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Research On the Potential Threat and Risk Management of Existing HDD Boreholes to Urban Security

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Abstract

Existing horizontal directional drilling (HDD) boreholes, as legacy issues from urban underground space development and utilization, are increasingly posing significant potential threats to urban safety. This paper systematically analyzes the threat categories and impact mechanisms of existing HDD boreholes on urban safety, with particular focus on their induced ground subsidence, structural damage to buildings, and risks to underground pipeline integrity. Building upon mechanistic analysis of these threats, we propose a comprehensive assessment framework encompassing risk identification, evaluation, and control measures, designed to provide theoretical support for safety risk management of existing HDD boreholes in urban areas. The research demonstrates that existing HDD boreholes indeed constitute substantial urban safety hazards, necessitating immediate implementation of effective risk prevention and mitigation strategies. These findings emphasize the critical importance of enhancing safety management for existing HDD boreholes while offering valuable insights for optimizing urban safety assurance systems.

Keywords

Horizontal Directional Drilling (HDD), Boreholes, Urban Safety, Risk Identification, Risk Assessment, Risk Control.

1. Introduction

With accelerated urbanization and deepening underground space development, Horizontal Directional Drilling (HDD) technology has been widely adopted in urban infrastructure construction [1]. However, existing HDD boreholes generated during its application—legacy issues of urban underground space utilization—are increasingly emerging as critical factors affecting urban safety. These residual HDD cavities may trigger ground subsidence, structural damage to buildings, and safety risks to underground pipelines, posing potential threats to urban security.

This study aims to systematically analyze the threat types and impact mechanisms of existing HDD boreholes on urban safety, and proposes a comprehensive framework for potential threat assessment encompassing risk identification, evaluation, and control based on threat mechanism analysis. Through this research, we seek to provide theoretical support for safety risk management of existing urban HDD boreholes and offer reference insights for enhancing urban safety assurance systems. The research employs an integrated methodology combining literature review, case studies, and theoretical modeling. Firstly, the formation mechanisms of existing HDD boreholes and their safety implications are investigated through systematic literature analysis. Subsequently, real-world case studies are conducted to examine urban safety issues caused by these boreholes. Finally, a methodological framework for potential threat assessment is developed through mechanism analysis, accompanied by corresponding risk control strategies.

2. The Formation of Existing HDD Boreholes and Their Implications for Urban Safety

2.1. Formation mechanisms of existing HDD boreholes

HDD is a trenchless method for underground pipeline installation, which involves drilling a pilot borehole from the surface, gradually enlarging the borehole diameter, and finally pulling the pipeline into the completed borehole [2] (see Fig. 1).

Fig. 1 Schematic diagram of HDD underground pipeline installation method

This technology has been widely adopted in urban infrastructure construction due to its advantages, such as minimal environmental impact on the ground and rapid construction speed [3]. However, during the application of HDD technology, existing cavities may form due to complex geological conditions, inadequate quality control during construction, and other factors. These cavities may include incompletely backfilled boreholes, voids caused by changes in geological conditions, and enlarged cavities resulting from construction quality issues.

The formation of existing HDD boreholes is attributed to a variety of complex causes, including: complex geological conditions, such as the presence of weak strata or karst development; inadequate quality control during construction, such as insufficient backfilling or excessive reaming; unreasonable design, such as improper cavity location selection or oversized borehole design; and inadequate post-construction maintenance and management, such as failing to promptly identify and address cavity enlargement issues.

2.2. Implications of existing HDD boreholes for urban safety

The impact of existing HDD cavities on urban safety is primarily reflected in the following aspects: First, these cavities may alter the distribution of underground stress, leading to ground subsidence and subsequently affecting the stability of surface structures and infrastructure. Second, the presence of cavities may change the flow direction of groundwater, impacting the distribution and utilization of groundwater resources [4]. Third, cavities may serve as pathways for the migration of underground pollutants, increasing the risk of groundwater contamination [5]. Finally, the existence of cavities may compromise the safe operation of underground pipelines, raising the risk of incidents such as pipeline ruptures and leaks [6].

The impact of existing HDD cavities on urban safety cannot be underestimated. By analyzing their causes, it is evident that the combined effects of these factors lead to the formation and persistence of existing HDD cavities, posing a potential threat to urban safety. To mitigate these risks, measures such as strengthening construction supervision, optimizing design, and improving maintenance management must be implemented.

