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# Discussion on the environmental adaptability of weather-resistant measures for earthen sites in China

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## Abstract

Earthen sites are important remains of past human societies. Weather-resistant measures comprise a major part of conservation efforts for earthen sites. Marked advancements in weather-resistant techniques have been made in recent years. Earthen sites are characterised by large numbers, large scales, various types, complex compositions, and diverse existing environments. Weather-resistant measures differ significantly in their environmental adaptability. The environmental adaptability of weather-resistant measures severely restricts further development and popularisation of weather-resistant technology at earthen sites. Based on the environmental and weathering characteristics of existing earthen sites in China, the consolidation and failure mechanisms of several weather-resistant measures (penetrating consolidation, sacrificial layers, soft capping, protective structures, and backfilling protection) were examined. The potential areas to increase the success of the different weather-resistant measures were obtained combined with the characteristics of various environmental boundaries.

**Keywords:** Earthen site, Weather-resistant measure, Environmental adaptability

## 1 Introduction

Earthen sites are relics left during production, life, and other activities throughout human history. Earthen sites carry not only abundant historical information but also the wisdom of human social development. Earthen sites are important cultural heritage sites. Earth is the earliest building material used by humans. Earthen sites also constitute one of the earliest building types in human history. Earthen sites are widely distributed worldwide. Based on different functional usages, ancient Chinese earthen sites can be broadly divided into five categories, namely, Neolithic residential sites, ancient cities, mausoleums, Great Wall sections and ancillary defence structures, and excavated pits, caves, kilns and cellars (Li et al. 2009). Approximately one-third of China's 767,000 immovable

cultural relics comprises earthen sites. More than 70% of 21,000 kms of the Great Wall and 43,000 related facilities are constructed of earth. In China, earthen sites exhibit the characteristics of large numbers, various types and wide distributions.

Most earthen sites are exposed. Under the action of environmental factors over thousands of years, different types of decay phenomena could develop at these earthen sites, which could seriously affect preservation. According to the types of protection measures, the decay process at earthen sites can be divided into two categories. One category involves structural decay, which affects the stability of sites, such as collapse, undercutting, and cracking. Through many years of interdisciplinary research and technological improvement, many mature technologies have been applied in regard to the structural decay process at earthen sites (Wang 2008, Sun et al. 2008, Chen et al. 2016), and satisfactory results have been obtained. The other category encompasses weathering decay. This phenomenon mainly develops in the shallow

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surface layer of sites and slowly erodes sites through different environmental factors.

In terms of protective types, weather-resistant protection measures can be divided into two categories. One category entails the enhancement in the mechanical strength of the weathering layer, and the other category aims to inhibit or reduce the impact of weathering factors. There are ways to accomplish both processes. At present, the mainstream weather-resistant measures employed at earthen sites include penetrating consolidation (Li et al. 2009), sacrificial layers (Wang et al. 2020), soft capping (Kent 2013), protective structures, back-filling protection, etc. Because earthen sites exhibit the characteristics of large numbers, diverse types, wide distribution ranges and complex environmental conditions, weather-resistant measures for earthen sites under different environmental conditions achieve varying adaptabilities.

Weather resistance via reinforcement is one of the core issues of earthen site protection. In recent years, notable progress has been attained in weather-resistant protection measures for earthen sites, but there remain problems that must be solved. At present, there are many types of weather-resistant reinforcement technologies. However, most of these technologies still occur at the laboratory testing and research stage, and few measures can be applied at earthen sites to achieve weather resistance and reinforcement. The evaluation system of the reinforcement effect on weather resistance is imperfect, and the scope of the different weather resistance measures remains unclear. This leads to incompatibility of various weather-resistant measures in practical applications. It is difficult to scientifically determine the applicable range of different protection measures. In this paper, the characteristics of weather-resistant measures across different earthen sites in China were examined.

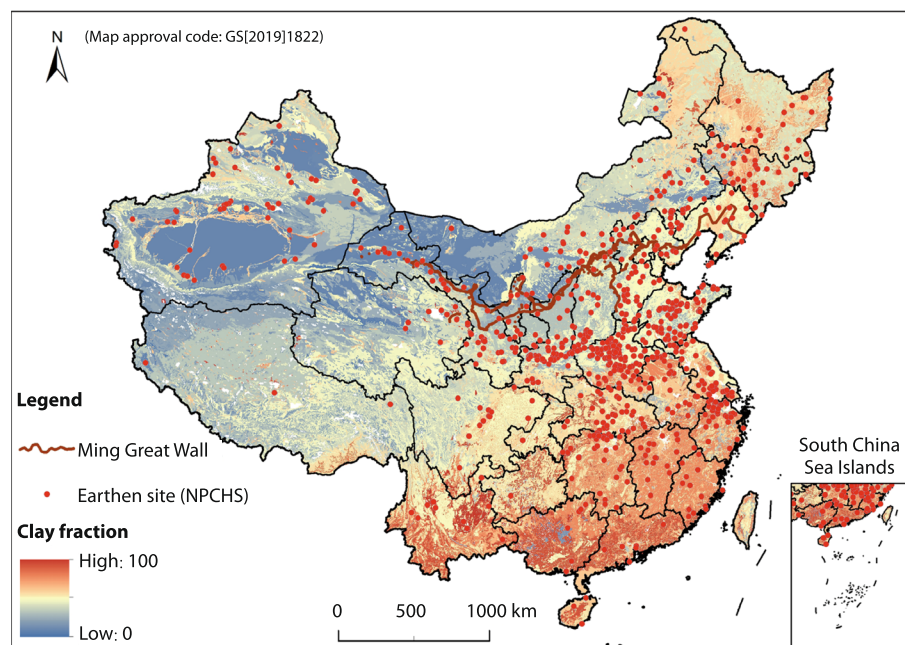
## 2 Existing environment and weathering characteristics of earthen sites

