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Review

Key Issues and Research Progress on the Deterioration Processes and Protection Technology of Earthen Sites under Multi-Field Coupling

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Abstract: Since 2006, with the implementation of a series of national research projects in the field of earthen site conservation, the Chinese theoretical foundation and technological conservation system for the protection of earthen sites in arid environments has gradually formed. However, there are some global problems such as an unclear relationship between characteristics of diseases on sites and their existing environment, unclear deterioration mechanisms under multi-field coupling, immature stability control technology under dynamic loading, the poor suitability of protection process quality assessment equipment, and a lack of systematic research on comprehensive protection synergy mechanisms. On the basis of summarizing the research achievements in the field of earthen site conservation in China for more than 30 years, and a large number of practical experiences in earthen site reinforcement engineering, this paper expounds the multi-field coupling characteristics of earthen site construction technology, the climatic environment, and dynamic loading and protection measure activities, clarifies the main characteristics of the protection of earthen sites in China at present, puts forward the key scientific and technical problems existing in the conservation of earthen sites, constructs a picture of the research on the conservation of earthen sites under the action of multi-field coupling, and discusses the protection projects of earthen sites under different environments. We hope the technological system can provide support for the transformation of earthen site conservation from the rescuing conservation stage to the stage of both rescuing and preventive conservation, and move the foundation of earthen site conservation towards the stage of preventive protection.

Keywords: heritage conservation; earthen sites; multi-field coupling; conservation technology

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1. Introduction

China has a long history with rich cultural connotations. The most powerful physical example of cultural heritage is illustrations which contain Chinese special philosophical thought, humanistic spirits, value principles, and moral rule to reflect the cultural spirits, mind, and confidence of the Chinese nation [1,2]. Cultural heritage sites include a large number of earthen sites, such as the Liangzhu site in the Yangtze River Basin, the Dahecun remains in Central China, the Sanxingdui ruin site in SW China, the Western Xia tombs in the Hetao Plain, the Great Wall, as well as passes, beacons, and ancient castles located in northern China, etc. [3]. Up to 2019, when the list of the eighth batch of National Key cultural relics under state protection was published, there were 5292 National Key cultural relic protection units containing 881 earthen sites, which included ancient sites, ancient buildings, ancient tombs, modern important historical sites, and representative architectural types with high historical, artistic, scientific, social, and cultural values (Figure 1). Such earthen sites are important physical examples and precious historical materials to study the politics, economy, military affairs, culture, and art of ancient nations, and can be used for witnessing the continuous integration, innovation, prosperity and development of Chinese and foreign cultures [4].

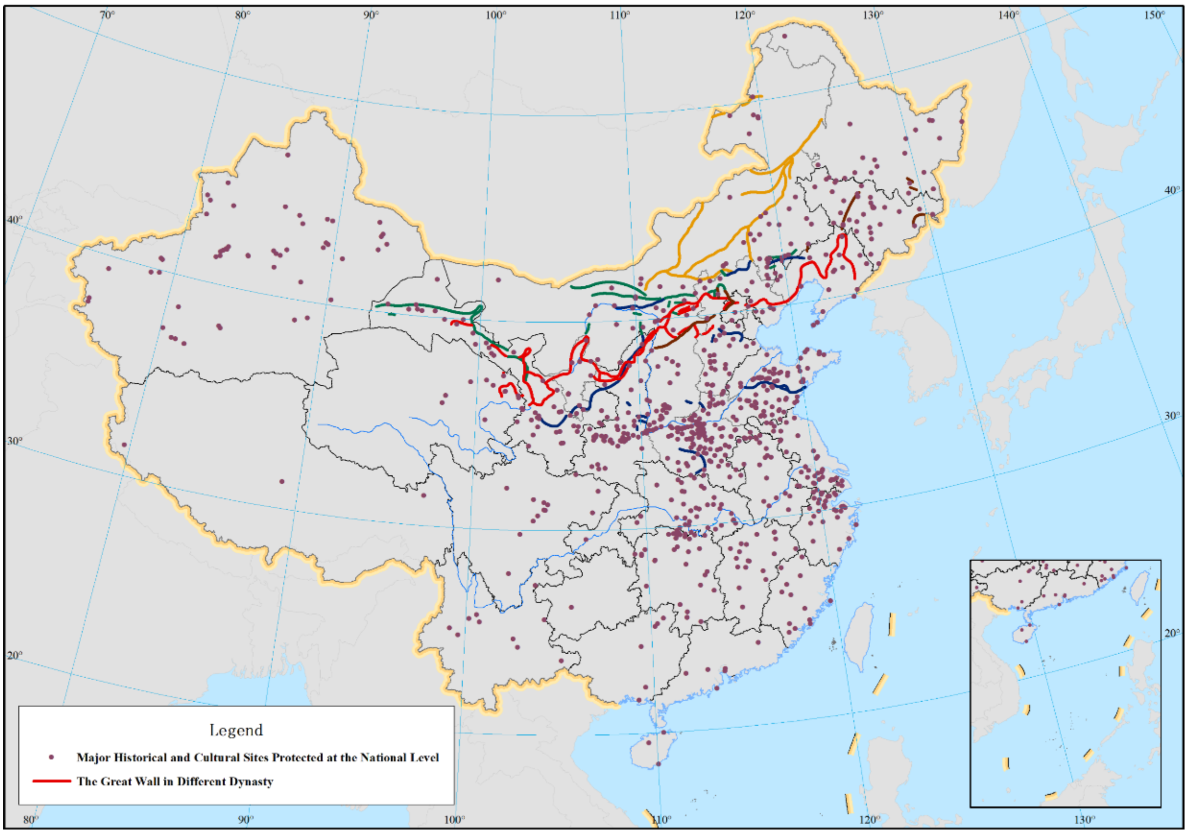

Figure 1. The distribution of earthen sites in China.

Under long-term natural and human influence, earthen sites face the development of deterioration, including collapse (Figure 2A), sapping (Figure 2B), cracks (Figure 2C), weathering (Figure 2D), vegetation erosion, water damage, and human activity destruction, seriously threatening their durable preservation and safe usage [5].

(**A**)

(**B**)

Figure 2. *Cont.*

(**C**) (**D**)

Figure 2. The deterioration of earthen sites in China. (**A**) Collapse; (**B**) sapping; (**C**) cracks; (**D**) weathering.

