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Review article

Underground Granaries: Performance, Mechanisms and Technological Challenges

Jinping Yang[1,2], Hehe Wang[1], Peizhen Li[2]*

[1] College of Civil Engineering, Henan University of Technology, Zhengzhou 450001, China
[2] Department of Disaster Mitigation for Structures, Tongji University, Shanghai 200092, China

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Abstract:
Amid increasing geopolitical uncertainty, extreme climate events, and escalating land scarcity, Underground Granaries (UGS) have reemerged as a crucial solution that balances grain storage security with efficient spatial utilization. Originating from early subsurface storage practices, UGS have evolved through various stages, with the current UGS 3.0 stage characterized by prefabricated construction, advanced waterproofing materials, and optimized environmental regulation. Despite significant progress in engineering technologies, unresolved complex coupling challenges persist, including the interaction between structure and soil, long-term performance of waterproofing systems, and the regulation of multiphysics coupling within storage environments. Furthermore, existing research lacks a holistic framework for multi-system integration. To address these challenges, this review introduces the concept of the "UGS generational framework (1.0–4.0)", outlining the technological evolution and integration logic of UGS. It systematically analyzes the shift from monolithic cast-in-place structures to prefabricated composite systems, as well as their coupling with geological conditions. The review also evaluates the connection design and durability of plastic–concrete (PC) waterproofing systems, and discusses the progression and technical challenges of environmental regulation strategies, ranging from passive geothermal utilization to active ventilation systems. Finally, the role of digital modeling and intelligent monitoring in the UGS 4.0 stage is explored, aiming to provide a clear technological roadmap and analytical framework for future UGS integration research and engineering applications.

1 Introduction

Amid increasing geopolitical uncertainty, extreme climate events, and disruptions in supply chains, the strategic significance of national food security has been increasingly emphasized (Pasqualone, 2025; Shahinyan et al., 2024). Simultaneously, accelerating urbanization and escalating land scarcity have driven the strategic relocation of food storage infrastructure into underground spaces (Qian and Guo, 2015). As a facility type offering inherent advantages such as thermal insulation, concealment, and efficient spatial utilization, Underground Granaries (UGS) have recently garnered renewed attention in both policy agendas and engineering practices.

Subterranean grain storage represents one of the earliest forms of human utilization of underground space. Archaeological findings indicate that purpose-built underground granaries for food storage date back over 7,000 years. As early as the Yangshao culture period, around 5000–6000 BCE, China had already developed bag-shaped grain storage pits characterized by narrow openings and wide bases(Qian and Guo, 2015; Yu, 2024). In 605 CE, during the Sui Dynasty, the Hanjia Granary and Xingluo Granary in Luoyang marked the initial establishment of a state-level underground storage system in China (Qian and Guo, 2015; Hou, 2022). Globally, underground grain storage evolved independently across various regions-from bottle-shaped pits in the Middle East and North Africa, to traditional underground cellars in sub-Saharan Africa and India (Qian and Guo, 2015; Abdurahman, 2023), and to clusters

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* Corresponding author.
E-mail address: jping_yang@haut.edu.cn (Yang JP); 18438302536@163.com (Wang HH); lipeizh@tongji.edu.cn (Li PZ)

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Fig. 1 Hanjia granary site (Yu, 2024)

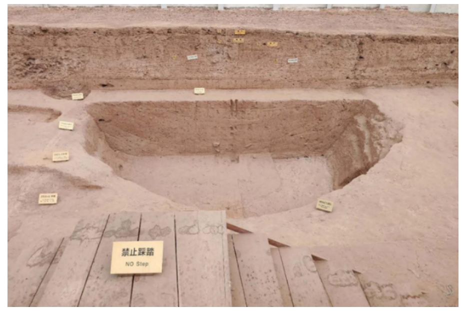

Fig. 2 Liyang granary site (Hou, 2022)

Fig. 3 Grain pit near Fort St. Elmo, Valletta(Pasqualone, 2025).

Fig. 4 Floriana grain pit site (Pasqualone, 2025)

of underground silos in the Mediterranean, extensively documented by Valls and others (Valls et al., 2015). Despite their rudimentary structures and diverse construction techniques, these early systems effectively leveraged the insulating and humidity-stabilizing properties of the soil, which helped slow grain degradation and mitigate infestations by insects and mold (Pasqualone, 2025; He and Xiao, 2002). These empirically driven storage practices laid the foundation for modern underground storage prototypes and can be categorized as UGS 1.0 — a passive storage phase driven by local terrain and practical experience. As shown in Figs. 1 through 4, common historical forms of underground granaries include oval, bag-shaped pits, stone-lined chambers, and rectangular rammed-earth silos. These configurations reflect early adaptive strategies for ventilation, moisture control, and thermal insulation, representing typical examples of earth-or stone-excavated UGS 1.0 systems.

By the mid to late 20th century, the development of underground granaries transitioned to a more systematic approach, driven by military preparedness and national food reserve strategies. For instance, during World War II, the Argentine government constructed 1,474 underground granaries, each with a storage capacity of approximately 600 tons, aimed at large-scale, long-term grain preservation (Qian and Guo, 2015). In China, a series of defense-oriented underground granaries were built during the 1960s and 1970s, marking the onset of continuous technological development and engineering exploration (He and Xiao, 2002). During this period, monolithic cast-in-place reinforced concrete became the dominant structural system(Xiong et al., 2015, 2016; Jin et al., 2020), establishing the UGS 2.0 stage—characterized by the adoption of modern engineering techniques to construct standardized grain storage facilities. However, issues such as long construction durations, high costs, and limited adaptability gradually became apparent. With the advent of prefabricated construction, modular structural systems, and advanced waterproofing materials, the UGS 3.0 stage emerged. This phase primarily addresses the challenges of UGS 2.0, such as structural coordination, waterproof integrity, and construction efficiency(Wang et al., 2019, 2021, 2019, 2021). Emphasizing industrialized construction, joint detailing, and integrated waterproofing systems, UGS 3.0 has become the primary focus of ongoing research and engineering practice.

Despite advancements in technical systems, underground granaries continue to face three interrelated and complexly coupled challenges in critical domains:

(1) Structural resilience and interaction with rock mass: Although prefabricated structures offer significant advantages in construction efficiency and standardization, the stability of structural joints and their interaction with surrounding rock under extreme loads, seismic events, and long-term operational conditions require further investigation(Zhang et al., 2024, 2021, 2022; Jin et al., 2023).

(2) Multi-barrier waterproofing and durability control: The infiltration pathways at the groundwater-structure interface are highly complex. Current waterproofing systems are still in the exploratory stage regarding long-term durability, the coupled effects of thermal-physical properties of materials and structural deformation, as well as intelligent monitoring and self-healing mechanisms(Zhang et al., 2020, 2023; Chuai et al., 2021; Zhang et al., 2022).