Weathering of earthen sites refers to changes in soil structure due to environmental changes, erosion under internal and exogenic forces, human activities and time factors, which causes soil structure variations and damages the appearance of cultural relics (Wang et al. 2014). Weathering is manifested as a weakening or disappearance of the binding force between soil particles at the surface of sites and an increase in particle spacing and even shedding, resulting in surface thinning and morphology change (Zhou 2003). Weather-resistant measures comprise a series of protective methods that inhibit the weathering process while maintaining the structure stable. Chinese academics generally consider internal and external causes as the two main weathering factors

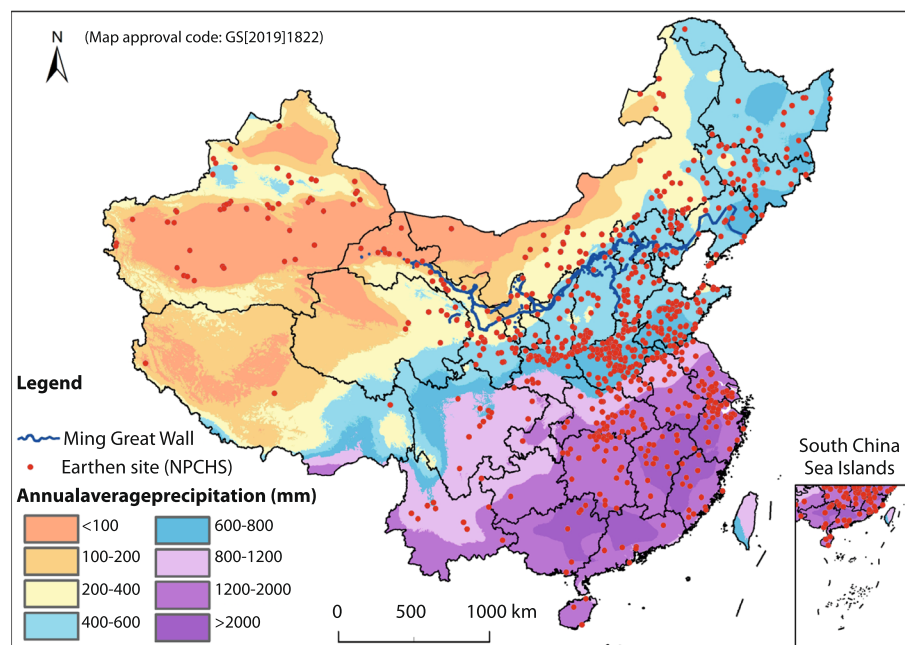
at earthen sites. Internal causes consider the earthen site composition and nature, while external causes mainly cover environmental factors that could influence the integrity of earthen sites. Combined with the definition of earthen sites proposed by Zuixiong Li (2013), Qiang-qiang Pei (Pei et al. 2019) and Huyuan Zhang (Zhang et al. 2008), the number (NCHA 2012) and distribution characteristics of earthen sites in National Protected Cultural Heritage Sites were obtained. The weathering characteristics of earthen sites were examined based on the existing environment.

Ancient humans often used local materials in the process of earthwork construction. The difference in soil particle size and mineral composition results in notable differences in the physical and mechanical properties of soil. Therefore, these differences could also result in earthen sites with different shapes, varying construction techniques and distinctive characteristics, such as earth excavation, earth ramming, adobe masonry, and wet mud stacking (Pei et al. 2019). Diverse construction technologies, soil properties and environments could yield different weathering degrees and preservation states of earthen sites. The soil particle size greatly influences the weathering conditions at earthen sites and the choice of reinforcement material. Among various parameters, the clay content is the key factor. This quantity directly affects the mechanical strength and weather-resistant ability of soil. According to the Chinese Soil Science Database, the distribution of the clay content at earthen sites exhibits distinct characteristics (Fig. 1). In humid areas (annual precipitation higher than 800 mm) of China, the clay content in site soil is high. This makes these sites more prone to shrinkage, cracking, expansion, and disintegration under weathering decay (Elert et al. 2015). However, in arid areas (annual precipitation lower than 200 mm) of Northwest China, the clay content is low. Therefore, the mechanical strength of earthen sites is relatively low, and their ability to resist wind erosion is low.

