction operations to various engineering construction and maintenance processes. In this context, this paper analyzes the specific application of digital twin technology in hydraulic engineering based on its foundations. Taking the reinforcement and anti-seepage digital twin application of a certain embankment section as an example, it explores the reinforcement and anti-seepage construction effects of embankment engineering with the involvement of digital twin technology under complex hydrogeological conditions. The research shows that this technology can significantly improve the control accuracy of slurry diffusion, the identification ability of seepage risks, and the adaptability of engineering construction. Its application provides a replicable digital solution for the governance model of hydraulic engineering.

Keywords: Digital twin technology; Embankment reinforcement; Anti-seepage construction; Hydraulic engineering; Geological conditions

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1. Introduction

Embankment engineering serves as the first line of defense against flood disasters in the water conservancy system. The safety of embankment engineering is directly related to the flood control capability of the area where the hydraulic engineering is located and the safety of people's lives and property [1]. Due to factors such as frequent extreme climate, complex geological conditions, and aging of embankment bodies, some embankments may experience high and frequent occurrences of seepage problems [2]. For a long time, traditional methods have been used for the reinforcement and anti-seepage construction of embankments, which involve directly reinforcing or applying anti-seepage treatments to corresponding areas after identifying problems or hidden dangers [3]. However, due to technical limitations, these methods often suffer from issues such as insufficient precision or delayed feedback, making it difficult to meet the refined and intelligent management needs exhibited by modern hydraulic engineering projects [4, 5]. Therefore, in recent years, there has been a gradual increase in the application of technical tools such as digital twin technology to dominate the detailed control of construction [6]. This paper takes a certain embankment anti-seepage reinforcement project as an example to explore the specific application of digital twin technology in this instance, verifying its practical value in improving construction accuracy and other aspects. It aims to provide a replicable technical path and practical basis for embankment reinforcement and anti-seepage construction empowered by digital technology.

2. Basic application of digital twin technology in embankment reinforcement and anti-seepage construction

2.1. Overview of digital twin technology

Initially applied in the aerospace manufacturing field by the US Department of Defense, digital twin technology is used to simulate the real-time operating status of complex engineering systems [7]. In recent years, with the improvement of information infrastructure, the application of this technology has gradually expanded to various fields such as industrial manufacturing, smart cities, and infrastructure [8]. However, domestically, this technology is still more commonly applied in the field of engineering construction, and hydraulic engineering is a suitable field for the application of digital twin technology. In this field, the greatest value of digital twin technology lies in its ability to create a virtual-real fusion mapping model, enabling real-time perception, simulation, prediction, and control of the state of real-world engineering projects in digital space. This allows for more precise design and control of various aspects of the project, including design, construction, operation, and maintenance [9].

The basic principle of digital twin technology is to input data such as status information, environmental data, and construction parameters collected by sensors into the model system and build a virtual structure corresponding to the real structure on a digital platform. Using methods such as 3D modeling, finite element simulation, and machine learning, the evolution and simulation of geological information, structure, and process parameters are carried out. The system feeds back the output results of the model to the construction management platform to guide on-site operations, thereby improving construction accuracy.

2.2. Application path of digital twin in hydraulic engineering

Embankment engineering is one of the infrastructures that protect cities and agricultural areas from floods. However, most domestic embankments were built a long time ago and often have complex structural hidden dangers. Coupled with recent climate anomalies causing floods, problems such as leakage, piping, and collapse, which are concealed and sudden, often occur [10]. The technical advantages of digital twin technology make its application in embankment construction effective for improving the reinforcement and anti-seepage of embankment engineering. For projects with multiple operation surfaces synchronized and tight schedules, the digital twin platform can provide more scientific basic information for construction scheduling, centrally display the status, risks, and warnings of each operation segment, and support management in issuing data-based instructions and allocating resources.

3. Case study of digital twin application for reinforcement and seepage control in a certain embankment section

3.1. Project background

The embankment section in this project has a total length of 370m and serves as a flood control facility in an old urban area. With a service life exceeding 25 years, it has encountered structural issues such as seepage at the embankment toe, collapse on the embankment back, and uneven settlement of the embankment crest during flood seasons in recent years. To enhance the seepage resistance and structural stability of this embankment section, the operation and maintenance team introduced digital twin technology into this embankment operation and maintenance, and conducted geophysical exploration and survey work in the early stage. The data is shown in **Table 1**.