(3) Multiphysics coupling regulation of the grain storage environment: The interior of an underground granary forms a complex “grain storage ecosystem” involving multiphysical interactions among the “thermal-moisture-gas-biological” fields. Existing studies primarily focus on single or dual-field analyses, lacking comprehensive modeling of the overall cou-

pling mechanisms within the ”grain-granary-environment” system(Dunkel, 1995; Zhang et al., 2023; Jin et al., 2025; Wang et al., 2016).

The root of these challenges lies in the persistent tendency to treat structural systems, waterproofing, and storage environments as independent domains for optimization, leading to a lack of cross-system collaborative design and multiphysics coupling regulation frameworks. To address this gap, this review introduces and systematically discusses the “Four-Generation Framework of Underground Granaries (UGS 1.0–4.0)” with the aim of establishing a comprehensive understanding of UGS evolution from both vertical (historical development) and horizontal (system integration) perspectives, as illustrated in Fig. 5.

This framework consists of four distinct developmental stages:

(1) UGS 1.0: Characterized by early storage systems based on geographical conditions and empirical judgment;

(2) UGS 2.0: Defined by structurally sound and standardized underground granaries constructed using cast-in-place reinforced concrete;

(3) UGS 3.0: Marked by engineering optimization through the integration of prefabricated and composite structures with advanced waterproofing materials;

(4) UGS 4.0: A forward-looking phase, exploring multiphysics coupling mechanisms, system integration, intelligent regulation, and lifecycle resilience management, with the goal of creating a “living ecosystem”-style intelligent geological storage system.

In summary, this review adopts the “Four-Generation Framework” as its central narrative to trace the technological evolution of the three core subsystems—structure, waterproofing, and environment—and to explore their paradigm shift toward an intelligent ecological model. Building upon this foundation, it further envisions the development trajectory of UGS 4.0, driven by digital twin technologies, AI-based sensing, and integrated system design.

2 Evolution and integration of underground granary structural systems

The evolution of underground granary structural systems reflects significant advancements in engineering, driven by the complexities of subterranean mechanical environments. Current research highlights two major design trends: first, a shift from focusing solely on isolated structural components to considering the integrated interactions between the structures and the surrounding geological conditions; second, a growing emphasis on construction efficiency, durability, and resilience, alongside the traditional focus on strength and stiffness. This chapter systematically examines the progression of load characterization, structural typology, and key technologies across the developmental stages of Underground Granaries (UGS 1.0 to UGS 3.0).

2.1 Evolution of structural systems: from monolithic cast-in-place to prefabricated composite

To address the challenges posed by complex underground environments and enhance construction efficiency, the structural systems of underground granaries have progressively transitioned from traditional monolithic cast-in-place methods to prefabricated composite configurations. These varying structural forms exhibit substantial differences in terms of material selection, construction complexity, degree of mechanization, and applicability. Tab.1 presents a comparative analysis of the structural characteristics, advantages, and limitations of several typical underground granary types, illustrating the core trajectory of structural system evolution.

Monolithic cast-in-place reinforced concrete (RC) silos were extensively used in early modern underground granaries due to their structural integrity and the relatively mature construction techniques available at the time. However, as project scales expanded and construction demands became more stringent, this structural form revealed several limitations, including extensive wet operations, prolonged construction timelines, high costs associated with formwork and support systems, and difficulties in leakage repair, as shown in the sectional diagram of the underground granary in Fig. 6 (Wang et al., 2019). In response to these challenges, Xiong et al.(Xiong et al., 2015, 2016) introduced a soil pressure estimation method based on empirical measurements and theoretical analysis, emphasizing the significant impact of edge constraints on structural stress distribution and recommending refined modeling using the finite element method. Subsequently, Jin et al. (Jin et al., 2020), through engineering tests and numerical simulations, validated the typical stress distribution patterns along the depth of silo walls. To overcome the limitations of conventional designs, Zheng et al.(Zheng et al., 2009) proposed a new configuration involving rectangular ring silos, identifying critical issues such as roof deflection and stress concentration in edge columns, thus contributing to structural innovations in silo design.

In response to the limitations of traditional structures regarding construction efficiency and cost-effectiveness, researchers have increasingly shifted towards new systems incorporating prefabrication and composite structural designs. Wang et al. (Wang et al., 2019) proposed an innovative design approach for underground granaries based on prefabricated technology and steel-concrete composite structural systems. The central concept of this approach involves prefabricating key components—such as granary wall panels—in a factory setting and assembling them quickly on-site, thereby reducing construction time, minimizing wet operations, and enhancing quality control. The outcomes of this approach are illustrated in Fig. 7.

A series of studies have systematically evaluated the mechanical performance and applicability of prefabricated steel-concrete composite structures for underground granaries. In structural load-bearing investigations, Wang et al. (Wang et al., 2021) confirmed the validity of the equivalence principle in prefabricated steel-concrete composite silo walls through comparative simulations and experimental testing. Zhang et al. (Zhang et al., 2023, 2025) proposed an equivalent joint design method and validated its structural equivalence under joint stiffness requirements through full-scale tests and numerical simulations. For specific new granary types, such as semi-underground, double-layered shallow circular granaries, Jin et

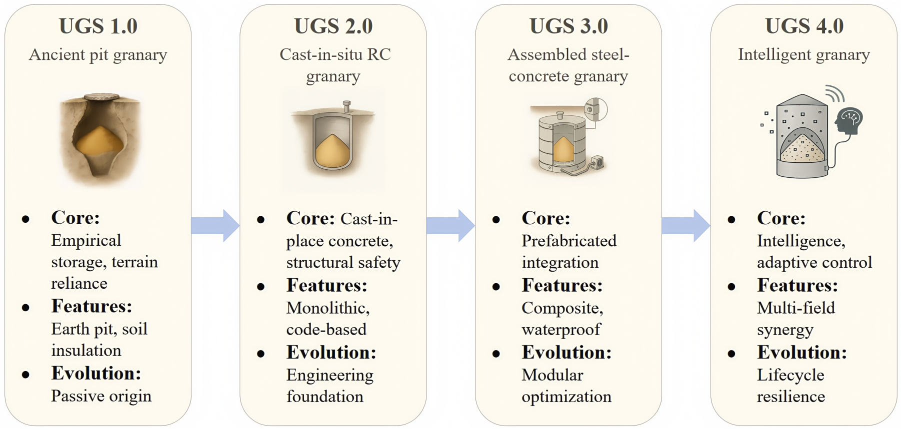

Fig. 5 Four-generation pedigree of underground granaries (UGS 1.0–UGS 4.0)

Tab. 1 Comparison of Several Typical Underground Granaries (Wang et al., 2019)