Recently, some research groups and scholars from the Getty Conservation Institute, USA, the International Scientific Committee on Earthen Architectural Sites under the International Council on Monuments and Sites (ICOMOS), the Catholic University of Peru, the University of Oxford, and the Nara Cultural Property Research Institute, Japan, have made rich academic achievements in the field of earthen site protection. They mainly researched the causes of deterioration, evaluated the development degree of deterioration and protective materials, and proposed methods for the investigation and health consultation of the deterioration of earthen sites, and such protection technologies have been successfully applied to seismic reconstruction projects of Peruvian earthen sites and Moroccan soil site reconstruction projects [6,7]. They have carried out research on the concepts and principles of site protection to form international guidelines for the preservation, protection, and utilization of earthen architectural sites, and such research achievements have been widely applied to immovable cultural heritage sites throughout the world [8]. Furthermore, the structural design and seismic protection of earthen sites were researched to reveal the seismic characteristics and damage behaviors of earthen sites, forming the methods of site assessment and reinforcement [9,10]. The technology of the surface anti-weathering of earthen sites was researched, and soft cover against weathering was promoted [11]. The investigation methods for earthen site situations were researched and a conservation program was proposed based on scientific investigations [12].

Earthen site protection in China started in the 1920s, when measures to resist wind erosion and rain erosion, and ensure anchorage and fissure grouting, were implemented in Pochengzi of Guazhou, which experienced the rescuing protection phase and gradually transitioned to both rescuing protection and preventive protection, having made a series of important achievements [13]. In the field of earthen site protection in China, consolidation technology, preventative protection, and reinforcement materials were studied to formulate national and industry standards of earthen site protection and develop a series of technology systems, including desalination [14], rammed reinforcement [15–17], anchorage reinforcement [18,19], fissure grouting [20,21], and surface anti-weathering [22]. Such achievements have been widely used in the protection projects of earthen sites in arid environments and have been explored in damp environments [23]. In terms of deterioration types and the occurrence environment of earthen sites, a classification system of the deterioration of earthen sites in arid and damp environments was built, and monitoring technology was developed. With regard to new protective materials, PS [24], grout calcined ginger nuts [25,26], ginger nut and Aga soil [27], SH [28], calcium-based liquid hydraulic hardening agent [29], inorganic bond materials [30], and organosilicon-modified acrylic resin non-aqueous dispersion [31] were invented and researched. Such research achievements were successfully applied in the protection projects of more than 200 National Key cultural relic protection units, having ensured the safe conservation and effective utilization of many precious cultural heritage sites, directly guaranteeing the declaration of many world cultural heritage sites.

However, China has a vast territory, and soil materials and earthen sites have diversified forms and complex building technologies [32]. The climate difference between the north and south is large, and the deterioration types of earthen sites are diverse [33]. The reinforcement of earthen sites started relatively late, and the reinforcement technology and quality control of earthen sites in different environments lack related measures. Due to heterogeneous economic development in western and eastern China, the implementation of the prevention, management, and utilization of earthen sites is different. Hence, in the multi-field coupling influences of environmental elements (including rainfall, temperature, sunlight, wind, etc. [34]), external force loads (such as earthquake and human activities), as well as protective measures(including protection, management, and utilization [35]), earthen site protection in China still faces some challenges, such as the unclear relationship between the characteristics of deterioration on sites and their existing environment, the unclear deterioration mechanisms under multi-field coupling, immature stability control technology under dynamic loading, the poor suitability of protection process quality assessment equipment, and the lack of systematic research on comprehensive protection synergy mechanisms.

This paper summarizes the research work on earthen sites located in China since the 1960s and clarifies the characteristics of earthen site materials and occurrence environments, and proposes current problems and shortages in the field of earthen site conservation. Aimed at these problems, six key scientific technical problems are considered for further research in the field of earthen site conservation under multi-field coupling, and some suggestions are put forward for the research of these problems to finally construct a technical system of earthen site protection and reinforcement, including eleven consolidation technologies for subaerial earthen sites and archaeological profiles under arid, wet, and damp environments to provide support for the transformation from rescuing conservation to giving equal importance to rescuing and offering preventive protection for Chinese earthen sites. Furthermore, this paper will also provide an important reference for earthen site protection and consolidation in other countries along the silk road. This review is composed of six sections. In addition to the Introduction, the research objects' characteristics, an analysis of the overall status of protection, key scientific technical problems, the construction of research thoughts, and a description of the protection and reinforcement technology system are included. The last section is the Conclusion.

2. The Characteristics of Building Materials, the Occurrence Environment of Earthen Sites, and Existing Protection Problems

2.1. The Poor Strength of Building Materials and Various Building Technologies

As one of the main building materials in ancient China, soils were applied by different technologies to carry out construction activities, reflecting the principle of local material utilization. Due to the cause differentiation of quaternary deposits, the building materials of earthen sites located in Tianshan between the north and the south, the Hexi corridor, the Loess Plateau, the Inner Mongolian Plateau, the Northeast China Plain, the North China Plain, the Middle-Lower Yangtze Plain, the Sichuan Basin, etc., contain different particle sizes of soils such as sand, clay, and silt, which were mixed or used alone. For example, the earthen sites located in the Quaternary alluvial fan to the north of the Yellow River and the Gobi Desert were mostly built with a mix of gravel, sand and soils, and the earthen sites located in the Loess Plateau and the Middle-Lower Yangtze Plain were mainly constructed with clay and silts [32]. As such, building materials have different particle size distributions, and their basic physical and mechanical properties are different. On the other hand, compared with stone and concrete, the mechanical strength of soil materials is much lower, and their resistance to rain, sunlight, wind, and earthquakes is also very poor (Figure 3).

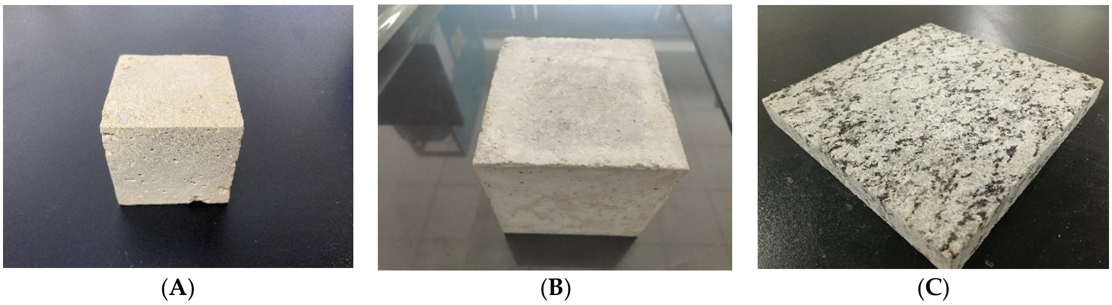

Figure 3. Main parameters of different typical building materials. (**A**) Site soils. Density (g/cm^3): 1.25–1.95. Compressive strength (MPa): 0.4–2.3. (**B**) Concrete. Density (g/cm^3): 1.9–2.5. Compressive strength (MPa): 15–80. (**C**) Granite. Density (g/cm^3): 2.63–2.75. Compressive strength (MPa): 100–300.

