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BIM-based Collaborative Mechanism for Integrated Design and Construction of Utility Tunnels: Postprint

Authors: Yungang Chen, Jixiang Ding

Date: 2018-10-26T00:00:00+00:00

Abstract

To enhance the efficiency of design-construction integration in the construction process of urban underground utility tunnels, this study analyzes the reasons for insufficient coordination in design-construction integration of utility tunnels under the traditional mode from three perspectives: information flow, professional coordination, and process management. Based on BIM technology, the entire design and construction process of utility tunnels is optimized, and three optimization modes are proposed: a BIM-based design collaborative mechanism for utility tunnels, a construction collaborative mechanism, and a design-construction integration linking mechanism. The feasibility of this design-construction integration collaborative mechanism is validated through case analysis, and practical experience demonstrates that the optimization mode provides certain reference value for achieving deep integration across various stages of design and construction.

Full Text

Research on the Collaboration Mechanism for Integrated Design and Construction of Utility Tunnels Based on BIM Technology

CHEN Yungang[1], DING Jixiang[2]
[1] Anhui University of Technology, Maanshan 243000, Anhui, China
[2] Anhui University of Technology, Maanshan 243000, Anhui, China
Email: mascyg@163.com

Abstract: To improve the efficiency of design-construction integration in urban underground utility tunnel projects, this paper analyzes the root causes of inadequate coordination in traditional utility tunnel projects from three perspectives: information flow, professional collaboration, and process management. Based on Building Information Modeling (BIM) technology, the entire design and construction process is optimized, and three collaborative mechanisms are proposed: a BIM-based design coordination mechanism, a construction coordination mechanism, and a design-construction integration interface mechanism. A case study demonstrates the feasibility of this integrated design-construction collaboration mechanism, showing that the proposed optimization models offer valuable insights for achieving deep integration across all project phases.

Keywords: utility tunnel; BIM technology; integrated design and construction; collaboration mechanism research

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Urban underground utility tunnels play a crucial role in addressing urban maladies such as "aerial spider webs"and "road zipper"effects, significantly enhancing urban scientific management and intensification [1]. With strong support from national policies and fiscal investment, urban underground utility tunnels have achieved substantial development in China. However, due to the construction industry' s long-standing reliance on traditional delivery methods and insufficient motivation to adopt advanced technologies or reform outdated management models, design and construction entities remain fragmented, hindering effective information coordination [2-3]. Given BIM technology' s characteristics of high integration and enhanced collaboration in building engineering, its application to utility tunnel design and construction stages offers practical significance for improving coordination and overall project efficiency [4].

1.1 Analysis of Professional Coordination Issues in Utility Tunnel Design

Utility tunnels, also known as municipal utility corridors, integrate urban power, water supply, drainage, communication, gas, heating, and other municipal pipelines into a shared underground space, forming a scientific, standardized, and intensive urban infrastructure [5]. The large construction volume, unique structural shapes, numerous involved specialties, long construction cycles, and high technical complexity inevitably create challenges, particularly during design and construction phases. Therefore, analyzing information flow and professional coordination issues in utility tunnel design and construction holds practical significance.

Utility tunnel design primarily includes standard cross-section selection, cross-sectional dimension design, selection of pipeline types and sizes, and pipeline design at intersection nodes [6]. These tasks can be categorized into two main components: tunnel structure design and pipeline integration design. Based on professional disciplines, utility tunnel design is divided into three categories: architecture, structure, and MEP (Mechanical, Electrical, and Plumbing).

Through detailed analysis of the traditional utility tunnel design process, we deconstructed the three major design phases (conceptual design, preliminary design, and construction drawing design) as illustrated in [Figure 1: see original paper]. This figure depicts the complete traditional design workflow from conceptual design to final drawing archiving. In this conventional model, architecture, structure, and MEP disciplines only exchange information at designated review points, with minimal horizontal data transmission between specialties. Most information exists as 2D CAD drawings and text documents, which cannot comprehensively reflect design data status, leading to information loss during transfer.

Three fundamental problems emerge in the traditional design model: (1) **Information flow limitations**: Information extraction occurs only at rigid design milestones, with virtually no horizontal data transmission between disciplines. The reliance on planar CAD drawings and documents as information carriers fails to fully represent design data status, causing information loss. (2) **Professional collaboration barriers**: Clear task divisions and rigid, stage-based design patterns create severe disconnections between architecture, structure, and MEP disciplines. Coordination requires formal consolidation meetings, which are time-consuming and inefficient. (3) **Process management challenges**: The severe fragmentation between disciplines and design phases forces design managers to extract progress information from milestone nodes based on experience. The need for repeated, large-scale information extraction compromises real-time information sharing, introducing delays that restrict collaborative work and cause multiple redesign cycles, ultimately impacting overall design progress.