Serial No.	Structural Type	Construction Materials	Main Advantages	Main Disadvantages
1	Earthen Kiln Granary	Soil	Lowest cost, simple structural design	Small capacity, large footprint, outdated technology, low mechanization
2	Cave Granary	Stone, Reinforced Concrete	Low cost, simple structural design, sturdy	Small capacity, large footprint, prone to condensation, outdated technology, low mechanization
3	Bell-shaped Granary	Brick, Reinforced Concrete	Low cost, easy construction	Small capacity, high soil condition requirements, immature technology
4	Conventional Blasting-formed	Soil	Low cost, easy construction	Long construction period, high cost, poor waterproofing
5	Synchronous Blasting-formed	Concrete	Low cost, easy construction, high efficiency	Long construction period, high cost, poor waterproofing
6	Rectangular Shaft-enclosed	Reinforced Concrete	Less affected by soil conditions, small footprint, large capacity, high degree of mechanization	Long construction period, high cost, poor waterproofing
7	Circular Shaft-enclosed	Reinforced Concrete	Less affected by soil conditions, small footprint, huge capacity, high degree of mechanization	Long construction period, high cost, poor waterproofing
8	Pile-enclosed Composite	Reinforced Concrete	Less affected by soil conditions, large capacity, advanced technology, high degree of mechanization	Long construction period, high cost, poor waterproofing
9	Large-diameter Reinforced Concrete	Reinforced Concrete	Less affected by soil conditions, large capacity, advanced technology, high degree of mechanization	Long construction period, high cost, poor waterproofing
10	Prefabricated Steel Plate-Concrete Composite	Steel Plate, Reinforced Concrete	Less affected by soil conditions, fast construction, good waterproofing, low comprehensive cost, large capacity, advanced technology, high degree of mechanization	High technical difficulty

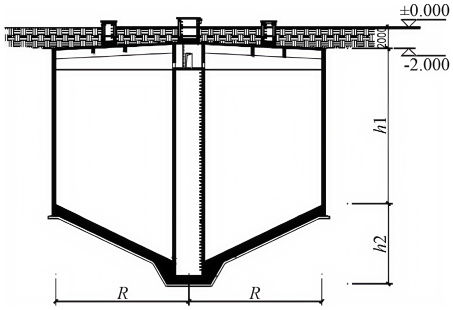

Fig. 6 A large diameter reinforced concrete underground granary (Wang et al., 2019).

Fig. 7 Implementation effect of prototype test (Pan et al., 2019)

al. (Jin et al., 2023; Jin et al., 2024) conducted mechanical analysis during the construction phase and evaluated their static performance. Regarding support structures, Pan et al. (Pan et al., 2019) combined finite element modeling with full-scale field testing to verify the stability and applicability of a novel reusable rigid-flexible composite support system for underground granaries. Collectively, these studies have established a theoretical foundation for the design of modern prefabricated underground granaries, marking a shift from traditional cast-in-place construction to a more efficient and controlled industrialized prefabrication approach.

2.2 Key technologies of prefabricated composite structures: component performance and joint connections

As underground granary structural systems evolve toward industrialized construction, prefabricated composite structures have garnered increasing attention for their potential to enhance construction efficiency. Concurrently, the engineering reliability of both component performance and joint connections has become a central focus of research. Related studies primarily address three key areas: load-bearing evaluation at the component level, optimization of joint design, and system-level integrated adaptability analysis.

In terms of component performance, the steel-concrete composite granary wall, as the primary load-bearing element of prefabricated underground granaries, plays a crucial role in ensuring overall structural integrity through its stability and load-carrying capacity. Wang et al. (Wang et al., 2021) investigated the axial compression behavior of these components using simulated specimen loading and nonlinear finite element analysis, uncovering the mechanisms of load transfer, deformation progression, and failure development. They identified concrete strength as a critical factor affecting both initial stiffness and ultimate bearing capacity. For theoretical modeling, Chuai et al. (Chuai et al., 2021) derived elastic stress formulas for double-layer cylindrical shells composed of dissimilar materials, based on elasticity theory, and validated them through finite element analysis. This provided a useful computational tool for the preliminary design and strength assessment of composite structures. In terms of non-primary load-bearing connections, Liu et al. conducted bond performance tests between steel plates and aerated concrete blocks, examining the influence of varying adhesive interface areas on bond strength.

As a critical component ensuring structural continuity and coordinated response, joint connections play a pivotal role in the overall performance of prefabricated systems. Wang et al. (Wang et al., 2019), through finite element simulations and full-scale testing, validated the "equivalence" hypothesis regarding the load-bearing and deformation capacities of prefabricated joints, proposing that these joints can be treated as equivalent to cast-in-place structures, thus providing a theoretical foundation for the equivalent design of prefabricated systems. Building on this, Zhang et al. (Zhang et al., 2023, 2025) introduced a joint design method based on "equivalent stiffness" and confirmed its applicability and reliability for composite granary wall systems through full-scale experiments.

To further optimize joint configurations, researchers have proposed several innovative solutions. Zhang et al. (Zhang et al., 2021) introduced the use of trapezoidal load-transferring steel plates as vertical connecting elements, which enhance the flexural capacity and yield performance of joints. In terms of structure–function integration, this component was incorporated into the waterproofing interface to create a vertically integrated structure-waterproof joint, with experimental results demonstrating its dual functionality in both structural load-bearing and interface compatibility (Zhang et al., 2023). To simplify construction and reduce welding complexity, a hybrid bolted–welded connection was proposed. Its performance was validated through tests and simulations, showing good ductility and coordinated deformation capacity while maintaining adequate load resistance (Zhang et al., 2024). Further parametric analysis identified concrete strength, steel plate strength, and the thickness of the internal waterproof steel plate as key factors influencing the safety margin of joints, providing an optimized basis for engineering design (Zhang et al., 2024). Collectively, these studies provide critical support for the systematic optimization of joint construction in prefabricated underground granaries, as shown by the on-site construction in Fig. 8.

Overall, the key technological framework for prefabricated underground granaries has gradually been established, incorporating the mechanical behavior of structural components, optimization strategies for joint connections, and integrated design approaches that link structure, construction, and waterproofing. This system offers essential technical support for efficient construction and reliable operation under complex service conditions.

Fig. 8 On-site construction of prefabricated underground granary (Zhang et al., 2021, 2024)

2.3 Coordination between structure and geological environment: anti-floating, seismic resistance, and stability

The structural safety of underground granaries is influenced not only by their construction and materials but also by the complex surrounding geological environment. Over the course of their service life, the primary external loads—including groundwater buoyancy, seismic excitation, and earth pressure—induce response behaviors that differ significantly from those of above-ground structures. Recently, greater emphasis has been placed on integrating geological conditions, structural characteristics, and construction factors into unified design and analysis models, thereby establishing a design framework based on soil-structure interaction.

2.3.1 Anti-floating design and buoyancy control

Due to their considerable burial depth, high foundation stiffness, and strong structural airtightness, underground granaries are susceptible to significant buoyant forces, especially in situations such as rising groundwater levels or rainfall infiltration. Traditional anti-buoyancy design strategies typically rely on increasing the structure's self-weight or installing rigid capping elements, such as anti-uplift beams, to enhance resistance (Wang et al., 2013). However, several studies have shown that the friction between the structure and backfill soil, along with the self-weight of the soil mass, also play a significant role in the overall buoyancy resistance.