Along with the persistent development of society, ancient Chinese building technologies using soils have also been constantly improved. For example, the ancestors of primitive society often dug holes and lived in horizontal caves, vertical caves, semi-caves, etc. [36]. With social development, building forms evolved from pit dwelling to ground living, to mud pile ups and to earthen wall with wooden frames, which made the locellus separate out [37]. Influenced by the properties of undisturbed soils, the earth architecture evolved to the earliest rammed construction in the Yangshao period [38] and adobe in the Longshan culture period [39]. Additionally, the construction technology of wet mud piles exists in earthen sites located in Kuqa, Kashgar, and Tashkurgan of Xinjiang [40]. Thus, it can be seen that all kinds of construction technologies were used to build earthen sites across the whole of China, such as earthen dugs, mud pile ups, plate-building technology using rammed earth, adobe construction, and wet mud piles (Figure 4).

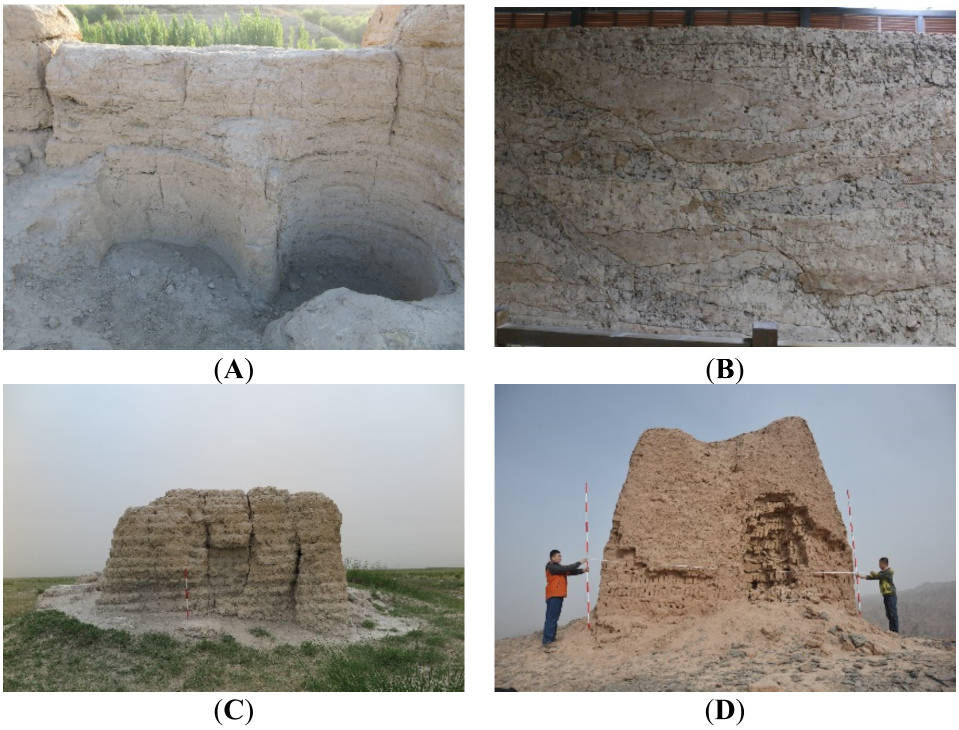

Figure 4. *Cont*.

(**E**)

Figure 4. Earthen sites built with different technologies. (**A**) Earthen dug; (**B**) mud pile up; (**C**) plate-building technology; (**D**) adobe construction; (**E**) wet mud pile.

2.2. Various Occurrence Environments and Complex Deterioration Types

China spans a wide latitude from north to south, and its climatic zone includes the tropical zone, subtropical zone, warm temperate zone, middle-temperature zone, cold temperate zone, and Qinghai–Tibet cold zone [41]. The humidity index of precipitation was different in different districts where earthen sites were located, ranging from 16 mm in Turpan to 500 mm in Yuncheng City, and even to 1800 mm in Hangzhou. Therefore, earthen sites were widely distributed in different climate environments, including arid (extreme arid, arid, and semi-arid), wet (semi-wet and wet), and damp (damp and over damp) (Figure 5). Moreover, due to different protection and utilization requirements, parts of the earthen sites were conserved in sheds, and according to their building forms, the occurrence environments can be classified as open air, semi-open, semi-enclosed and enclosed environments [42,43].

(**A**) (**B**)

(**C**)

Figure 5. Typical earthen sites in arid, wet, and damp environments. (**A**) Jiaohe Ruins; (**B**) Yuwang Castle (It's from Internet); (**C**) south wall of Liangzhu ancient city.

However, with differences in climatic zones, building materials, and construction technologies, the deterioration characteristics of earthen sites under different environments are different. For example, earthen sites in the arid environment in NW China have mainly developed scaling off, cracks, collapse, sapping, and gullies [44], while earthen sites in the damp environment in SW and SE China have mainly developed drying shrinkage cracking, vegetation deterioration, and collapse [45,46]. In the meantime, the same deterioration types developing in different environments will present different characteristics. For example, in the arid environment, vegetation deterioration was developed sporadically with the growth of herbs or small shrubs and the damage form of root chopping, while earthen sites in damp environments developed woody plants, herbs, lower plants, and mold with a higher vegetation coverage rate (part of a site having more than 95% vegetation coverage) (Figure 6).