Water and temperature are important environmental factors influencing the weathering of earthen sites. Water affects earthen site weathering via rainfall, snowfall, groundwater, capillary water, and relative humidity. Precipitation is the main source of water. The spatial distribution of precipitation at earthen sites in China exhibits the following characteristics: the annual precipitation decreases from southeast coast inland to northwest inland regions (Fig. 2). The Great Wall of the Ming dynasty basically coincides with the 400 mm annual average precipitation contour line. Within the aforementioned 400 mm contour line, open earthen sites are widely distributed, especially along the Great Wall. The number of earthen sites is the largest within the 400–800 mm precipitation range (semi-humid area).



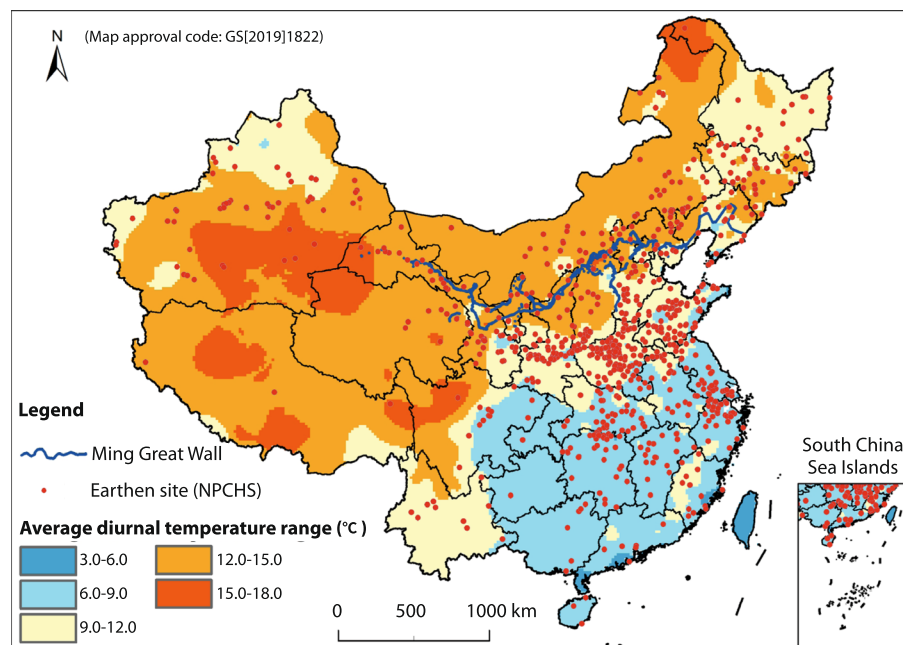
**Fig. 1** Distribution pattern of the fraction of clay particles at earthen sites in China (Source: National Earth System Science Data Center, National Science & Technology Infrastructure of China. Accessed 2018. <http://www.geodata.cn/data/datadetails.html?dataguid=1587975113163>. Background map approved by Map Vetting Center, Ministry of Natural Resources, PRC)



**Fig. 2** Characteristics of the annual average precipitation at earthen sites in China (Source: Resource and Environment Science and Data Center of Institute of Geographic Sciences and Natural Resources Research, CAS. Accessed October 2020. <https://www.osgeo.cn/data/wfae1>. Background map approved by Map Vetting Center, Ministry of Natural Resources, PRC)

Seasonally, there exists a large difference in precipitation between summer and winter. The southeast area receives half of its annual precipitation in summer. In arid areas,

winter precipitation accounts for only one tenth of that in summer. As a single factor, the temperature slightly influences the weathering process at earthen sites.



**Fig. 3** Characteristics of the annual average temperature and diurnal temperature range at earthen sites in China (Source: China Meteorological Data Service Center. Accessed June 2020. <http://data.cma.cn>. Background map approved by Map Vetting Center, Ministry of Natural Resources, PRC)

Temperature is often coupled with other factors as an auxiliary factor participating in weathering, which accelerates the weathering speed and aggravates the weathering degree. The spatial distribution characteristics of the various elements of temperature are also important for the applicability of weather-resistant measures. The average annual temperature in the southeastern coastal areas of China is higher than that in the northwestern inland areas. However, the diurnal temperature range in the northwestern areas is much larger than that in coastal areas (Fig. 3). Severe temperature differences could exacerbate weathering due to other environmental factors.