Liu et al. (Liu et al., 2019, 2021) conducted buoyancy tests on the backfill material, known as "2:8 lime soil" and introduced the concept of a "warning water level" as an early indicator for anti-uplift safety. Their findings also emphasized that variations in interface friction, under different working conditions, significantly affect structural stability. Fig. 9 illustrates the experimental setup for the 2:8 lime soil, while Fig. 10 presents a silo model of an underground granary backfilled with this material in a practical application. Zhang et al. (Zhang et al., 2019), through systematic investigations of underground silos embedded in sandy and clayey soils, proposed the Floating Buoyancy Coefficient (FBC) to assist in more economical and safer parameter selection for structural design. Xu et al.(Xu and Yu, 2021) further explored the soil-structure interaction mechanisms, revealing the underlying processes of soil deformation and interface slip that contribute to buoyancy reduction. Collectively, these studies represent a paradigm shift in anti-uplift design philosophy, moving from a "structure-only resistance" model to a more integrated "structure–soil collaborative" approach.

2.3.2 Seismic response and seismic performance

Seismic ground motions, as multidimensional and non-stationary loads, induce dynamic response characteristics in underground granaries that differ fundamentally from those observed in above-ground structures. Due to the combined effects of lateral confinement from surrounding soil and delayed wave propagation, underground structures may experience complex input patterns, including traveling waves and multi-directional load combinations during strong earthquakes. Zhang et al. (Zhang et al., 2025), through numerical simulations, demonstrated that seismic waves incident from various directions significantly influence the acceleration and stress distribution within silo structures. The response is particularly intensified under coupled excitations, suggesting that the coupling effects of multi-directional seismic inputs must be carefully considered in structural design.

To further enhance the seismic resilience of underground granaries, recent studies have introduced the concept of the Nonlinear Energy Sink (NES), aiming to establish a coupled energy-dissipation system between the silo and the surrounding soil. Yang et al.(Yang et al., 2025) developed a vibration reduction model based on NES theory, where the soil medium is modeled as a nonlinear elastic boundary. Their research demonstrated that this approach can effectively dissipate seismic energy across a wide frequency band and mitigate resonant responses, thus providing a theoretical foundation for the design of vibration mitigation strategies for underground granaries under extreme seismic conditions.

2.3.3 Soil-structure interaction and overall stability

In addition to buoyancy and seismic loads, both static and dynamic earth pressures exerted by the backfill soil are critical factors in the design of underground granaries. Xiong et al. (X-

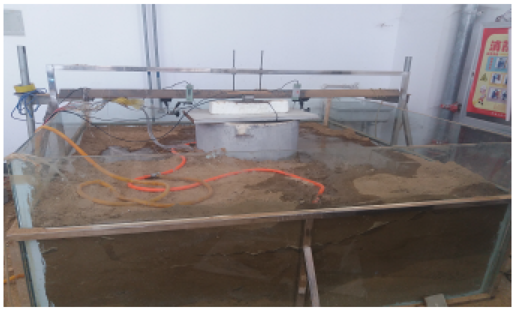

Fig. 9 Test of backfilling 2:8 lime soil (Liu et al., 2019)

Fig. 10 Model of underground granary silo with backfilling 2:8 lime soil (Wang et al., 2022)

iong et al., 2015, 2016), through theoretical analysis and finite element modeling, recommended using conservative passive earth pressure as boundary conditions in structural design to account for uncertainties such as construction-induced disturbances and surface overloading. Building on this, Jin et al. (Jin et al., 2020) further validated the applicability of this approach in engineering practice through full-scale silo wall tests and numerical simulations.

During the excavation and backfilling, the structure–soil–support system develops a complex coupled response mechanism. If not properly controlled, this can lead to stress concentrations and structural cracking. Zhao et al. (Zhao et al., 2023) conducted mechanical performance simulations of diaphragm wall support systems for underground grain silos during construction, revealing that variations in support stiffness significantly impact structural lateral displacement and internal force peaks. Yue et al. (Yue et al., 2024) further modeled the effects of different backfilling sequences and material properties, developing a stress evolution model for structural elements during construction, which provides quantitative guidance for optimizing layer-by-layer construction strategies.

The structural performance of underground granaries depends not only on the strength of individual components and optimized configurations, but also on the coordinated response between the structure, surrounding soil, groundwater, and construction processes. As the structural system evolves toward prefabricated forms, the concept of geotechnical-structural collaborative design is transitioning from theory to practice. This approach emphasizes integrating structural and geological considerations as a unified system throughout both the design and construction phases, thus laying the foundation for the subsequent integration of waterproofing and environmental control systems.

3 Waterproof barriers of underground granaries: materials, interfaces, and long-term reliability

As the UGS system progresses towards industrialization and prefabrication, the associated technical challenges in waterproofing systems have also evolved. While the UGS 1.0 – 2.0 stages predominantly relied on structural sealing, the UGS 3.0 stage shifts focus to a coordinated waterproofing approach that integrates materials, structural components, and interface performance. This chapter examines the plastic-concrete (PC) composite system, interface bonding, and joint construction, evaluating their adaptability and addressing current limitations.

3.1 Challenges in waterproofing technology

Underground granaries, being deeply buried, long-serving, and sealed grain storage facilities, impose significantly stricter technical demands on the stability and durability of waterproofing systems compared to typical underground structures. On one hand, fluctuations in groundwater levels, soil water infiltration, and structural deformation during service can easily create complex and variable seepage pathways, leading to serious moisture-related risks. On the other hand, the grain storage environment is highly sensitive to humidity control, and any leakage can directly jeopardize the quality and safety of the stored grain. Consequently, developing a waterproofing system that ensures long-term water-tightness, strong interface compatibility, and multi-source adaptability has become a fundamental challenge in the engineering of underground granaries.

Currently, the design of waterproofing systems faces three major challenges. First, due to the extended service life of underground granaries, traditional flexible membranes or rigid waterproof layers are prone to degradation when exposed to prolonged hydrostatic pressure, temperature–humidity cycles, and mechanical disturbances, resulting in aging and interface failure, thus compromising long-term water-tightness. Second, in prefabricated or composite structures, the large number of connection joints and the complexity of joint geometries significantly increase the risk of leakage, as joint deformation and interface discontinuities create potential pathways for seepage. Third, in multi-layer waterproofing systems, the lack of unified bonding control and synergistic mechanisms between different materials hinders the achievement of overall system consistency.

To address the waterproofing challenges posed by the complex operational conditions of underground granaries, research is evolving from the traditional “protective covering” approach to a “structure–function integration” paradigm, focusing on interface coordination and system-level integration. In their review of the evolution of underground grain storage technologies, Pasqualone et al. (Pasqualone, 2025) emphasized the importance of incorporating advanced materials and intelligent monitoring systems to enhance structural safety, waterproofing capacity, and smart control in modern underground granaries. Currently, the application of polymer waterproof membranes, composite coatings, and prestressed integrated technologies is driving the transition of waterproofing systems from simple material optimization to comprehensive sealing designs based on interface mechanics and system coupling. In this context, the PC composite waterproofing system, specifically designed for prefabricated construction, is receiving increasing attention.