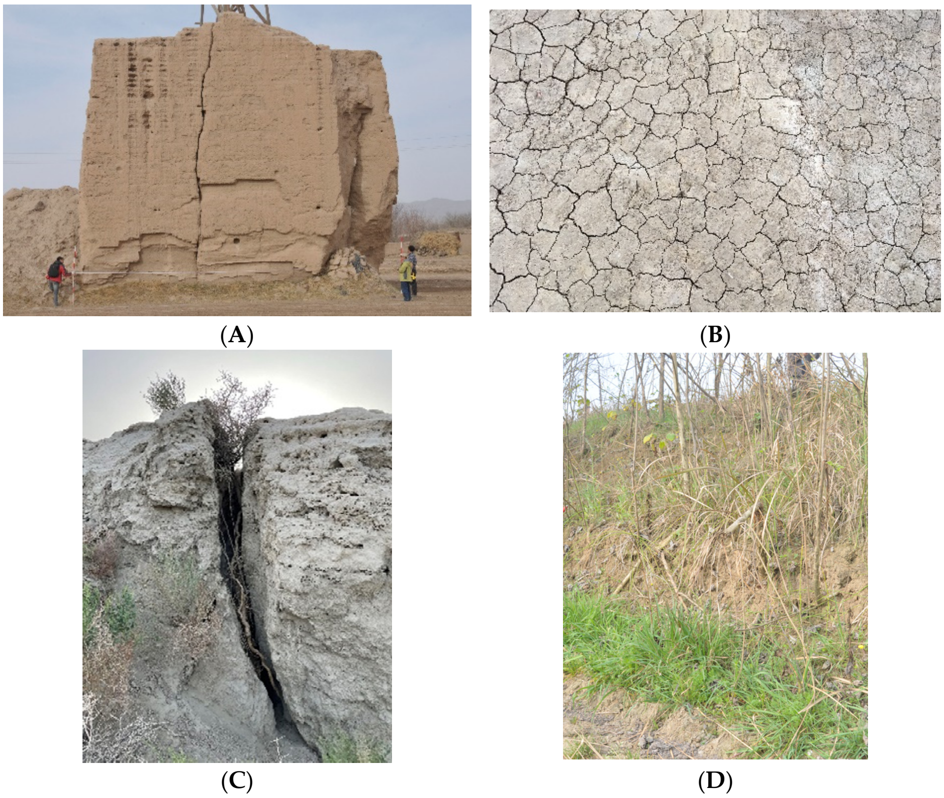

Figure 6. Comparison of typical deterioration types developed in earthen sites of different environment types. (**A**) Cracks in earthen sites in the arid environment; (**B**) drying shrinkage cracking in earthen sites in the damp environment; (**C**) vegetation deterioration in earthen sites in the arid environment; (**D**) vegetation deterioration in earthen sites in the damp environment.

2.3. Imperfect Protective Technology System and Unbalanced Development in the North and the South Regions

Since 2006, along with the implementation of National Science and Technology Support Program projects, including research on the key technologies of earthen site protection, research on the key technologies for the preservation of prehistoric earthen sites under damp environments, and integration and application demonstrations of complete sets of earthen site protection technologies in arid environments, systematic progress has been made in the research of earthen sites in China. Combined with research achievements based on extensive engineering practice in arid regions, protective consolidation technologies in the arid environment have gradually been formed by anchoring, grouting, rammed roof-propping, and anti-weathering, which have protected many earthen sites [47]. Compared with the arid environment, although many protective concepts and materials for earthen sites in the damp environment have been researched and explored in practice, an effective protective reinforcement system has not been formed until today due to the particularity of the occurrence environment of abundant open rain and shallow underground water level, and the close and semi-closed conservation environment of archaeological profiles. Therefore, currently, the conservation and reinforcement research regarding Chinese earthen site protection has characteristics of an imperfect protective technology system and unbalanced development in the north and south regions.

2.4. Unsystematic Protection Quality Control and Insufficient Evaluation Equipment

In nearly 30 years of earthen site protection research and engineering practice processes, the basic theory of earthen site protection in the Chinese arid environment has been gradually explored. A series of protective consolidation materials and complete sets of special protection technology and equipment have been invented to realize scientific and standardized protection, having protected many endangered earthen sites. However, in the practice process of protective consolidation, key technical nodes of different reinforcement measures need to be researched further, and research on the key node control threshold is not thorough enough.

Meanwhile, the technical equipment used in the field of cultural relic protection has generally been introduced from the mature equipment of geotechnical engineering, as most technical indicators and operating instructions are often inconsistent with the basic principles of cultural relic protection, and thus cannot be directly used. There is little equipment that can be used to evaluate the effect of protection and reinforcement in practical engineering practice. Although some research groups developed equipment improvement methods and put forward some evaluation methods, the applications in actual engineering practice are not extensive enough, and the effectiveness of the evaluation needs further validation (Figure 7).

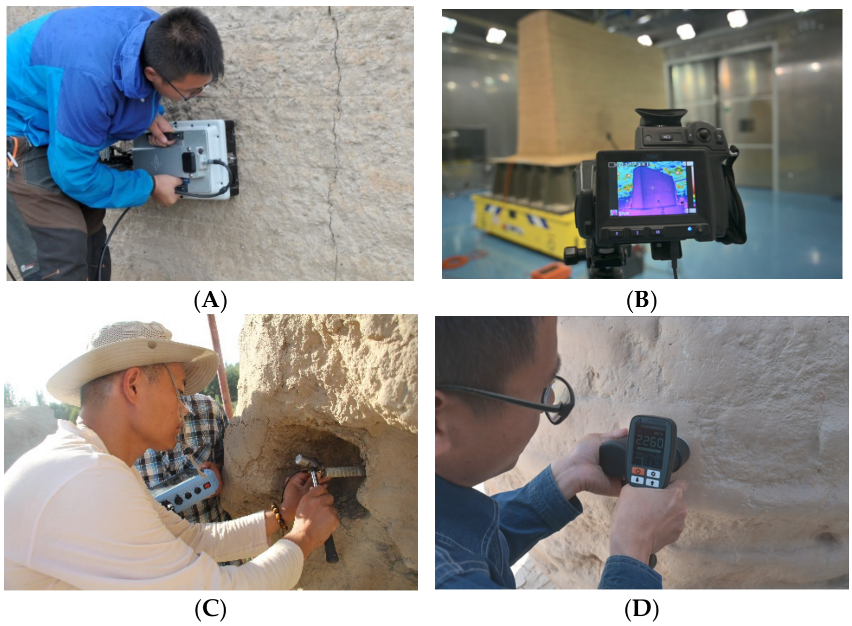

Figure 7. Common equipment for reinforcement effect evaluation of earthen site protection. (**A**) Ground-penetrating radar (GPR); (**B**) thermal infrared imager; (**C**) anchor non-destructive detector; (**D**) wave velocity meter.

2.5. Uncoordinated Development of Management, Protection and Utilization

As an effective witness to the long history of the Chinese nation, earthen sites carry a lot of important historical connotations, so their protection and utilization are effective carriers of Chinese culture confidence. However, restricted by social and economic development and the concept of protection and utilization, the protection of earthen sites in different regions in China still faces problems, such as the attached importance to protecting and making light of management and utilization, as well as the unsystematic and incomplete balanced development of management, protection, utilization, and research on the basis of the outstanding universal value of earthen sites [48]. For example, a large number of protection reinforcement, monitoring, and early warning protection systems for some important earthen sites were implemented to construct archaeological site parks and apply for world cultural heritage recognition, but the training force of administrative staff and daily maintenance professional and technical personnel was weak. In the meantime, some earthen sites are far away from cities, and thus face a weak foundation for management, protection, and utilization.

3. Key Scientific Technology Issues of Earthen Site Protection under Multi-Field Coupling

3.1. Relationship between Deterioration and Occurrence Environment of Earthen Sites

The degradation of earthen sites is the result of long-term combined functions of natural elements, building materials and technologies, and human activities, including surface weathering, structural damage, and vegetation erosion, which endanger the safety of earthen sites and threaten their long-preserved conservation. Moreover, different environment types result in different building materials and complex construction technologies. Therefore, it is key to reveal deterioration mechanisms, construct protection and reinforcement technology systems of earthen sites in different environment types, form effective quality control methods for protection and reinforcement, and develop effect-evaluation devices by classifying occurrence environment types, clarifying building technologies and deterioration development, establishing classification systems of deterioration, and determining the inner relationship between building technology, deterioration chains and the occurrence environment of earthen sites.