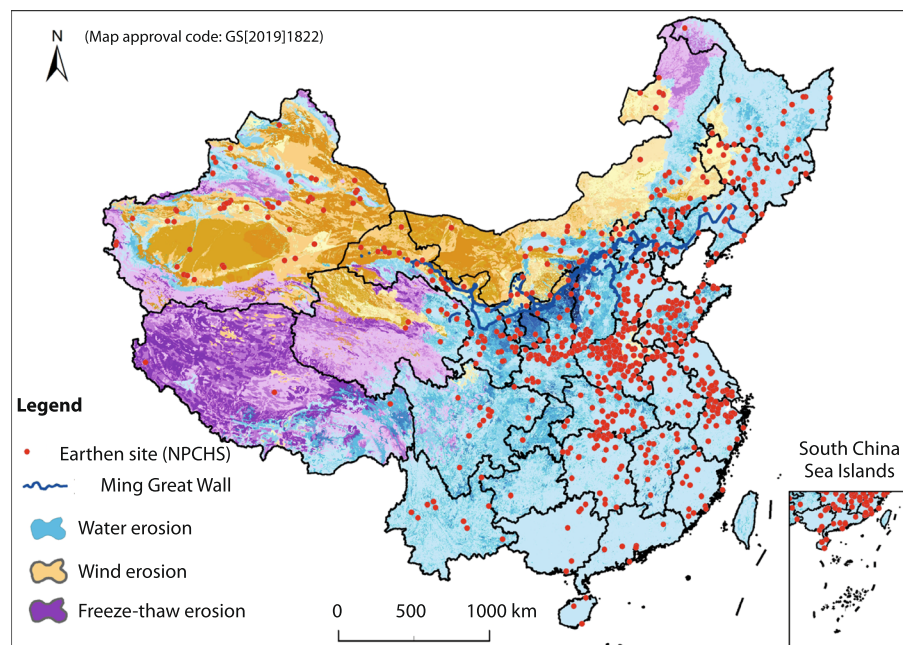
In China, the erosion characteristics of soil can also reflect the weathering characteristics of earthen sites to a certain extent. The 400 mm isohyetal line marking the boundary between water and wind erosion basically coincides with the Ming dynasty stretch of the Great Wall (Fig. 4). Wind erosion occurs mainly in arid and semi-arid areas in China. The number of sites in this region is relatively small, but these sites are mostly open sites, which are directly affected by wind erosion. In arid and semi-arid areas, consolidation of the weathering layer is an ideal measure to improve the resistance to wind erosion. Water erosion is mainly concentrated in semi-humid and humid areas. This region contains the largest number of earthen sites. The power of water erosion stems from precipitation. Precipitation causes weathering via scouring, groundwater flow, air humidity and other processes. The main types of weathering decay include shrinkage

cracking, expansion disintegration, mould, and rain erosion (Wang 2013a). In humid areas, the protection of earthen sites mainly considers the moisture content factor. At the present stage, protection methods aim to maintain site stability by controlling the water content or to change the protection conditions of earthen sites in humid areas into that those of earthen sites in arid areas (Zhang et al. 2011). Specific protection measures should be considered combined with the micro-environmental and decay characteristics of each site.

### 3 Adaptability of the different weather-resistant measures

#### 3.1 Penetrating consolidation

Considering the scale of earthen sites, preservation environment, weathering characteristics and soil properties, penetrating consolidation application at earthen sites is currently a popular research direction (Pan et al. 2020, Li et al. 2011, Wei et al. 2012, Chen et al. 2018, Zhang et al. 2021). Penetrating consolidation improves the weather-resistant ability of soil by penetrating the weathered layer at the surface of sites to increase the mechanical strength. Researchers have developed a wide variety of consolidants, which can be divided into inorganic materials (Li et al. 2011, Wei et al. 2012), organic materials (Zhang et al. 2021), and composite materials (Chen et al. 2018) according to their properties. These consolidants are typically adsorbed onto the surface of soil particles, thus strengthening the connection between

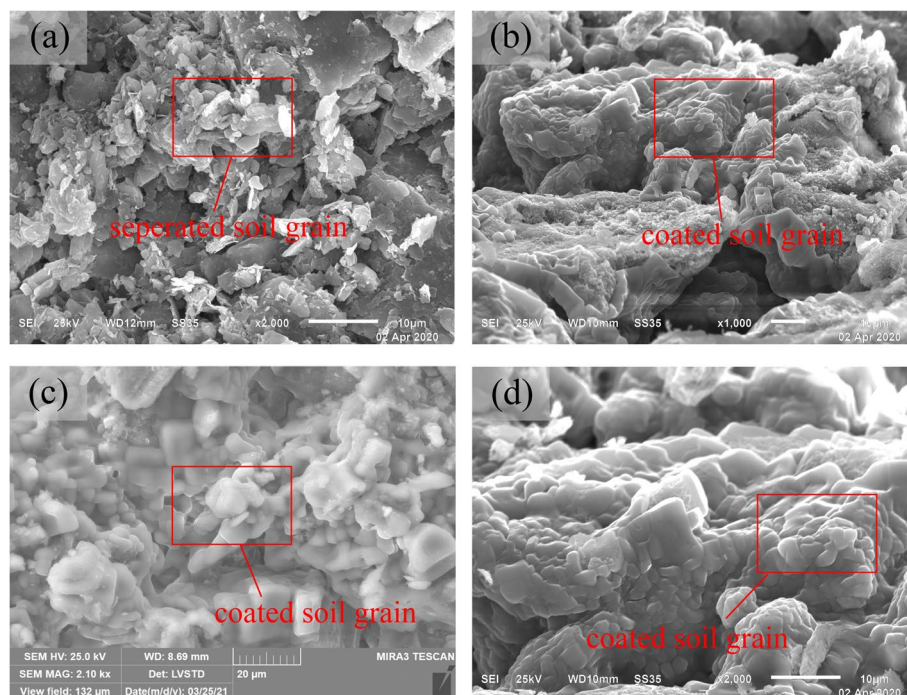


**Fig. 4** Spatial distribution pattern of the different erosion types occurring at earthen sites in China (Source: Resource and Environment Science and Data Center of Institute of Geographic Sciences and Natural Resources Research, CAS. Accessed 2018. <https://www.resdc.cn>. Background map approved by Map Vetting Center, Ministry of Natural Resources, PRC)