3.2 Mechanical performance and design of plastic–concrete composite waterproofing systems

Prefabricated underground granaries impose stricter demands on the integration of waterproofing and structural systems. The PC composite structure, which connects polypropylene (PP) panels with concrete components, provides a promising solution by combining watertightness with mechanical load-bearing capacity. In this system, a composite wall is typically formed through stud-bolt connections, with the PP panel serving as the inner waterproof lining and the concrete acting as the primary load-bearing element. Together, they effectively resist groundwater pressure and environmental loads.

Under single water pressure, both the thickness of the PP panel and the configuration of the stud bolts significantly influence the structural performance. Studies have shown that as the thickness of the PP panel increases from 10 mm to 20 mm, the load-bearing capacity grows nonlinearly. When the thickness exceeds 15 mm, the failure mode shifts toward the stud-bolt connections (Zhang et al., 2022). In a series of water pressure resistance tests, researchers further evaluated the watertight performance under varying stud spacings ranging from 200 mm to 400 mm. The results indicated that smaller spacings improve the cooperative load-bearing capacity between the panel and the connection points, while larger spacings can trigger composite failure modes, such as weld detachment at the joints, stud slippage, and cracking of the PP panel (Zhang et al., 2022, 2020; Wang et al., 2022).

Under combined loading conditions, such as water pressure coupled with axial force or bending moment, the system exhibits more complex responses. Zhang et al. (Zhang et al., 2023) conducted experimental investigations on inner lining components of underground granaries subjected to axial compression and water pressure, revealing that axial loading induces additional tensile strain, which reduces the water pressure resistance of the PP panel and alters its failure path. Further studies demonstrated that under the combined effects of bending moment and water pressure, the structural components are prone to shear failure at the connection bolts. Moreover, when the dimensions or thickness of the connection plate exceed a critical threshold, the increase in load-bearing capacity begins to plateau, indicating that the connection joints are a key limiting factor in enhancing the overall system performance (Zhang et al., 2022).

These studies highlight the key controlling factors of the PC composite waterproofing system under multi-load conditions, including panel thickness, stud spacing, and interface bonding strength. The system's overall performance is not solely determined by a single component, but rather by the interaction of multiple factors. Consequently, it is crucial to optimize joint configurations and material layouts simultaneously during the design phase.

3.3 Interface mechanisms and assurance of long-term watertightness

The long-term reliability of PC composite waterproofing systems primarily hinges on the stability of interface bonding and the sealing capacity of structural joints. In complex underground environments, material interfaces often represent the weakest points in the waterproofing system, vulnerable to forming leakage pathways due to fluctuating temperature and humidity conditions or mechanical disturbances. Therefore, it is essential to systematically understand the interfacial mechanisms and evaluate the performance of critical joint configurations.

At the microscale, the connection between PP sheets and concrete primarily relies on mechanical anchorage. Yin et al. (Yin and Wang, 2020), through pull-out tests and theoretical modeling, investigated the slip–bond behavior of threaded polypropylene rods embedded in concrete. Their findings demonstrated that the interfacial stiffness increases nonlinearly with accumulated slip, exhibiting bonding characteristics distinct from those of conventional steel reinforcement. These results provide a theoretical foundation for the interface modeling and reliability assessment of PC composite systems.

Regarding structural joints, Zhang et al. (Zhang et al., 2023) proposed a trapezoidal steel plate vertical joint configuration that integrates both structural connection and waterproofing functions for prefabricated steel–concrete underground granaries. Experimental and numerical results demonstrated that this configuration notably improves joint stiffness and load-bearing capacity under bending conditions, while maintaining exceptional waterproof performance. Therefore, it is highly suitable for high-performance joint protection designs in underground granary applications.

Regarding the connections of the waterproof layer, weld quality is a crucial factor influencing the watertightness of the system. Zhang et al. (Zhang et al., 2022) performed hydrostatic pressure tests to compare the pressure resistance of various weld configurations. The results indicated that failure generally begins in the welded region, rather than the base material, emphasizing that weld reliability is highly sensitive to both the welding process and geometric design. As a result, welded joints represent one of the weakest links in the waterproofing system.

This chapter examines the typical waterproof configurations, key connection mechanisms, and performance limitations of prefabricated UGS systems, analyzing both the formation of watertightness and the failure pathways. Current research highlights that the performance of interface bonding and the sealing configurations of joints are crucial factors in ensuring the long-term stability of the waterproofing system.

4 Storage environment of underground granaries: passive utilization and active intelligent regulation

The grain storage environment is a fundamental aspect of the overall performance of UGS. From the early reliance on geothermal conditions in UGS 1.0 to the integration of ventilation and energy consumption control in UGS 3.0, regulatory mechanisms have evolved from passive adjustment to intelligent systems driven by multiphysics coupling. This chapter reviews the mechanisms behind quasi-low-temperature environments, the optimization of ventilation systems, and recent advancements in intelligent sensing technologies.

4.1 Formation mechanisms of quasi-low-temperature environments and passive regulation

One key advantage of underground granaries is their ability to maintain a "quasi-low-temperature" state by harnessing the thermal inertia and insulation properties of the subterranean environment, without requiring active cooling systems. In this environment, grain temperatures consistently stay within the range of 10–20°C year-round, providing superior thermal stability compared to aboveground storage. This stability effectively inhibits pest reproduction and slows biochemical reactions, forming the essential physical foundation for sustainable, eco-friendly grain storage.

The formation of the quasi-low-temperature environment is influenced by the coupling of multiple factors, primarily including the geothermal background, structural configuration, material properties, grain bulk characteristics, and initial operating conditions:

(1) Geothermal dominance mechanism: Numerous simulations and field studies have shown that grain temperature ultimately stabilizes at the surrounding thermally stable soil layer, with heat diffusing inward, causing the temperature gradient to gradually diminish. Wang et al. (Wang et al., 2016), using Computational Fluid Dynamics (CFD) simulations, demonstrated that, in a quiescent state, grain bulk exhibits a temperature gradient dissipating from the exterior to the interior. Chen et al. (Chen et al., 2014) highlighted that the 16–18°C stable temperature zone at a depth of 2–3 m serves as the primary heat source, resulting in minimal fluctuations in grain temperature and a stable thermal environment. Fig. 11 shows the heat exchange schematic of a typical underground grain silo under the geothermal dominance mechanism. Jin et al. (Jin et al., 2023) further validated through field measurements that temperature changes at the center and bottom of underground granaries occur slowly, with a marked lag in seasonal response.