3.2. The Mechanism of Surface Weathering and the Structural Instability of Earthen Sites

In essence, the surface weathering of earthen sites is the evolutionary process of soil skeleton structure which gradually becomes weathered, loose, and peels off under the multi-field coupling of water, temperature, salt, and mechanics. Considering the different controlling factors of the occurrence environment, revealing and characterizing the surface weathering process and the damage mechanism of the subcutaneous layer of earthen sites constructed with different technologies under the condition of multi-scale, multi-field coupling and time sequence combination is important for research into surface anti-weathering technologies, consolidation mechanisms, and inefficacy mechanisms, and reinforcing effect evaluation.

Considering the structural damage characteristics of different construction types of earthen sites, the calculation of the stability of the site body and reinforcement measures in the current protection practice is generally based on the limit equilibrium method or the numerical simulation of different platforms, but the limit equilibrium method is over-conservative, and cannot support fine protection. Furthermore, the numerical simulation calculation has non-uniform platforms, parameter values from researchers, model establishment, and calculation methods, leading to large differences in calculation results. Therefore, in the numerical simulation of stability evaluation for earthen sites, it is key to propose the construction and selection methods of geometry, the constitutive model, mechanical parameters, and structural characteristics for carrying out research on stability control technologies.

Additionally, due to the low strength of building materials, collapse, toppling, and other destructive damages would easily happen to the earthen sites that develop cracks, sapping, etc., under the functions of earthquakes, vehicle vibration, and other dynamic effects. Clarifying the structural instability mechanism of earthen sites built by different construction technologies under dynamic loading is very important to control the structural stability of earthen sites.

3.3. The Preventing and Controlling Technologies for Surface Weathering and Structural Instability of Earthen Sites

For a long time, surface weathering and structural instability have been difficult problems for the protection and reinforcement of earthen sites, and they are also directly related to the content of engineering measures for cultural relic protection and earthen sites. The technical system of earthen site protection and reinforcement in arid environments has gradually been formed, including anchor bolt anchoring, fissure grouting, rammed roof-propping, and surface weathering prevention. Bamboo composite bolt, wood bolt, steel bolt, and glass fibers have been developed or introduced, the grout of PS-F, PS-C, and calcined ginger nuts have been prepared, rammed roof-propping technologies with improved soil with calcined ginger nuts have been proposed, and PS-based chemical weathering reinforcement materials have been used in engineering practice; thus, this technology system is suitable for rammed earthen sites, but has some limitations for other earthen sites in different environments built by different technologies. Hence, according to the law of surface weathering and the structural damage of earthen sites in different environments built by different technologies, anti-weathering technologies need to be developed and improved, including chemical reinforcement, biological mineralization, soft capping and protective sheds; a series of structural stability control techniques for different environments need to be proposed; the durability of different materials and measures should be determined; the scope of the application of various measures should be confirmed; and stability control measures with a technical index system based on material strength enhancement and structural improvement should be established. These are the key technical challenges of earthen site protection. Conquering these problems will be beneficial to the long-term preservation and safe utilization of earthen sites in China.

3.4. Water Transport Mechanism and Prevention and Control Techniques

Controlling deteriorations caused by water transport is a long-term problem and challenge in the field of cultural heritage protection, and earthen sites in both arid and damp environments are facing deterioration caused by water transport. For example, owing to water transport, earthen sites in the arid environment develop sapping in their bottom, and earthen sites in the damp environment develop drying shrinkage, cracking, and water pouring (Figure 8). Such problems will threaten earthen sites to develop collapse, degradation, and flush erosion, in addition to the amount of water involved. Therefore, carrying out research on the mechanisms of water transport and damage will play a positive role in revealing deterioration mechanisms and forming protection technologies for earthen sites.

(**A**) (**B**)

Figure 8. Water deterioration in arid and damp environments. (**A**) Sapping caused by water transport; (**B**) water pouring.

Considering the water source, such as snowfall, precipitation, underground water, etc., which earthen sites have to face, especially for underground water problems for earthen sites in wet and damp environments, combined with the deterioration characteristics of water, the technical system of water disaster prevention and control is based on "drop discharge resistance", and considers the problems of soil particle loss and structural damage caused by water transport. This will lay a foundation for the beneficial environment of earthen site conservation and other protective consolidation measures.

3.5. Quality Control in the Protection Process and Evaluation Technology of Reinforcement Effects

The establishment of protective consolidation technology systems can provide a technical route and an implementation scheme for the deterioration management of earthen sites. However, how to obtain good reinforcement effects and long-term serviceability, how to build key technical nodes of protective consolidation measures and control index thresholds, and how to select consolidation evaluation methods and equipment are very important questions. Therefore, to address problems such as incomplete quality control method systems in the protection process and the poor suitability of special evaluation devices, proposing indicators and thresholds of quality control and effect evaluation in the protection process, establishing corresponding technology systems of quality control and effect evaluation, confirming the detection index and accuracy, as well as the detection method and application scenario, developing special equipment for quality control and effect evaluation in the protection process, and realizing non-destructive/small-loss, fast, high-precision and reliable methods of quality control and effect evaluation in the consolidation process of earthen sites has become the best way to protect and reinforce earthen sites to achieve good results.

3.6. Comprehensive Protection Technologies under Synergistic Effects

The ultimate goal of earthen site protection is to display the rich values and connotations contained in these precious cultural heritage sites for present and future generations, but currently the inharmonious and inconsistent phenomena of management, utilization, protection, and research around earthen sites are problematic. Hence, on the basis of the outstanding universal value of earthen sites, with earthen site protection technology and site conservation status in arid, wet, and damp environments in mind, analyzing and evaluating the influence of management, prevention, protection, and utilization of the sites, proposing guidelines and regulations for the use of management, prevention, intervention and utilization measures in different regional environments and conservation conditions, and establishing a comprehensive collaborative protection system integrating the recognition, preservation, and inheritance of earthen sites, paying equal attention to management and protection technologies, and combining prevention with protection and maintenance, are the important measures for long-term preservation and the safe utilization of earthen sites.

4. Construction of Research Ideas for Earthen Site Protection under Multi-Field Coupling

4.1. Research on Regional Characteristics and Occurrence Relationship of Earthen Site Deterioration

4.1.1. The Classification of Regional Occurrence Environment

In accordance with the natural physical geographical environment and tectonic environment, with temperature, humidity, sunshine, rain, snow, wind, etc., in mind, in occurrence areas of earthen sites, and with reference to the research results of regional environmental climate zoning based on precipitation, aridity, and humidity index, the occurrence environment regions of earthen site protection can be classified as arid, wet and damp; based on formation lithology, landform, active faults, earthquakes and other internal dynamic geological actions, the regional geological occurrence environment of earthen sites with building materials and earthquake risk can be classified to illustrate the environmental characteristics of different regions. These works will lay a foundation for construction technology, degradation mechanisms, protection technology and effective protection evaluation of earthen sites.