soil particles (La Russa et al. 2019). The soil in Suoyang city, a typical site with a low clay content in Northwest China, was selected as a sample. Potassium silicate (PS [Li et al. 2011], inorganic material), ethyl orthosilicate (organic material) and nano-SiO<sub>2</sub> sol (composite material), which have been widely used as reinforcement materials, were employed to observe the bonding relationship between soil particles before and after reinforcement. The following conclusions could be drawn from this experiment: before reinforcement, soil particles occurred in the form of dangling or granular contact structures, and cement was observed in the pores. The skeleton particles were mainly single particles with lamellar forms, and most particles occurred in point contact (Fig. 5a). After consolidation treatment, soil particles were adsorbed or coated by consolidants. Point contact between particles was gradually transformed into surface contact. With increasing contact area, a dense network structure was formed via particle agglomeration and cementation (Fig. 5b-d) to increase the soil mechanical strength. In most cases, during weathering layer reinforcement, consolidants are adsorbed on the surface of clay mineral particles. The reinforcement process generates adhesive films that adsorb or encapsulate clay mineral particles without affecting the skeleton and pores between the clay particles. Pores remain connected, so the soil permeability is almost unaffected. At the same time, these materials tend to provide a very good stability

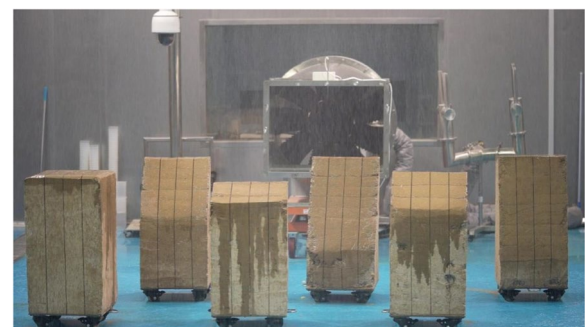
and weather-resistant ability. Under certain conditions, consolidation treatment is an ideal weather-resistant reinforcement measure. High-modulus K<sub>2</sub>SiO<sub>3</sub> (PS) provides a satisfactory treatment effect in the arid region of Northwest China (Li and Wang 1997).

However, penetrating consolidation also suffers certain limitations. Due to the adsorption of clay minerals, the reinforcement material is adsorbed by surface clay minerals in the penetration process from the surface to the interior, which leads to colloidal agglomeration. During penetration, the solute and solvent are separated. The solute becomes increasingly enriched in the surface layer, while the solvent continues to deeply penetrate, resulting in a smaller thickness of penetrating reinforcement. The higher the clay content is, the more obvious the above phenomenon. Therefore, penetrating consolidation cannot be used to reinforce relatively thick weathering layers. When the weathering layer is thick, consolidants cannot completely penetrate, and a layered interface with different mechanical properties can be formed in the weathering layer. The external environment can easily affect the generated interface and cause the reinforcement layer to detach. In terms of temperature, the thermal expansion coefficient of soil generally ranges from 6 to 12E-6/K. Even at a temperature difference of 60 °C, the thermal expansion rate is lower than 1%. In addition, the employed reinforcement materials effectively connect soil skeleton particles in different



**Fig. 5** Soil microstructure before and after chemical consolidation with different materials: (a) untreated soil, (b) treated with PS, (c) treated with colloform nano-SiO<sub>2</sub>, and (d) treated with orthosilicate (Source: the authors)

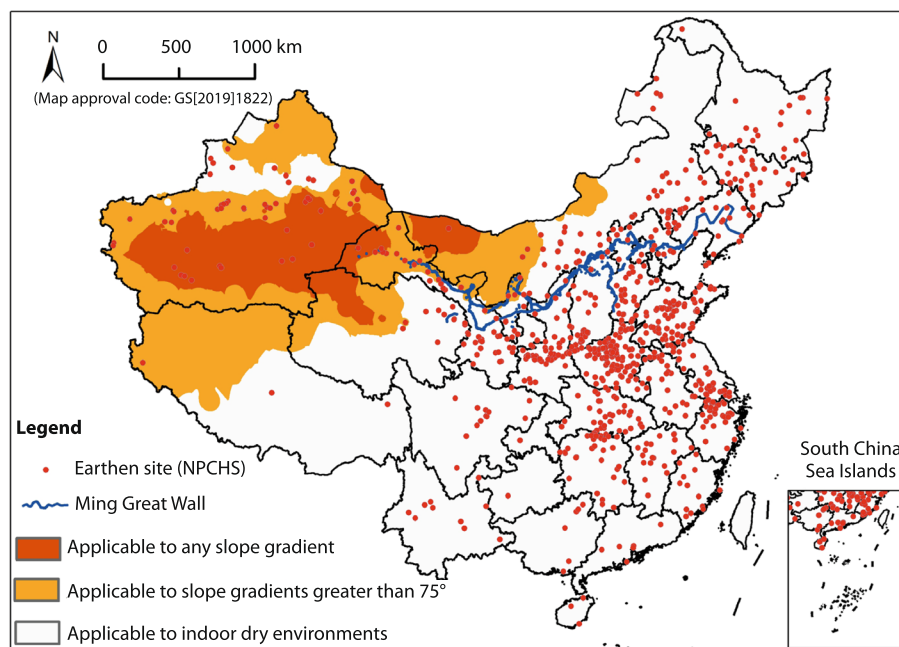
ways, which results in directional expansion of mineral components, thus limiting irregular expansion and deformation of soil particles. The magnitude of differential expansion and contraction caused by temperature is very small. Therefore, the influence of temperature on the reinforcement layer is not obvious. In the case of water, soil expands and contracts to different degrees under the action of water. The soil expansion and contraction rates across different sites vary between 1 and 10%. While the applied reinforcement material solidifies the treated soil, the activity of clay minerals is also constrained. The capacity of soil to expand and contract under water can be inhibited after reinforcement (Elert et al. 2008). Differential expansion and contraction on both sides of the reinforcement layer is the main reason for failure of the reinforcement layer. The experiment indicated that soil expansion and contraction mainly occurred at the capillary water stage. Whether or not capillary water crosses the interface of the reinforcement layer is the critical condition for the application of penetrating consolidation (Zhang 2021). Under certain conditions, penetrating consolidation represents an ideal weather-resistant reinforcement measure. PS materials have also been verified to provide satisfactory weather-resistant effects in arid areas of Northwest China (Li et al. 2008). Penetrating consolidation materials develop similar consolidation and failure mechanisms. By simulating rainfall conditions