(2) Structural and material properties: The thickness and thermal conductivity of the silo's enclosing structure directly influence the heat transfer pathway. Wang et al.(Wang and Li, 2014), using the Galerkin method to establish a heat conduction model, indicated that the heat transfer process is highly sensitive to the material's thermal conductivity, with higher conductivity significantly increasing the heat flux density. Chen et al. (Chen et al., 2023), through experiments and simulations comparing the hygrothermal responses of various lining materials, found that polypropylene exhibits smaller temperature fluctuations and lower relative humidity during cold seasons, showcasing its superior performance in suppressing condensation.

(3) Influence of grain bulk characteristics: The arrangement, compaction, and stacking structure of grain kernels significantly impact the internal temperature distribution. Zhang et al. (Zhang et al., 2023) found that lower porosity leads to slower heat diffusion and more stable grain temperatures. Experimental studies by (Jin et al., 2024, 2025) on semi-underground double-layer shallow circular silos demonstrated that the upper layer is more susceptible to external climate influences, while the lower layer exhibits a quasi-steady-state temperature distribution, forming distinct vertical temperature stratification. Fig. 12 illustrates the structural cross-section of a Semi-Underground Double Shallow Silo (SUDSSS). Similar stratification phenomena were also observed by Wang et al. (Wang et al., 2022) in circular underground silos. Additionally, (Panigrahi et al., 2023) developed a three-dimensional transient CFD model for a large-scale silo, systematically simulating the heat–moisture transfer process. The study highlighted the influence of boundary conditions, thermal properties of grain kernels, and numerical discretization strategies on hygrothermal evolution, thereby enhancing the quantitative understanding of nonlinear multiphysics coupling in complex grain bulk structures.

(4) Effect of initial conditions: The season of grain loading and the initial grain temperature play significant roles in the thermal evolution within underground silos. Experimental and simulation studies by (Jin et al., 2021) showed that grain loaded during the summer, with its higher initial temperature, requires a longer time to reach thermal stability. In contrast, winter-loaded grain more quickly stabilizes at a low-temperature storage state. Furthermore, the thermal response within the silo exhibits a noticeable time lag—external temperature fluctuations typically take 1–2 months to propagate to the center of the grain bulk, highlighting the excellent thermal buffering capacity of underground silos.

Overall, the quasi-low-temperature environment in underground granaries depends on the multi-field coupling and coordinated regulation between geothermal conditions, structural configurations, and grain bulk characteristics. This foundational mechanism provides the theoretical basis for future advancements in intelligent sensing, energy-efficient control, and environmental evolution forecasting. This principle is also reflected in historical underground storage practices. For instance, the medieval grain storage system in Padowetz, Brno, Czech Republic, maintained long-term environmental stability through natural ventilation and structural maintenance. Its passive regulation approach provides valuable insights for enhancing the environmental resilience and durability of modern underground silos. Fig. 13 presents excavation photos and stratigraphic markings of this system (Lisá et al., 2017).

4.2 Active ventilation systems and energy efficiency optimization

Although underground granaries benefit from utilizing geothermal conditions to maintain a quasi-low-temperature environment, passive regulation alone is often insufficient in situations such as high-moisture grain storage, early-stage heat buildup, or localized hot and humid anomalies. In these cases, active ventilation systems are crucial for regulating grain temperature, dispersing heat and moisture, and ensuring the safety

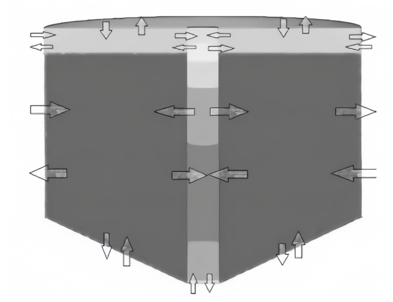

Fig. 11 Schematic diagram of heat exchange in underground granary (Chen et al., 2014)

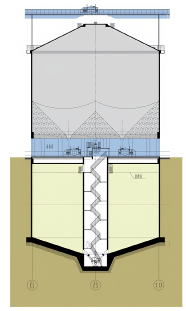

Fig. 12 Semi-underground double-layer shallow round granary (Jin et al., 2025)

and stability of the grain storage environment.

Existing studies have concentrated on the configuration and parameter optimization of ventilation systems. Zhang et al. (Zhang and Cao, 2013; Zhang et al., 2014), using CFD simulations and analyses, examined the impact of silo bottom geometry, ventilation duct cross-sectional shape, and screen arrangement on airflow distribution and ventilation efficiency. The results indicated that incorporating a conical silo bottom, circular ventilation ducts, and positioning the screens at the duct base can significantly enhance airflow uniformity and cooling efficiency while reducing energy consumption. These findings provide valuable quantitative support for engineering optimization.

In high-moisture grain storage conditions, active ventilation plays a crucial role in alleviating temperature increases. Zhang et al.(Zhang et al., 2022) conducted an empirical study on the mechanical ventilation performance of plastic-lined underground granaries, revealing that during static storage, grain piles tend to self-heat, forming high-temperature hotspots. However, the ventilation system effectively reduced the temperature in the middle and lower regions of the grain pile to below 10°C within 10 hours, successfully managing localized overheating. The study also highlighted that the cooling efficiency is closely linked to the layout of the ventilation ducts, with uniform air distribution strategies significantly enhancing the overall cooling performance.

Therefore, as a critical element of environmental regulation in underground granaries, the effectiveness of active ventilation systems relies on the systematic optimization of key parameters and their precise alignment with specific operational conditions. By combining numerical simulations with experimental validation, both energy efficiency and environmental control can be significantly improved, providing robust support for the diverse storage needs of underground silos. To further illustrate the dynamics of internal temperature and humidity variations, as well as the response mechanism of the active ventilation system, Fig. 14 presents a schematic diagram of the integrated temperature gradient and environmental response.

4.3 Toward refined management: challenges of multiphysics coupling

The environmental control of underground granaries is evolving from single-parameter regulation to an understanding of and control over multiphysics coupling mechanisms. As early as the 1990s, (Dunkel, 1995) emphasized that large-scale underground bulk grain storage is not a static process, but rather a complex ecological system composed of grain kernels, insects, fungi, and other organisms. The storage environment involves highly interactive factors such as temperature, moisture, gas composition, structural stress, and microbial activity, making it challenging for single-factor regulation to manage its dynamic evolution. Therefore, achieving refined management requires an accurate understanding of the coupling mechanisms between thermal, moisture, gas, and biological processes. In their review of digital twin development for underground spaces, Babanagar et al.(Babanagar et al., 2025) highlighted key challenges in modeling multiphysics coupling, including model granularity, data interoperability, and feedback mechanisms, emphasizing the need for cross-disciplinary modeling approaches and unified semantic frameworks. This perspective introduces frontier challenges in the systematic modeling and refined control of underground grain silo environments.