4.1.2. Research on the Relationship between Earthen Site Construction Technology and Regional Occurrence Environment

According to historical data, building materials, building form, structural characteristics, and construction technology, the specific number, names, types, and locations of earthen sites in China can be investigated, and the classification standard of earthen sites can be proposed and applied. Moreover, the evolution process of different building technology with historical development can be explored to reveal the evolution characteristics of the traditional construction technology of earthen sites. By selecting representative earthen sites in different climatic and geological environments, the correlation between building technologies and occurrence environmental elements such as landform, climate, stratum lithology, and geological structures can be analyzed to clarify the relationship between earthen site construction technology and regional occurrence environment. These works can provide basic information for research on the development characteristics of the deterioration of earthen sites.

4.1.3. Research on the Relationship between Deterioration Chains and Regional Occurrence Environments

The typical deterioration of earthen sites in different environments and construction technologies can be investigated based on the current deterioration classification system of earthen sites to establish the classification and grading standards of deterioration. By selecting typical sites, the development characteristics of deterioration, including surface weathering, gullies, cracks, sapping, and collapse, can be finely measured and quantitatively characterized. Comprehensively taking into account climatic and geological environmental elements, the characteristics of the development scale, and distribution, the evolution of deterioration in different environments can be collected and analyzed to clarify dominant causes in different development phases of deterioration in the division environment. Moreover, we can explore the periodic development law and internal relation of different deteriorations, reveal the chain relationship of transformation and stacking among different deteriorations, and build the deterioration chains of earthen sites in different regional occurrence environments, providing the basis for further research on the mechanisms, control and cooperative protection of deterioration.

4.2. Research on Weathering Mechanisms and Prevention Technologies

4.2.1. Weathering Mechanism of Earthen Sites in Multi-Field Coupling

On the basis of the relationship research on regional environment and deterioration, the boundary conditions and loading modes of multi-field coupling for climatic elements in different occurrence environments can be confirmed. According to the environmental characteristics of arid, wet, and damp regions, the simulation of environmental conditions in a time sequence of multi-field coupling can be established; the full-scale simulation experiment walls with different technologies can be prepared; the multi-field coupling simulation experiment can be carried out; influencing factors, including water, temperature, salt and mechanics in multi-field coupling, can be quantitatively characterized; the evolution process of earthen sites from weathering produce, introduction, development and accelerated destruction in different conditions can be recognized; and the deterioration characteristics of different evolutionary processes can be illustrated. Then, the mechanism of weathering development in multi-field coupling can be revealed.

4.2.2. Comprehensive Anti-Weathering Technologies for Earthen Sites

The technologies include the evaluation of earthen sites using different reinforcement materials to develop reinforcement material ratio and technology suitable for different types and degrees of weathering deteriorations, the definition of the scope and conditions of different protective materials, and the formation of chemical reinforcement technology with adjustable strength, good compatibility, and strong weather resistance. The function mechanism of biomineralized materials can be researched, and biological mineralization anti-weathering technology can be explored. By selecting and cultivating biological soft capping species with strong adaptive and environmentally friendly abilities, earthen sites using soft cover anti-weathering technology can be developed. Through assessing the earthen sites' conservation status and the protection technology of semi-enclosed and closed site protection sheds, the guidelines for the design of earth site protection sheds can be proposed. Thus, a complete set of anti-weathering technology, including chemical reinforcement, biological mineralization, soft cover, and shelter in different preservation conditions, can be integrated.

4.2.3. Applicability and Durability of Anti-Weathering Technology

By comparing and analyzing macro and microstructure characteristics and properties of samples among unconsolidated, chemically consolidated, biomineralization and soft capping reinforcement, long-term service performance and the failure mechanisms of different protection measures can be revealed, and the mechanisms and protective effects of semi-enclosed and enclosed site protection sheds on earthen sites can be evaluated. The environmental adaptability and durability of different protection measures can be confirmed, and the suitability range of different anti-weathering measures can be proposed.

4.3. Study on Structural Instability Mechanism and Preventive Control Technology of Earthen Sites under Static and Dynamic Loads

4.3.1. Study on Response Mechanism and Stability Evaluation Method of Earthen Sites under Static and Dynamic Loading

By finding out the relationship between the stability of earthen sites with different construction and traditional techniques, architectural forms, and structural and deterioration characteristics, proposing construction and selection methods with geometric form, constitutive models, mechanical parameters, and structural characteristics in the numerical simulation of earthen site stability evaluations, and quantitatively describing the gradual and instantaneous destruction processes of site bodies, the structural response mechanism of the site under static forces can be revealed. The model suitable for the stability calculation of earthen sites can be developed, and through the verification of the full-scale simulation test and modification of the calculation model, the stability evaluation methods of earthen sites should be formed. By performing the full-scale simulation tests of shaking tables, destruction modes under different dynamic loads can be researched to reveal the dynamic response law. The numerical simulation will be carried out based on the physical simulation test results, and then progressive and transient failure models of earthen sites under dynamic loading can be constructed, and the evaluation method and quantitative index of site stability under dynamic loads can be proposed.

4.3.2. Research on the Technology of Structural Stability Control under Dynamic Loads

By preparing a simulated test wall made with roof-propping reinforcement, anchorage grouting, strapping cable pulling, and other protective measures, the dynamic response and damage degree of the site body and reinforcement system under dynamic action can be studied using a simulated shaking table experiment, and the vibration response characteristics of earthen sites and reinforcement systems can be analyzed to clarify mutual feed mechanism and response law. Taking advantage of numerical simulation to optimize stability control measures, the anti-seismic property should be improved; support reinforcement technologies with compatibility between solid and sapping parts, anchorage grouting technology matching anchorage grouting with cracked site sections, and the technique of binding cable pull with the loose site and tight binding cable will be formed. Moreover, stability control measures and technical index system based on material strength enhancement and structural improvement can be proposed.

4.3.3. Applicability and Durability of Structural Stability Control Technology

By using numerical simulation to calculate the service performance and structural failure mechanism under different environmental conditions, the environmental suitability of roof-propping reinforcement, anchorage grouting, and strapping cable pulling should be evaluated. Through performing multiple loading tests on the shaking table, the dynamic coupling and sequence combination conditions of different reinforcement measures can be identified, the damage degree of the structure after different vibration frequencies will be detected in a timely manner, the failure mechanism and modes of the site structure can be revealed, the durability of different structural stability control techniques can be evaluated, and then a series of evaluation methods for the structural stability of earthen sites can be formed.