**Fig. 6** Rainfall simulation experiment of PS reinforcement materials (Source: the authors)

in Northwest China (Fig. 6), combining rainfall and failure mechanisms, slope design at different sites, and monitoring the preservation status of the reinforcement layer and layered interface during rainfall cycles, the application scope of penetrating consolidation materials could be preliminarily obtained.

Considering the weathering characteristics of sites, soil properties and spatial-temporal distribution characteristics of precipitation, penetrating consolidation exhibits a higher probability as a suitable choice for consolidation interventions at earthen sites in extremely arid areas of China (Fig. 7). There also exists a correlation between the slope of earthen sites and precipitation. The impact



**Fig. 7** Potential areas for the application of penetrating consolidation in China (Source: Zhang 2021. Background map approved by Map Vetting Center, Ministry of Natural Resources, PRC)

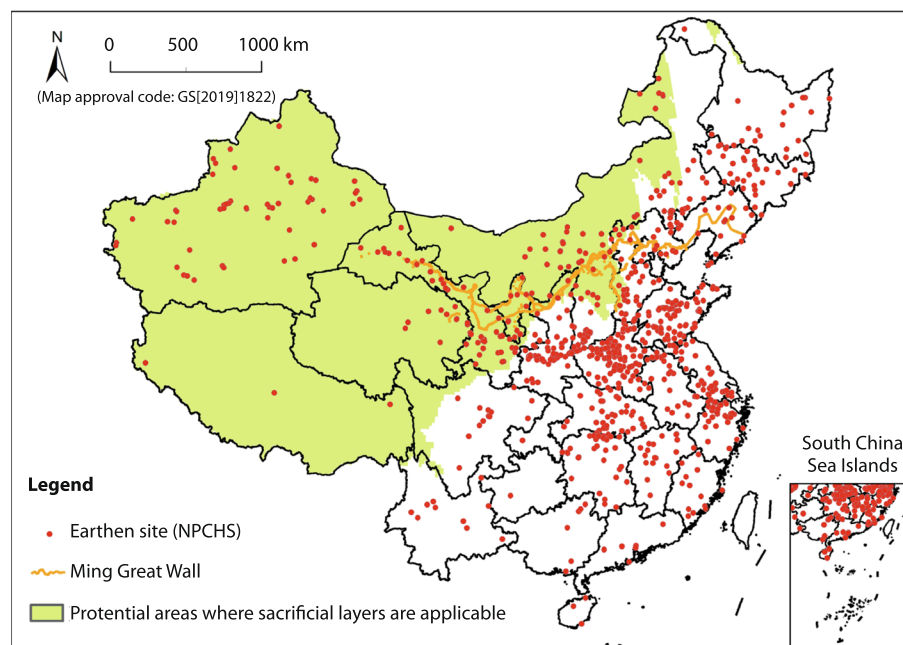
of slope on rainfall must be considered. The higher the slope of the site surface is, the lower the rainfall per unit area of the slope and the lower the penetration amount. Under the precipitation intensity in arid areas, the precipitation penetrating depth is smaller than the thickness of the reinforcement layer, and the dry–wet change process slightly influences the interface of the reinforcement layer. Therefore, penetrating consolidation provides a better durability. However, the applicability should also be determined after evaluation and field experiments based on the catchment characteristics of the site surface. In an indoor environment or unaffected by water conditions, this measure could also be considered after experimentation. The selection of appropriate protection measures for a specific site must be evaluated after determining the site cultural significance and site, environmental, and material conditions.