3. Typology and Mechanistic Pathways of Urban Safety Hazards Induced by Existing HDD Boreholes

3.1. Typology of urban safety hazards induced by existing HDD boreholes

The threat posed by existing HDD (Horizontal Directional Drilling) cavities to urban safety primarily manifests in three aspects: ground subsidence, structural damage to buildings [7], and compromised integrity of underground pipelines [8]. These cavities may induce differential settlement through soil disturbance, generate stress concentrations that weaken building foundations, and create preferential pathways for utility corrosion or leakage–collectively forming a multi-hazard cascade that challenges urban resilience.

3.1.1. Ground subsidence

Ground subsidence stands as the most immediate and conspicuous threat arising from existing HDD boreholes. These subsurface voids disrupt underground stress distribution, inducing compressive deformation in overlying soil layers that propagates upward as surface subsidence. The settlement frequently exhibits spatial heterogeneity (termed differential settlement), generating ground fissures, localized collapse depressions (see Fig. 2), and other geomorphological disruptions that critically undermine infrastructure serviceability and pose existential risks to urban populations.

Fig. 2 Ground Subsidence Mechanisms Induced by Existing HDD Boreholes

3.1.2. Structural damage to buildings

Building damage is another important threat posed by existing HDD boreholes. Ground settlement and uneven settlement may lead to displacement and deformation of building foundation, and then lead to wall cracking, structural instability and other problems [9]. In severe cases, it can even cause the whole building to tilt or collapse, resulting in heavy casualties and property losses. In addition, the vibration caused by the boreholes may also cause damage to the structure of the building, especially in the event of natural disasters such as earthquakes, this damage may be further amplified.

3.1.3. Safety risk of underground pipeline

Underground pipeline security risk is another important threat to urban security posed by existing HDD boreholes. The existence of boreholes may change the stress state of underground pipelines and increase the risk of pipeline breakage, leakage and other accidents [10]. Especially near the hole, the line may deform or break due to stress concentration (see Fig. 3). In addition, the hole may also become a channel for underground pollutants to migrate, increasing the risk of pipeline corrosion. The combined effect of these factors may lead to the failure of the underground pipeline system, resulting in accidents such as gas leakage and water supply interruption, which seriously affect the normal operation of the city and the safety of residents.

Fig. 3 Damage to pipes caused by existing HDD boreholes

3.2. Impact mechanism of existing HDD boreholes on urban security

The existing mechanisms of HDD boreholes affecting urban security are complex and diverse, including mechanical mechanisms, hydrogeological mechanisms and chemical mechanisms. The mechanical mechanism mainly involves underground stress redistribution and soil deformation caused by boreholes [11]. The hydrogeological mechanism mainly involves the influence of pores on groundwater flow and formation permeability [12]. The chemical mechanism mainly involves the influence of pores on the migration and reaction of chemical substances in the formation [13]. These mechanisms often interact to determine the extent and scope of the impact of existing HDD boreholes on urban security.

3.2.1. Mechanical mechanism

The mechanical mechanism is mainly concerned with the effect of boreholes on the mechanical stability of surrounding soil and structure. The presence of HDD boreholes can alter the stress distribution of the formation, causing the following problems:

(1) Formation settlement: the formation of boreholes may lead to the redistribution of stress in the surrounding soil, which will lead to formation settlement. Such subsidence can cause damage to infrastructure such as surface buildings, roads and underground pipelines.

(2) Soil deformation: The soil around the hole may undergo plastic deformation or creep, especially in soft soil or loose strata. This deformation can lead to cracks or local collapses.

(3) Structural instability: If the hole is located near the foundation of a structure such as a building or bridge, it may affect the stability of the foundation and cause the structure to tilt or collapse.

3.2.2. Hydrogeological mechanism

The hydrogeological mechanism is mainly concerned with the influence of caverns on groundwater flow and formation permeability. HDD boreholes can change the path and speed of groundwater flow, which can cause the following problems:

(1) Groundwater seepage: the hole may become a channel for groundwater flow, changing the original groundwater flow pattern. This can lead to changes in the water table and affect the foundation stability of surrounding buildings.

(2) Increased formation permeability: The existence of boreholes may increase the permeability of the formation, making it easier for groundwater to penetrate into the surface or the foundation of the building, increasing the risk of collapse and liquefaction of the foundation.

(3) Water pollution: If the hole passes through the source of pollution or polluted strata, it may become a channel for the migration of pollutants, leading to groundwater pollution, and then affect the safety of urban water supply.