4.4. Research on the Damage Mechanism of Water Transport and Prevention and Control Technology

4.4.1. Research on the Damage Mechanism of Water Transport

Combined with the water resources of earthen sites, including precipitation and underground water, their boundary conditions and loading modes in arid, wet, and damp environments can be constructed. Referring to representative sections of earthen sites in different environments, full-scale test wall and archaeological profile models can be prepared, and the process and distribution characteristics of water transport under rainfall and groundwater can be monitored in these models. Then, the breeding process of typical deterioration types such as water accumulation, gully, and pipe gushing at the top and bottom of the model and the degradation process of the model root caused by repeated changes in the groundwater capillary infiltration line can be quantitatively characterized, and the mechanisms of water transport and damage under rainfall and groundwater will be illustrated.

4.4.2. Prevention and Control Technology of Water Damage

Combined with the relationship between deterioration chains and the regional occurrence environment, the full-scale model and test wall can be prepared for typical deteriorations such as water accumulation at the top and root, gullies, and groundwater immersion erosion in earthen sites. Calcined ginger nuts and lime should be used to carry out the remediation of drainage in the top and bottom and gullies. By performing a simulated rainfall test to evaluate the durability, compatibility, and coordination of measures with different proportions, the prevention and control technology of water damage in the arid environment can be utilized. Based on the wet and damp environment, engineering practice, and field tests, the drainage of regional groundwater and the monitoring of water level for site bodies can be carried out, combined with hydrogeological engineering to form groundwater level control technology. Using the full-scale model of groundwater soaking, replacement and drainage tests will be performed, and wall stability and the particle loss in the replacement grooves should be monitored to form the groundwater replacement and drainage technology, which will integrate stability support, particle protection of the trench wall, pebble replacement, and top backfill restoration of the trench.

4.5. Research on Equipment Development and Evaluation Methods of Quality Control of the Protection Process

4.5.1. Quality Control and Effect Evaluation of Anchorage Grouting

Comprehensively considering the construction technology, the properties of construction materials, the scale and characteristics of dangerous soil, and the evaluation results of mechanical stability, the suitability range of anchorage grouting for earthen sites reinforcement can be discriminated. For anchorage technology, the key control nodes will be condensed, the quality control index and corresponding threshold values of the anchorage process can be determined, and the quality control technology system of the anchorage process can be formed. Based on the requirements of the evaluation of the anchorage effects, an effect-evaluation model will be established, and a technical system of anchorage effect evaluation can be constructed to realize the health diagnosis and evaluation of the anchorage system in the service period. For grouting reinforcement technology, according to the quality demand of the whole grouting process, the key control nodes will be condensed, the quality control index and corresponding threshold values of the grouting process can be constructed, and the quality control technology system of the grouting process can be formed. The grouting effect evaluation technology system can be constructed to evaluate the grouting health diagnosis and the service period.

4.5.2. Quality Control and Effect Evaluation of Roof-Propping Reinforcement

The application scope of traditional ramming and masonry reinforcement technology can be determined based on the simulation test wall and engineering practice, comprehensively considering the geometrical form of sapping, construction materials and technology, and the stability evaluation results under static and dynamic loads. According to the quality requirements of the whole process of the ramming, the key control nodes will be condensed, the quality control indexes and corresponding thresholds will be determined, and the quality control technology system of the ramming can be formed. According to the quality requirements of the whole process of masonry roof support, the key control points can be condensed, the process quality control indexes and corresponding thresholds can be determined, and the quality control technical system of masonry roof support can be formed. Based on the evaluation requirements of ramming and the masonry roof-propping reinforcement effect, the comprehensive evaluation system of roof-propping reinforcement can be established to realize the health diagnosis and evaluation of roof-propping reinforcement in its service period.

4.5.3. Quality Control and Effect Evaluation in the Anti-Weathering Reinforcement Process

Based on the characteristics of surface anti-weathering technology, the physical and mechanical properties of earthen sites, the special requirements of cultural relic safety, and the application scope of chemical reinforcement, biomineralization, and soft capping techniques should be discriminated. According to the quality requirement of the anti-weathering process technology, the key technology and parameters that influence reinforcement process quality control will be researched to refine the key control nodes, determine the process quality control index and the corresponding threshold, form the quality control technology system of anti-weathering reinforcement, and quantitatively evaluate the compatibility and weather resistance of different reinforcement measures. The indirect determination mathematical model of the key parameters of the evaluation of weathering resistance can be explored to realize the rapid determination of the evaluation parameters of the reinforcement effects of weathering resistance on the surface of earthen sites and meet the health diagnosis and quantitative evaluation of the impact of weathering body reinforcement.

4.5.4. Quality Control Equipment and Effect Evaluation Equipment for the Reinforcement Process

Combined with the demand for quality control and effect evaluation for the special equipment for anchor grouting, topside reinforcement, and surface anti-weathering, sensor components with good stability and performance optimization can be discriminated to carry out the structure optimization of the sensor and improve the complex environment adaptability, accuracy and reliability of corresponding sensors. By carrying out the miniaturization integration of measurement function components and selecting typical sites to verify the reliability and stability of various sensors, the damage to the earthen sites can be minimized to the greatest extent. A complete set of special equipment for the rapid determination of earthen sites with multiple indicators will be developed to achieve the non-destructive/minor damage, rapid, high-precision, and reliable goals of quality control and effect evaluation in the reinforcement process of earthen sites with different measures.

4.6. Study on Synergistic Mechanisms of Comprehensive Protection Measures for Earthen Sites

In order to reverse the situation of "emphasizing reinforcement and neglecting prevention and management" in earthen site protection, the status of the comprehensive protection of earthen sites in China will be systematically investigated, and the impact and contribution of management, prevention, intervention, utilization, and other protection measures on the recognition, preservation, and inheritance of site values can be analyzed and evaluated. Using the theory of risk management, the risk sources resulting in site degradation will be recognized to find out the dominant degradation control risk factors. By using the fuzzy analytic hierarchy process (AHP), comprehensive protective measures, including management, prevention, intervention, and utilization will be optimized to form the compatibility, commensalism, and promotion model. The synergetic optimization scheme can be put forward, the technical standards can be set, and a comprehensive protection system with the integration of cognition, preservation, and inheritance can be constructed.