### 3.2 Sacrificial layer

The weather-resistant mechanism of the sacrificial layer aims to cover the site surface with a mud layer to ensure that exogenic forces first destroy this mud layer to protect the site. The sacrificial layer method can reduce the influence of weathering factors. To prolong the life of the sacrificial layer, plant fibres are usually added to improve the erosion resistance of the sacrificial layer. Hemp fibres exhibit a very high toughness. Owing to their toughness, the addition of hemp fibres improves not only the overall mechanical strength (Tang et al. 2010) but also the soil

ductility in general. The process of environmental factors impacting sites is not uniform, especially the effect of temperature, and water often penetrates from the outside to the inside. Therefore, the soil surface layer can produce uneven stresses. The soil structure can be destroyed under the action of nonuniform stresses. When the local stress is too high, this may even cause structural damage. Stress concentration can be effectively dispersed, and the weathering due to stress concentration can be reduced after the addition of hemp fibres to soil. The addition of hemp fibres in the sacrificial layer not only reduces soil water loss but also reduces uneven stress concentration within the soil structure. In the process of water loss, hemp fibres in soil can effectively disperse the stress attributed to shrinkage. Under the action of the suitable ductility of hemp fibres, the development of fractures is inhibited. Similarly, soil expansion can be inhibited when encountering water, and bidirectional inhibition can reduce the development of cracks. At the same time, the random distribution of hemp fibres in the sacrificial layer can reduce erosion under the influence of precipitation.

Although the physical characteristics of the sacrificial layer improve its resistance against exogenic forces, the sacrificial layer can only delay the weathering process at sites. Once the sacrificial layer is eroded by exogenic forces, the sacrificial layer loses its weathering resistance. The durability of the sacrificial layer determines its lifetime. As the sacrificial layer increasingly thins and eventually disappears, this method becomes ineffective.



**Fig. 8** Potential area where sacrificial layers can attain an improved durability (Source: Zhang 2021. Background map approved by Map Vetting Center, Ministry of Natural Resources, PRC)

Compared to penetrating consolidation, sacrificial layer protection exhibits certain limitations, especially a change in appearance. The sacrificial layer should not be the first choice. This protection measure should be implemented when other protection methods are not applicable. Therefore, at outdoor earthen sites, the sacrificial layer, as a temporary and reversible protective measure, could be used to protect the site in the short term and inhibit the weathering process due to exogenic forces in the absence of proper protection measures. Considering the thickness, erosion resistance of the sacrificial layer and external environment, the sacrificial layer can attain a suitable durability when rainfall remains below 25 mm/h (Zhang 2021). The potential areas for the application of sacrificial layers include extremely arid, arid, and semi-arid areas (Fig. 8).

### 3.3 Soft capping

Soft capping refers to the use of moss or other vegetation to cover earthen sites, which can reduce erosion at earthen sites under the influence of rain and can play a protective role. Soft capping itself provides dual effects on the protection and destruction of earthen sites. If the presence of soft capping is beneficial to long-term site preservation, this indicates that soft capping is a useful measure. At present, the following viewpoints on the protection mechanism of soft capping are mainly held: soft capping reinforces weathered soil on the site surface. The pores between weathered soil particles are filled with

moss and lichens, which can improve the soil mechanical strength (Chen et al. 2017). Dense fibrous moss roots, for example, bring soil and overburden closer together, and microscopic fissures can be repaired. The relatively dense structural plane or layer formed by soft capping and weathering layers can effectively reduce the development and occurrence of weathering decay. The expansion of soft capping can absorb soluble salt ions in the weathering layer, thus reducing soluble salt enrichment in the surface layer. Moss growth can absorb salt and promote salt transport between layers. This can lower the salt content in the weathering layer and can effectively inhibit flaking. Soft capping of the soil surface can reduce the flow velocity, change the soil permeability, and improve the soil anti-scouring ability, thus reducing soil erosion due to rainfall.

Soft capping should consider the adaptability of lichens and moss to the site environment. Factors influencing the growth and distribution of soft capping include precipitation, vegetation coverage, soil nutrient content, moisture and alkalinity. Among these factors, the decisive factor is rainfall. The greatest obstacles to soft capping application include field cultivation and post-maintenance issues. Whether soft capping can repair itself and maintain a balance without human intervention constitutes the premise of the soft capping function. Although the stability of the soil surface could be maintained in the short term after the death of soft capping, vitality loss of soft capping could continue to cause site weathering. In