1.2 Coordination Issues Among Construction Participants

Utility tunnel construction information encompasses all data generated throughout the construction process, while information flow represents the communication channels established among participants to address information asymmetry. The construction process includes pre-construction preparation (design site briefing), implementation (quality, schedule, and safety management), and final acceptance, involving multiple stakeholders such as owners, designers, supervisors, and contractors, along with massive amounts of construction information. Based on this information, we developed the traditional utility tunnel construction flowchart shown in [Figure 2: see original paper].

Analysis of this traditional construction model reveals three key deficiencies: (1) **Information carrier limitations**: The entire construction process relies on 2D CAD drawings for communication, creating difficulties for owners and contractors and making design issues difficult to detect, thereby increasing construction risks. (2) **Stage transmission problems**: The linear transmission between preparation, implementation, and acceptance phases lacks feedback mechanisms, causing issues from design briefings to propagate into construction phases, resulting in delayed problem identification and resolution. (3) **Partici-**

pant coordination gaps: As shown in [Figure 2: see original paper], designers, supervisors, and owners have insufficient participation during implementation, with no effective communication channels established among them. Additionally, various trades within the contractor operate in mechanical series without collaborative coordination.

1.3 Interface Issues Between Design and Construction Units

The transition from utility tunnel design to construction represents the transformation from conceptual design to physical infrastructure. Based on the work content of both phases, we mapped their interface as shown in [Figure 3: see original paper], revealing that construction drawing delivery serves as the sole information carrier between phases, with design information flowing unidirectionally from designers to contractors through 2D CAD drawings.

This designer-led model creates unidirectional information flow from design to construction, causing design defects to accumulate in the construction process. Such defects not only impact construction progress but also increase project costs. Three main shortcomings exist in this traditional interface: (1) **Constructability issues**: The one-way information flow means designers lack sufficient practical construction experience, reducing design constructability. Problems are only discovered during construction, causing significant time delays. (2) **Design-construction separation**: The two entities rely solely on 2D drawings for information transfer, which cannot completely convey design intent, maintaining their relative isolation. (3) **Contractor lag**: Since contractors receive drawings only after completion, they must start from scratch to understand design intent, wasting time and potentially leading to the problems mentioned above.

2 BIM-Based Optimization Models for Integrated Design-Construction

2.1 BIM-Based Design Coordination Optimization Model

Collaborative design in building engineering refers to a multi-disciplinary cooperative work model where various design specialties and managers work on a unified platform (central file) to achieve real-time information sharing and design efficiency, aiming to resolve design conflicts caused by poor discipline integration [9]. Addressing the design coordination issues identified in Section 1.1, we propose a BIM-based optimization that synchronizes design progress information through a utility tunnel BIM central file, allowing disciplines to extract reference data as needed. This breaks the conventional stage-based design pattern and rigid consolidation nodes, establishing the BIM-based collaborative design model shown in [Figure 4: see original paper].

In this model, the three major design disciplines (architecture, structure, and MEP) establish bidirectional data transfer channels with the utility tunnel BIM central file through synchronization and sharing. Disciplines also interlink to form an inter-disciplinary collaboration mechanism, while design managers review design outcomes by accessing the central file. As design progresses, the BIM model continuously improves. Upon approval from the design review department, a BIM drawing issuance command is executed, completing the design task. Compared with traditional methods, this approach enables disciplines to start essentially simultaneously, with structure and MEP disciplines beginning earlier relative to architecture. The horizontal and vertical information flow pattern reduces design cycles, minimizes information transfers, and embeds inter-disciplinary collaboration throughout the entire process, enabling immediate detection, feedback, and resolution of design defects, significantly improving collaborative efficiency.

2.2 BIM-Based Construction Coordination Optimization Model

Coordinated construction refers to the real-time collection and processing of construction information and data by management teams throughout the project lifecycle, establishing communication channels among all participants and trades to break "information silos" and improve construction management coordination efficiency [10]. The construction phase is the longest, most complex, and most personnel-intensive stage in a utility tunnel' s lifecycle, directly impacting project efficiency, schedule, cost, and quality [11-12]. Addressing the traditional construction issues identified in Section 1.2, we connect all utility tunnel project participants through a BIM building information model, establishing the information flow paths and collaborative work patterns shown in [Figure 5: see original paper].

In this BIM-based construction coordination model, designers first deliver the completed utility tunnel BIM model to the contractor and organize all participants for design briefing using the model. Identified issues are fed back into the BIM model for revision and improvement. Contractors then develop a BIM-based construction tracking model for real-time supervision of the implementation process, which designers, supervisors, and owners can access to monitor construction status. During final acceptance, this model serves as a reference data model for inspection. Compared with traditional methods, the BIM model permeates the entire construction process from design briefing through implementation to acceptance, enabling deep information exchange and collaborative work among all participants based on the BIM information model. This approach weakens construction stage boundaries and achieves organic integration of design delivery, implementation, and acceptance. Construction managers can use BIM technology to track progress in real-time, predict and preemptively address coordination issues among participants, and utilize the information sharing capabilities of BIM to effectively connect internal divisions within owner, designer, and contractor organizations, enabling better project understanding and collaborative work.