Table 1. Embankment engineering survey and technical parameters

Project number	Permeability coefficient range (cm/s)	Average levee height	Stratigraphic structure type	Defect types	Ground water dynamics	Exploration methods	Designed pile type
K0+680–K1+050	4.2×10^{-4}–7.1×10^{-4}	5.8m	Silty clay with medium sand interlayer	Toe piping, backside collapse, crest settlement	Seasonal fluctuation 0.9–1.3m	18 boreholes, 3 geophysical survey lines	High-pressure jet grouting piles φ650mm, pile length 8.0–9.0m, pile spacing 1.2m, single-fluid method

To meet the needs of on-site construction, displacement monitoring piles, water pressure sensing points, and slurry flow and pressure monitoring units were installed in the construction area, enabling real-time regulation and parameter tracing during the construction phase.

3.2 Application of digital twin technology in embankment seepage control and reinforcement construction

Based on digital twin technology, the project team established a construction control platform covering geological modeling and full-process feedback. In the early stage, data collection was completed for the project area through soil layer distribution information from 18 boreholes, three geological radar profile data, 90 days of groundwater dynamic monitoring data, and measured indicators such as pore water pressure and porosity. The collected data was then imported into the digital twin platform for modeling using BIM-GIS. The soil types, permeability characteristics, groundwater trends, and known problem areas corresponding to each embankment section were layered and mapped into a spatial coordinate system. To further improve the accuracy of modeling and on-site construction data, the model was closely integrated with monitoring units such as grouting equipment control terminals, pore water pressure sensing devices, and surface displacement meters. This allowed for synchronous collection and transmission of information such as flow rate, pressure, and diffusion radius during the construction process.

Simultaneously, based on the characteristics of three main stratigraphic units, the platform established a regional seepage parameter field. This field provided basic input conditions for slurry diffusion simulation and construction parameter prediction. After modeling was completed, the system used permeability and grouting response capability as the main criteria to classify the construction difficulty zones of the embankment sections. The physical parameters and diffusion resistance characteristics of the main stratigraphic units are shown in **Table 2**.

Table 2. Stratigraphic structural parameters and grouting resistance coefficients

Stratum Code	Soil layer name	Average porosity (n)	Permeability coefficient (k) (cm/s)	Water-bearing State	Grouting resistance coefficient (β)
I	Surface Silty Clay	0.42	4.5×10^{-4}	Saturated Fluctuation Zone	2.3
II	Medium Sand with Silt Interlayer	0.38	7.1×10^{-4}	Highly Permeable Zone	3.7
III	Underlying Gravel with Coarse Sand Layer	0.35	9.4×10^{-4}	Stable High-pressure Zone	4.8

And, the digital twin system adopts the unsteady seepage theory of porous media to establish a grouting diffusion model. The model control equation is shown in Formula (1).

$$\nabla\cdot[k(x,y,z)\cdot\nabla h] + q = S\cdot\vartheta h/\vartheta t \quad (1)$$

In the formula, k(x,y,z) represents the spatial permeability distribution function (bound to stratum division); h represents the groundwater head (cm); q represents the source term of injected grout (cm^3/s); S represents the storage coefficient of soil (dimensionless); and $\vartheta h/\vartheta t$ represents the rate of change of water head with time.

Meanwhile, the platform uses a simplified diffusion radius prediction model to evaluate the grout coverage area. The model is shown in Formula (2).

$$R(t) = [(3Q / 4\pi\mu \cdot t/r^\wedge 2 \cdot \cos\theta/\phi)]^\wedge(1/3) \quad (2)$$

In the formula, R(t) represents the grout diffusion radius at a certain time (m); Q represents the grouting flow rate (m^3/s); μ represents the dynamic viscosity of the grout (Pa·s); ϕ represents the porosity of the soil layer (consistent with the stratum table); θ represents the grouting angle (°); and r represents the pile radius (m).

After importing soil layer parameters and setting pile diameters/lengths for different pile segments, taking the K0+700 to K0+800 segment as an example, the parameters for each pile segment and platform feedback are shown in **Table 3**.