In practical operations, such coupling presents multiple challenges. The respiration of high-moisture grain piles can lead to localized accumulation of heat and moisture, creating “hot-humid spots” that accelerate grain quality degradation and promote insect infestation and mold growth (Bhardwaj and Sharma, 2024). Operational activities such as ventilation and grain discharge disturb the granular structure, which not only alters gas exchange pathways but also has the potential to disrupt the internal temperature and humidity fields within the grain mass (Wang et al., 2025). Furthermore, as underground granaries are increasingly used for strategic reserves, the scope of safety assurance has expanded to include higher-dimensional risk controls, such as structural stability, gas accumulation, and emergency accessibility (Shahinyan et al., 2024).

To address the complexities outlined above, information technologies have been progressively incorporated into environmental management systems. (Chen et al., 2014) proposed using Building Information Modeling (BIM) for the virtual modeling of underground granaries, facilitating multidisciplinary simulations that encompass structural behavior, waterproofing performance, and operational conditions. (Dunkel, 1995) further emphasized the significance of integrating sensor networks and remote monitoring to enable dynamic identification and responsive control of grain pile conditions. Building upon this, (Yu et al., 2021) developed a tunnel operation and maintenance decision-making framework based on digital

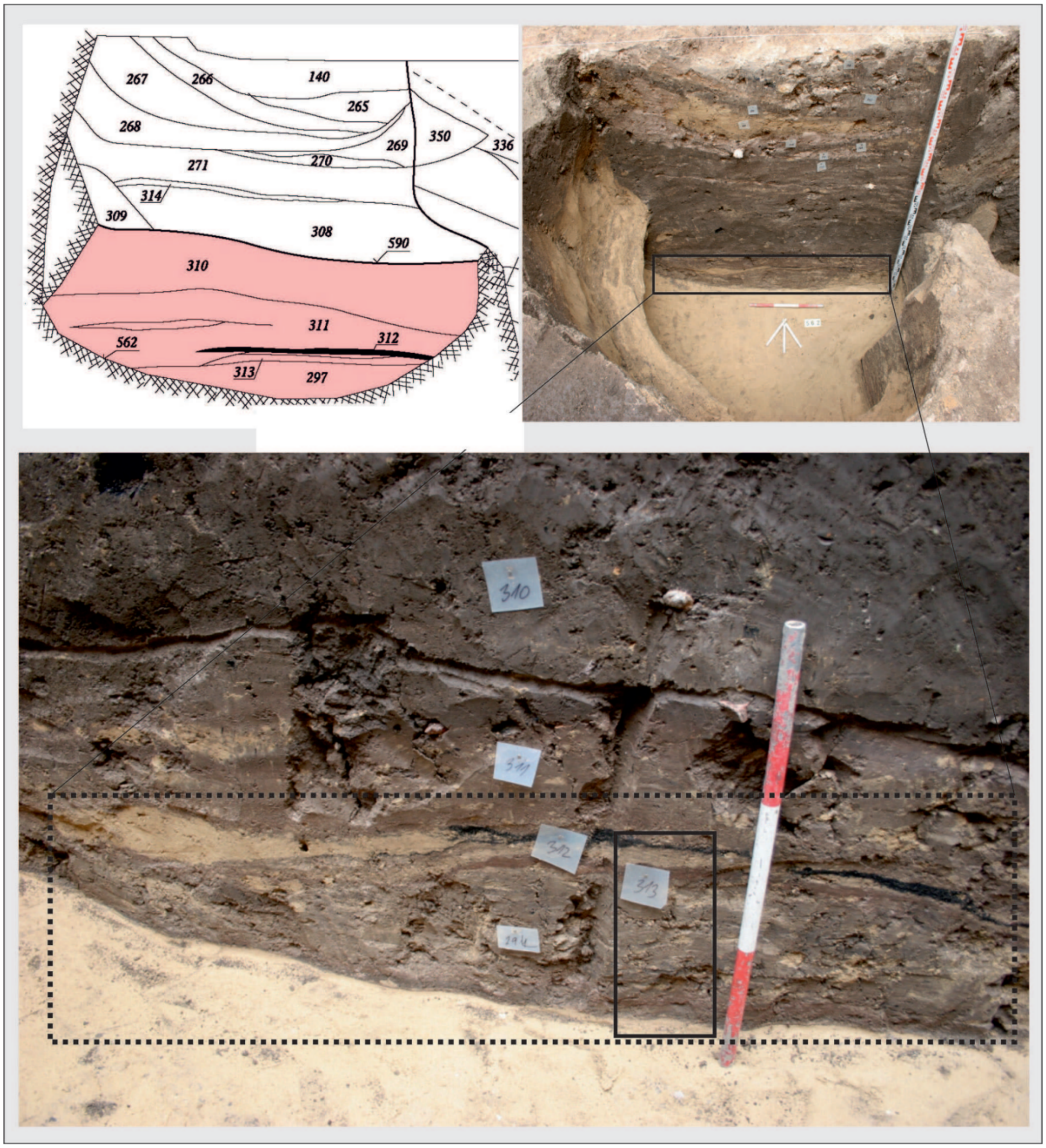

Fig. 13 Underground granary on Bašty Street and details of its bottom structure (Lisá et al., 2017)

twin technology, where multisource sensor data and simulation models are fused in real time to enable structural state identification, risk assessment, and dynamic strategy recommendations in a closed-loop manner. This research paradigm provides essential methodological support for advancing multiphysics coupling environmental control systems toward intelligent and autonomous decision-making. Furthermore,(Liu et al., 2025), in the context of tunnel boring machines, proposed a method that combines artificial intelligence with digital twins to create an intelligent operation and maintenance framework encompassing sensing, prediction, and control. This approach utilizes AI algorithms to perform real-time inferences on sensor data, dynamically links digital models for simulation and strategy scheduling, and showcases the potential for full-process closed-loop regulation in complex underground environments, offering valuable insights for the intelligent perception and active intervention of multi-physical-field coupled systems in underground granaries.

This chapter begins by exploring the formation of quasi-low-temperature conditions under the thermal stability of underground environments. It then extends to the optimization of active ventilation systems and the understanding of multiphysics coupling mechanisms, systematically reviewing the evolution of environmental control strategies from UGS 1.0 to UGS 3.0. Environmental regulation has shifted from passive thermal equilibrium, driven by geothermal conditions, to an active system that integrates ventilation and dynamic multi-factor adjustments. The current key challenge lies in developing a system-level analytical framework based on multi-field interactions, aiming to identify and coordinate the dominant vari-