2.3 BIM-Based Design-Construction Integration Optimization Model

To address problems caused by the traditional separation of design and construction, we introduce BIM technology into the design-construction interface process, using the BIM utility tunnel information model as a bridge to establish the design-construction interface model shown in [Figure 6: see original paper]. Unlike traditional interfaces, the BIM model enhances bidirectional information transfer between construction and design, enabling contractors to better understand design intent through 3D visualization and achieve seamless integration.

In this BIM-based design-construction interface model, designers deliver their 成果 to the construction phase as a BIM utility tunnel model. All participants review the design model during briefing and feed back non-compliant elements through the model to design management, achieving data synchronization and information sharing with the design-phase BIM central file. During implementation, contractors can reflect constructability issues back to designers through the construction tracking model. This interface model, mediated by the designer' s BIM central file, achieves seamless design-to-construction transition. Design outcomes no longer flow irreversibly to construction but achieve deep integration through the BIM model, blurring boundaries between phases and enabling early contractor involvement in design. This accelerates understanding of design intent and improves constructability while reducing rework.

3 Case Study

The utility tunnel project in Bowang District, Maanshan City, was planned to support the new district' s development and enhance regional comprehensive strength. The project includes 24 kilometers of utility tunnels along Liaohe Road, Haihe Road, and other sections, with a total investment of approximately 2 billion RMB. Its extensive layout, massive engineering information, and numerous participants distinguish it from conventional building projects. The adoption of an EPC general contracting model institutionally guarantees design-construction integration, while comprehensive BIM application facilitates coordination.

During implementation, designers used BIM technology throughout to develop architectural, structural, and MEP models. From the initial design stage, intra-disciplinary information was shared through file linking, enabling cross-referencing among plans, elevations, and sections. Furthermore, inter-disciplinary collaboration through central file extraction identified and self-corrected 714 issues including node collisions (pipelines conflicting with architecture), unreasonable architectural designs (overly small chamber corners), and improper pipeline arrangements. This enabled early problem resolution. As design progressed, the utility tunnel BIM central file continuously improved ([Figure 7: see original paper]), and real-time monitoring plus final review by the design audit department reduced redesign cycles for tunnel nodes from over 10 to just 1, shortened design periods from 7 days to 3 days, and significantly reduced design costs.

However, since the project still employed the traditional design-construction separation model (DBB) rather than having contractors participate in model development under EPC leadership using the BIM central file, constructability issues persisted. As shown in [Figure 8: see original paper], contractors discovered during construction model development that doors and windows in tunnel node stairwells were positioned too low, exposing continued constructability deficiencies. Additionally, contractors required extra time to comprehend design intent from the model, potentially causing incomplete information transfer and erroneous construction scheduling.

During construction, contractors developed a digital construction model based on the designer's BIM 成果 and used Navisworks construction simulation technology ([Figure 9: see original paper]) to optimize sequencing among excavation, concrete, rebar, formwork, hoisting, transportation, and procurement departments, enabling rational construction planning and methodology. The digital construction model tracked the entire construction process, collecting site information and summarizing it digitally within the model. Through the BIM-based construction coordination model, this information was shared with owners, designers, and supervisors, increasing stakeholder participation, reducing changes, shortening schedules, and lowering costs.

In this project, the EPC general contractor integrated the designer' s BIM central file with the contractor' s construction model. Although complete model fusion was not achieved, a prototype BIM-based design-construction integration collaboration mechanism was established, creating a new framework for external reporting, internal high-efficiency coordination, and centralized information management. Practice demonstrates that these three optimization models and collaboration mechanisms effectively improve utility tunnel construction management efficiency, accelerate information exchange, and reduce construction costs.

Conclusion

To address the long-standing separation between design and construction in utility tunnel projects and improve integration efficiency, this study analyzed problems in traditional design workflows and construction management models, applying BIM technology to establish three optimization models:

1. A design coordination optimization model that transforms rigid traditional workflows, enabling information sharing and collaborative work among architecture, structure, and MEP disciplines.
2. A construction coordination optimization model that blurs stage boundaries, facilitating integration across construction phases and improving stakeholder coordination.
3. A design-construction interface model that breaks the design-construction separation, advancing contractor involvement into the design phase to in-

crease mutual participation, improve constructability, and reduce rework.

The integration of these three BIM-based optimization models into a unified collaboration mechanism was validated through a real project case. Practice proves these models are operable and provide valuable references for utility tunnel project development.

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