3.2.3. Chemical mechanism

The chemical mechanism mainly involves the effect of pores on the migration and reaction of chemical substances in the formation. HDD boreholes can change the chemical environment in the formation, causing the following problems:

(1) Chemical migration: Pores may become channels for the migration of chemical substances (such as heavy metals, organic matter, etc.), resulting in the diffusion of pollutants to the wider formation or groundwater.

(2) Formation chemical reaction: The existence of boreholes may change the REDOX conditions in the formation, triggering or accelerating some chemical reactions. For example, it may lead to the dissolution or precipitation of minerals in the formation, affecting the mechanical properties of the formation.

(3) Corrosive effect: If the hole passes through the formation containing corrosive substances, it may have a corrosive effect on the underground pipeline or the foundation of the building, reducing its service life and safety.

The above three mechanisms often interact with each other and jointly affect urban security. For example, subsidence caused by mechanical mechanisms may change the flow path of groundwater, which in turn affects the migration and reaction of chemical substances. Therefore, when assessing the impact of existing HDD boreholes on urban security, it is necessary to consider these mechanisms and take corresponding monitoring and governance measures.

4. Framework for Multi-Hazard Risk Assessment of Existing HDD Boreholes

To address the latent risks posed by existing HDD boreholes to urban safety, tthis study proposes an assessment method framework that includes risk identification, risk evaluation, and risk control (see Fig. 4).

(1) Risk Identification is the first step in the assessment process, aiming to comprehensively identify and describe the various risks that may arise from existing HDD boreholes. This stage primarily involves methods such as field surveys, geological exploration, and data analysis to collect information on the location, scale, and morphology of the boreholes, as well as their surrounding environment. The goal is to identify potential risk sources and risk receptors [14].

(2) Risk Assessment is the core component of the assessment framework and consists of two steps: risk analysis and risk evaluation. Risk analysis employs a combination of qualitative and quantitative methods to assess the likelihood of various risks occurring and the severity of their

consequences. Commonly used methods include Fault Tree Analysis (FTA), Event Tree Analysis (ETA), and numerical simulation. Risk evaluation involves classifying and ranking risk levels based on the results of risk analysis, in accordance with relevant standards and regulations, to provide a basis for subsequent risk control.

(3) Risk Control is the final step in the assessment framework, focusing on formulating and implementing effective risk mitigation measures. Based on the risk assessment results, different control strategies can be adopted, including risk avoidance, risk reduction, risk transfer, and risk acceptance. Specific measures may include hole backfilling and reinforcement, the establishment of monitoring and early warning systems, and the development of emergency response plans. After implementing risk control measures, continuous monitoring and evaluation are necessary to ensure their effectiveness, allowing for dynamic adjustments based on actual conditions.