5. Discussion and Outlook

Since the 1990s, the research and practices around earthen site protection in China have experienced the stage of rescue protection, and the theoretical basis and technical systems for the protection and reinforcement of earthen sites in arid environments have been initially formed so that many precious earthen sites have been safely preserved. At present, practices of earthen sites conservation are being transformed from rescuing protection only, to attaching equal importance to rescuing and preventive protection. Considering earthen sites in the different occurrence environments, such as arid, wet, and damp environments, it is necessary to summarize and absorb the experience of protection research and the engineering practice of earthen sites in the arid environment on the basis of a large number of existing studies. Combined with the above research ideas of earthen site protection under the coupling of multiple fields, this research work, including building a comprehensive protection measures framework containing management, prevention, intervention, and utilization based on the outstanding universal values of earthen sites, and constructing a protection and reinforcement technology system for earthen sites under different environments, can improve the health status of earthen sites, and also lay a foundation for the future protection of Chinese earthen sites to step into the stage of preventive protection (Figure 9).

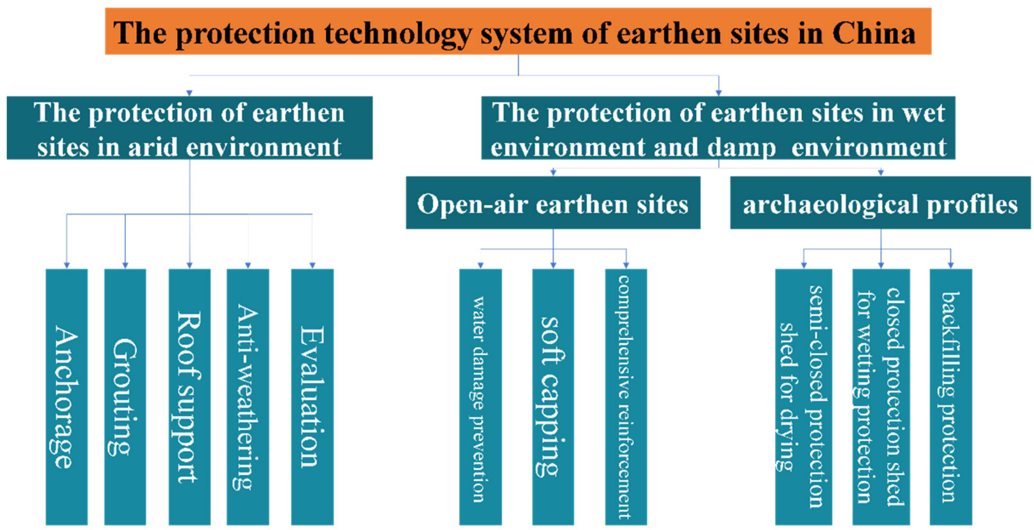

Figure 9. The frame illustration of the technology system of earthen sites in China.

Considering earthen sites in arid environments, based on the existing technology system including anchorage, grouting, roof-propping, and weathering prevention for earthen site protection, deterioration mechanisms can be further revealed, the mechanisms of reinforcement and failure in protection measures can be illustrated, the key technology nodes can be screened, the control index thresholds can be defined, and special protection and reinforcement effect-evaluation devices for earthen sites can be developed to form evaluation methods. Exploring the scientific path of the technological iteration of earthen sites in arid environments will accumulate more and more mature experience for the protection research and engineering practices of earthen sites in wet and damp environments.

With regard to the large open-air earthen sites in wet and damp environments, combined with the current situation of high coverage vegetation, vegetation deterioration should be cleaned up by scientific and reasonable means, and the historical features and contours of the site body should be reasonably displayed; by referring to the protective technology experience of earthen sites under arid environments, suitable protective materials and consolidation technologies suitable for wet and damp environments for cracks, collapse, gullies and other deteriorations have been developed. Considering the characteristics of shallow underground water level in wet and damp environments, change fill drainage technology was developed to lower the water table and drain the leaking water quickly. Finally, a protection technology system based on water damage prevention, taking the soft capping as the main and comprehensive protection and reinforcement as the auxiliary, should be preliminarily constructed, and a quality control system and protection effect evaluation system will be gradually formed.

In terms of the archaeological profiles of earthen sites in wet and damp environments, based on the protective framework of semi-closed protection sheds for drying protection, closed protection sheds for wetting protection [49], and backfilling protection for open-air environments, considering the requirements and management capabilities of protective sheds, and groundwater replacement and drainage measures, a protection technology system for the archaeological section of earthen sites in wet and damp environments can be formed, by combining with preservation environment control, site surface weathering and structural instability control prevention. Among them, by means of a semi-closed protection shed for drying and groundwater control, the site micro-environment can be transformed into a drought state, and then the earthen site protection technology in the arid environment can be used to reinforce earthen sites. In terms of closed wet environments, the protection shed can be used to control the micro-environment of the archaeological profile in a state of small fluctuation, to minimize the shrinkage crack and weathering caused by drastic changes in the environment; meanwhile, the use of physical, chemical, biological and other means in a closed environment controls the development of microbial deterioration.

6. Conclusions

In this paper, based on existing research in the field of earthen site protection and a lot of engineering practice experience, the main characteristics of the problems of earthen site protection under multi-field coupling effects, including construction technology, climate environment, dynamic load, and protection measures, were summarized, and the key scientific and technical problems in the protection of earthen sites were indicated. At present, the protection of earthen sites in China still needs strengthened by carrying out the following work:

1. Based on the compilation of the national earthen site list, combined with the research results of climatology and geology, the regional occurrence environment of earthen sites should be divided, and the classification standard of earthen sites and the classification standard system of earthen site deterioration should be clarified to construct and illustrate the relationship between site construction technology, deterioration development, and the regional occurrence environment.
2. Based on the multi-field coupling of climate environment, groundwater, and earthquake loads, the degradation mechanism of earthen sites should be researched to reveal the surface weathering mechanism of earthen sites in different environments and processed by different building technologies to build stable evaluation methods and structural damage mechanisms for earthen sites under static and dynamic

loads, and to reveal the water transport and damage mechanisms under rainfall and groundwater.

3. The technologies of surface weathering prevention, structure stability control, and the prevention and control of water damage should be researched and developed, which is applicable to different environments and technology types of earthen sites. The quality control index system in the protection process should be built, the applicability and durability of different protection measures should be clarified, and a complete set of quality assessment equipment and methods for earthen site protection should be developed.
4. Based on the outstanding universal value in earthen sites, under the synergistic effect of management, prevention, intervention, and utilization, the comprehensive protection technology system of earthen sites in China should be established, including the protection and reinforcement technology system of earthen sites in arid environments, technical systems for the protection and reinforcement of large open-air earthen sites, and archaeological sections in wet and damp environments.

Based on the recognition, research, and practice experience of our research group on Chinese earthen sites, the research content and conclusions in this review proposed the key problems, research thought, and technical systems suitable for Chinese earthen site protection, which has a certain reference value for other countries, but is not recommended to be directly copied. In the future, combined with the key issues and research ideas proposed in this paper, our group will gradually carry out further research in order to solve different problems of earthen site protection, providing more references for domestic and foreign counterparts.

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