Table 3. Pile segment parameter settings and platform adjustment conditions

Pile section no.	Pile length (m)	Pile diameter (mm)	Grouting volume (m^3)	Design pressure (MPa)	Platform intervention recommendation	Measured diffusion radius (m)
K0+700	8.5	650	2.8	1.2	—	0.98
K0+720	9.0	650	3.1	1.3	Increase pressure to 1.5 MPa	1.03
K0+740	8.0	650	2.5	1.1	Adjust water-cement ratio to 0.8	0.96
K0+760	8.5	650	2.9	1.2	Extend grouting time by 90 seconds	1.00
K0+780	9.0	650	3.2	1.3	Replace nozzle, switch to two-fluid grouting system	1.05
K0+800	8.0	650	2.6	1.1	Switch to two-fluid system, apply supplemental pressure	0.97

During the construction process, the platform established a feedback mechanism using a dual-channel monitoring unit for slurry pressure/flow, displacement meters, water pressure holes, and temperature-sensing chips. Simultaneously, the platform optimized the prediction model based on the criterion of minimum residuals, as shown in Formula (3).

$$J(\theta) = \sum_{i=1}^{n}\left[R_i^{sim}(\theta) - R_i^{meas}\right]^2 \sum_{i=1}^{n}\left[R_i^{sim}(\theta) - R_i^{meas}\right]^2 \quad (3)$$

In this equation, $R_i^{sim} R_i^{sim}$ represents the simulated diffusion radius of the i-th pile segment, $R_i^{sim} R_i^{sim}$ represents the measured diffusion radius, and θ represents the parameter set in the model that characterizes the formation resistance and slurry response.

3.3. Implementation effects

After deploying the digital twin platform model, the on-site process adaptability and construction accuracy of this embankment reinforcement and anti-seepage project have been significantly improved. The actual construction period of the project was 28 days, and 312 high-pressure jet grouting piles were completed. The mean error between the slurry diffusion radius and the model prediction was 0.18 m, which met the set tolerance threshold (± 0.25 m). Simultaneously, the project team established three types of evaluation indicators: grouting process response indicators, seepage pressure change monitoring indicators, and surface displacement control indicators, before, during, and after construction. The results are summarized in **Table 4**.

Table 4. Summary of construction response and monitoring effects supported by the digital twin platform.

Indicator category	Indicator name	Design/ Predicted value	Measured value (Average)	Deviation rate (%)
Grouting response	Grouting pressure (MPa)	2.3	2.26	1.74
Grout diffusion radius (m)	1.50	1.48	1.33	
Monitoring response	Pore water pressure reduction (kPa)	15.0	16.2	-8.0 (Exceeded)
Surface settlement (mm)	≤ 8.0	6.7	--	
Post-construction deformation trend	Levee crest horizontal displacement (mm)	≤ 2.0	1.6	--

The results indicate that the model predictions align well with the field responses, with a control deviation for the diffusion range of grouting below 2%. Groundwater pressure monitoring data shows that the pore water pressure has continuously decreased since the 5th day of construction and stabilized after the 20th day, implying that the grouting curtain has essentially formed and created an effective impermeable zone. According to continuous recordings using a laser rangefinder and GNSS coordinate comparison method, the maximum settlement value during construction was 6.7 mm, which is less than the originally designed warning value (8.0 mm), and there was no uneven settlement trend observed. The system automatically collected 836 sets of front-end monitoring data, performed 102 iterations of model correction, and achieved a mean response delay of 2.8 seconds for the construction dynamic prediction interface, meeting the requirements of real-time construction control.

Overall, the application of digital twin technology in this dike reinforcement and anti-seepage construction fundamentally improves operation control accuracy and construction visualization, providing modeling references and parameter adjustment experience for the management of similar problem sections in the future, which has certain reference and learning value.

4. Conclusion

In the context of increasingly emphasizing refinement and intelligence in water conservancy projects in modern society, the traditional reinforcement and anti-seepage construction mode adopted by dikes is obviously unable to meet the increasingly complex geological conditions and environmental response needs. However, the construction management system based on digital twin technology constructed in this paper systematically demonstrates the operability and remarkable effectiveness of this technology in practical engineering. Studies have shown that the digital twin platform has obvious advantages in geological heterogeneity identification, precise grouting parameter control, osmotic pressure response prediction, and construction disturbance management, which can effectively improve the safety redundancy of the dike structure and the sealing capability of the anti-seepage system. This provides a reproducible engineering paradigm for other water conservancy projects to achieve low-disturbance, high-precision, and high-adaptability construction. For the future development of this technology, we should further strengthen the deep integration of digital twin systems with IoT sensing and artificial intelligence algorithms, promote the digitization and intelligent upgrading of water conservancy projects, continuously improve the automation level of disease identification and the real-time optimization ability of treatment strategies, and provide solid support for large-scale dike hidden danger treatment and water safety.

Disclosure statement

The author declares no conflict of interest.

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