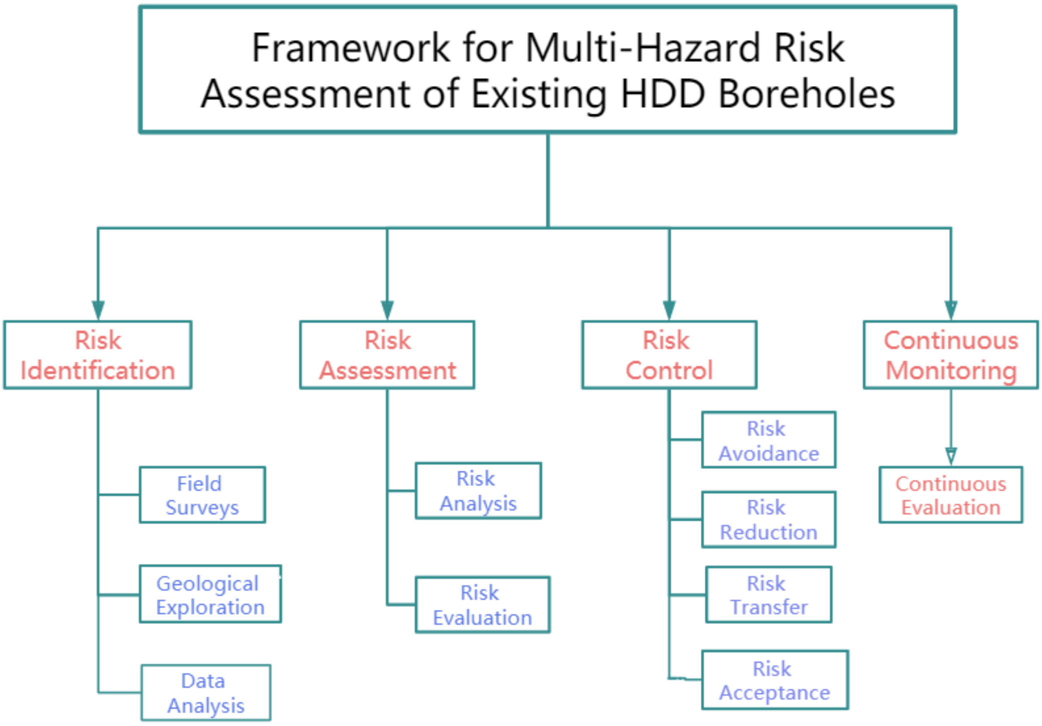

Fig. 4 Framework for Multi-Hazard Risk Assessment of Existing HDD Boreholes

The assessment framework proposed in this study not only considers the direct threats posed by existing HDD boreholes to urban safety but also accounts for potential secondary disasters and chain reactions they may trigger. Additionally, the framework emphasizes the integration of risk assessment and risk control, providing urban managers with a comprehensive and practical risk management tool.

5. Case study

5.1. Case Background

In order to verify the validity of the evaluation framework proposed in this study, we selected a typical case of existing HDD boreholes in a certain city for analysis. Located in the center of a city, the hole is about 1.0 meters in diameter and 8 meters deep, and was formed during an HDD construction five years ago. In recent years, there have been significant land subsidence and cracks in buildings in this area, which have aroused widespread concern among local authorities and residents (see Fig. 5).

5.2. Evaluation and treatment measures

Applying the assessment framework proposed in this study, we first carried out risk identification. Through site investigation and geological exploration, we found that the hole is located in a weak formation, surrounded by several high-rise buildings and important underground pipelines. The results of risk analysis show that the risk of ground settlement and building damage caused by the hole is high, and there is a certain risk of underground pipeline safety. Based on these analysis results, the risk rating for the hole is "high".

Fig. 5 Ground settlement and building damage

In view of this high risk level, we put forward the corresponding risk control measures. Firstly, it is recommended to backfill the boreholes immediately to stabilize the underground stress distribution. Secondly, it is suggested to install monitoring equipment in surrounding buildings and underground pipelines to establish real-time monitoring and early warning systems [15]. Thirdly, it is suggested to make a detailed emergency plan, including personnel evacuation, traffic control and other measures; Finally, it is recommended to strengthen long-term monitoring and management in the region, regularly assess the risk situation, and timely adjust control measures.

Through this case study, we verify the effectiveness of the evaluation framework proposed in this study in practical applications. The framework can not only comprehensively identify and assess the potential threat of existing HDD boreholes to urban security, but also provide a scientific basis for the development of targeted risk management measures. This case also further highlights the importance and urgency of strengthening the security management of existing HDD boreholes.

6. Conclusion

This paper systematically analyzes the threat types and impact mechanisms of existing HDD boreholes on urban security, proposes a potential threat assessment method framework including risk identification, assessment and control, and verifies the effectiveness of this framework through case analysis. The results show that the existing HDD boreholes pose a significant threat to urban security, which is mainly reflected in three aspects: ground subsidence, building damage and underground pipeline safety risk. The mechanisms of these threats are complex and diverse, involving many aspects such as mechanics, hydrogeology and chemistry. The proposed evaluation method framework provides theoretical support and practical tools for the security risk management of existing HDD boreholes in cities. The framework emphasizes the organic combination of risk assessment and risk control, which can help city managers to comprehensively identify risks, scientifically evaluate risks, and effectively control risks.

Based on the research results, we propose the following suggestions: (1) Urban management departments should attach great importance to the safety management of existing HDD boreholes and incorporate them into the urban safety risk prevention and control system; (2) A monitoring and early warning system for existing HDD boreholes should be established and improved to achieve early risk identification and early warning; (3) Relevant regulations and standards should be formulated and improved to regulate the management and maintenance of existing HDD boreholes; (4) Relevant technical research and personnel training should be strengthened to improve the scientific and effective risk management of existing HDD boreholes.

This paper provides a new idea and method for the security risk management of existing HDD boreholes in the city, which is of great significance for the improvement of urban security system. Future research can further explore the impact of existing HDD boreholes in different types and different environments on urban security, as well as more refined and intelligent risk management methods to provide more comprehensive and reliable protection for urban security.

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