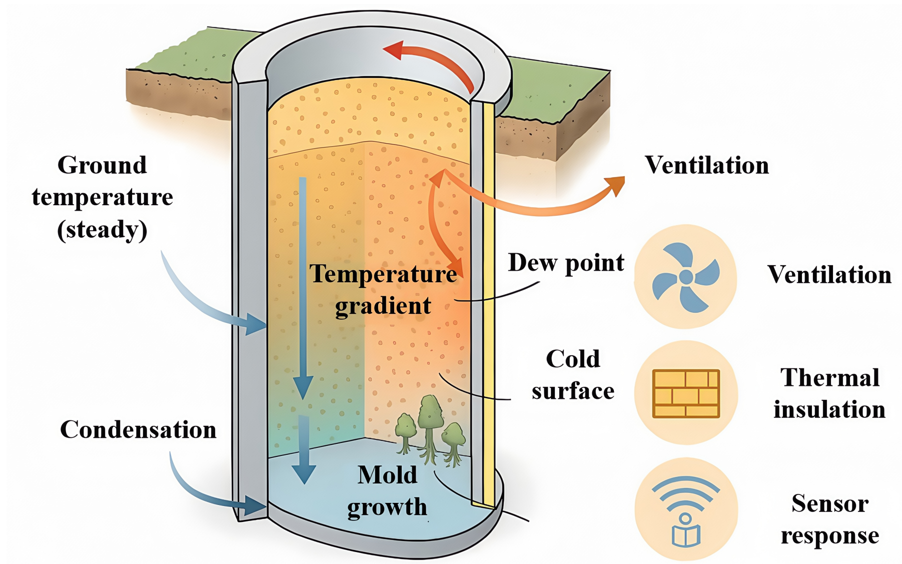

Fig. 14 Temperature gradient and ventilation effects in underground granary.

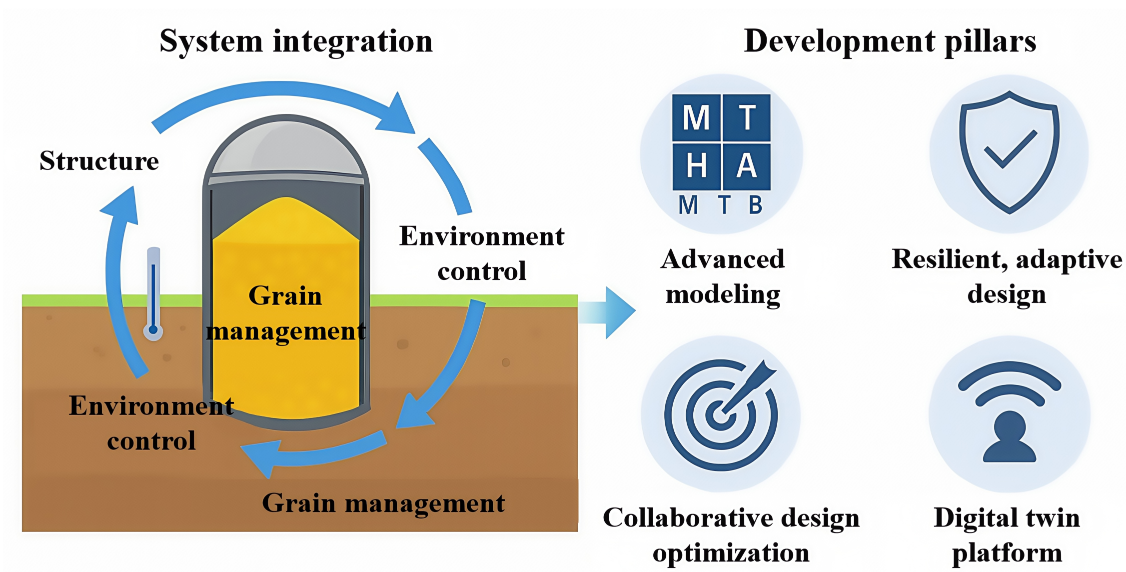

Fig. 15 Intelligent system framework for underground granaries (toward UGS 4.0)

Notes: MTHA: Moisture and Mold, Temperature and Thermal, Humidity and Heat, Aeration and Airflow Analysis. MTB: Monitoring Technologies for Below-ground.

ables within coupled processes. This will lay the foundation for intelligent regulation in the UGS 4.0 era. Fig. 15 illustrates the integrated system architecture and closed-loop control pathway for underground granaries, oriented towards UGS 4.0.

5 Conclusion and outlook

5.1 Conclusion: coordinated understanding of structural, waterproofing, and environmental systems

This review follows the four-generation evolution of UGS, tracing the technological transition from traditional empirical construction to modern engineered systems. It focuses on the development of the three core subsystems—structural systems, waterproofing systems, and storage environments—offering a comprehensive synthesis of their progression.

Underground granaries have evolved from monolithic cast-in-place structures to prefabricated composite systems, with design priorities shifting towards component performance, joint coordination, and soil-structure interaction. While construction efficiency and ease of assembly have improved, further research is needed to assess their overall stability under complex geological conditions, long-term service reliability, and dynamic structural behavior during discharge operations.

In waterproofing systems, the synergistic effects between materials, connection configurations, and interfacial mechanisms are becoming increasingly well understood. The plastic–concrete composite system has made significant progress in material compatibility and interfacial bonding. However, the reliability of connection joints and the long-term durability of weld seams remain key challenges in ensuring the system's sustained watertight performance.

In terms of environmental control, underground granaries leverage the thermal stability of surrounding soil to create a quasi-low-temperature environment, providing effective passive energy-saving benefits. Active ventilation plays a crucial role in regulating moisture and heat accumulation; however, its performance is limited by the structural configuration and system parameters. Current control strategies primarily focus on single-variable adjustments, lacking a comprehensive understanding of the coupled effects between temperature, humidity, and gas transport.

In summary, while progress has been made in the structural, waterproofing, and environmental systems, the coordination of multiphysics coupling and integration mechanisms among them remains insufficient. The four-generation UGS framework not only highlights the evolutionary path of underground granaries from isolated technologies to integrated systems, but also emphasizes that future research should focus on system integration and coupled regulation as the central direction.

5.2 Outlook: system integration and intelligent technologies toward UGS 4.0

Looking ahead, underground granaries are poised to transition into the fourth-generation stage (UGS 4.0), which focuses on system integration and intelligent regulation, transforming into a smart "geological-ecological entity" equipped with self-sensing, self-adaptive, and self-decision-making capabilities. To realize this vision, the key development directions include:

(1) Deep multiphysics coupling and dynamic regulation mechanisms: Develop cross-scale modeling and fully coupled analysis frameworks to systematically unveil the interactive mechanisms among thermal, moisture, gas, and biological fields, advancing dynamic coordination across structural, waterproofing, and environmental systems.

(2) Full-process information modeling and digital twin support platforms: Create digital twin platforms that span the entire lifecycle—from design and construction to operation and maintenance—enabling multi-source data integration and real-time interaction, supporting predictive analysis and intelligent management.

(3) Intelligent sensing and AI-driven regulation systems: Integrate multi-dimensional sensor networks to continuously monitor structural integrity and grain bulk conditions in real time. Employ machine learning and other AI techniques to detect anomalies, forecast risks, and optimize control decisions.

(4) Resilience-oriented system design and operational assurance: Develop resilience evaluation metrics at the system level and explore integrated design strategies incorporating redundancy and self-recovery features, thereby improving operational stability and safety redundancy of underground granaries under extreme conditions.

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Conflict of interest

The authors declare no competing interest.

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