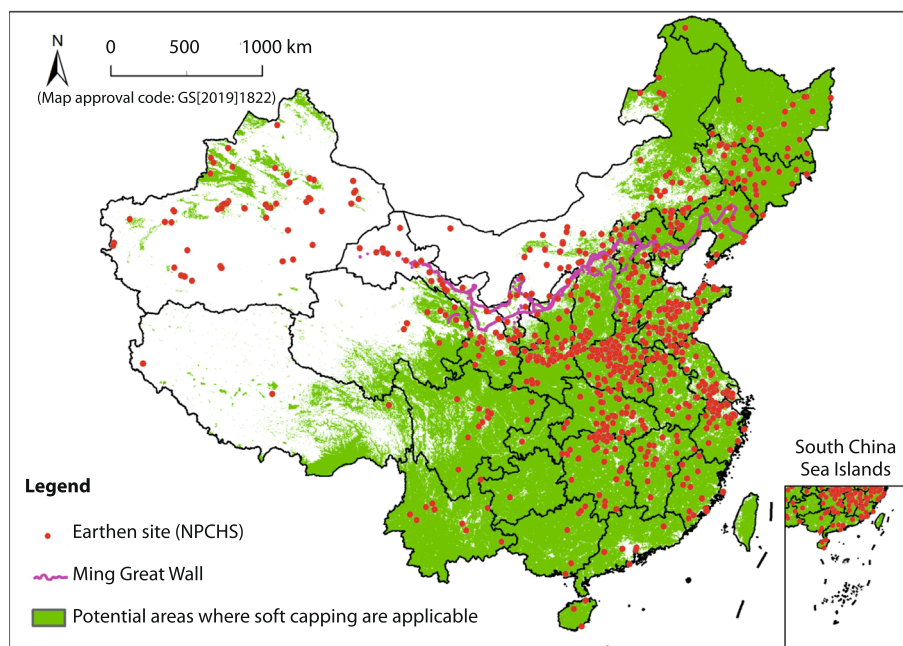
other words, soft capping is suitable upon adaptation to the environment and can maintain self-balance and provide a certain recovery ability. The Normalised Difference Vegetation Index (NDVI) can be used as a reference for soft capping. In recent years, remote sensing spectroscopy has been introduced into the study of lichens and mosses (Karniela et al. 1999). Their spectral characteristics were studied based on normalised reflectance data. The NDVI values for wet and dry moss crusts in arid and semi-arid areas in China reached 0.65 and 0.30, respectively (Fang et al. 2008). Based on this finding, the potential range of successful soft capping application can be determined (Fig. 9). The application of soft capping must also consider the influence and preservation status of the site.

### 3.4 Protective structures

Protective structures represent an important way to protect earthen sites from weathering. This reduces the weathering degree by blocking the influence of the external environment directly or indirectly. Protective structures comprise a relatively ideal way to reduce weathering. From blocking methods to external influencing factors, protective structures can be divided into fully enclosed modes and semi-enclosed modes. The architectural forms include protective sheds, exhibition halls and museums. Through statistics of the micro-environmental characteristics of protective structures

in different environments and blocking methods, fully enclosed buildings can provide a highly stable environment (Table 1). In the past, protective structures passively blocked the influence of environmental factors. In monitoring, researchers found that protective structures blocked the main factors causing weathering to achieve a relatively stable micro-environment. Protective structures, while reducing weathering rates, are still prone to other decay phenomena due to the unsuitable range of the micro-environment. Therefore, current protective structures are gradually changing from passive blocking to active control measures of environmental factors by adjusting the micro-environment to control the occurrence of secondary decay. This approach not only requires a large amount of energy but also requires maintenance fees that only rely on temperature and humidity control equipment to regulate the environment within protective structures. Therefore, the design of protective structures must consider long-term maintenance needs and costs. For example, temperature can be controlled by adjusting daylight hours through louvres, and ventilation can be designed depending on the building geometry to reduce humidity. Even the micro-environment can be controlled with low-energy consumption or green energy technology.

Protective structures are suitable for earthen sites in various climates, but each protective structure differs due to differences in site micro-environmental, display and



**Fig. 9** Potential areas for the application of soft capping in China (Source: Zhang 2021. Background map approved by Map Vetting Center, Ministry of Natural Resources, PRC)

**Table 1** Micro-environmental characteristics of protective structures for different environments and blocking methods

Sites	Architectural forms	Temperature (°C)			Relative humidity (%)		
		Annual average	Diurnal range	Annual variation	Annual average	Diurnal range	Annual variation
Banpo Museum (Wu 2013)	semi-enclosed	15.8	/	-3 ~ 31 °C	61	/	53%~70%
Emperor Qinshihuang's Mausoleum site museum (Li, Hu, and Du 2019)	semi-enclosed	/	< 3.5 (winter (Win.)) < 5.4 (summer (Sum.))	2.8 ~ 13.6 (Win.) 23.2 ~ 37.5 (Sum.)	/	< 8.0 (Win.) < 9.2 (Sum.)	20.0 ~ 57.6 (Win.) 43.0 ~ 78.5 (Sum.)
Hanyang Mausoleum (Li, Hu, and Du 2019)	fully enclosed	/	< 0.5 (Win.) < 0.4 (Sum.)	13.5 ~ 14.8 (Win.) 24.5 ~ 25.9 (Sum.)	/	< 2.8	73.8 ~ 76.5 (Win.) 73.0 ~ 82.2 (Sum.)
Jinsha Site Museum	semi-enclosed	19.6	12.9	3.3 ~ 41.2 °C	72.9	57.6	33 ~ 100
Dadiwan site	semi-enclosed	8.9	17.4	-18 ~ 39	74.6	54.1	42 ~ 100
Liangzhu site	semi-enclosed	15.8	8.7	-7 ~ 35	76%	32.8	35 ~ 100
Uighur Royal Buddhist Temple in Beiting	fully enclosed	17.0	1.7	9.9 ~ 31.0	35.9	6.0	20.2 ~ 64.7

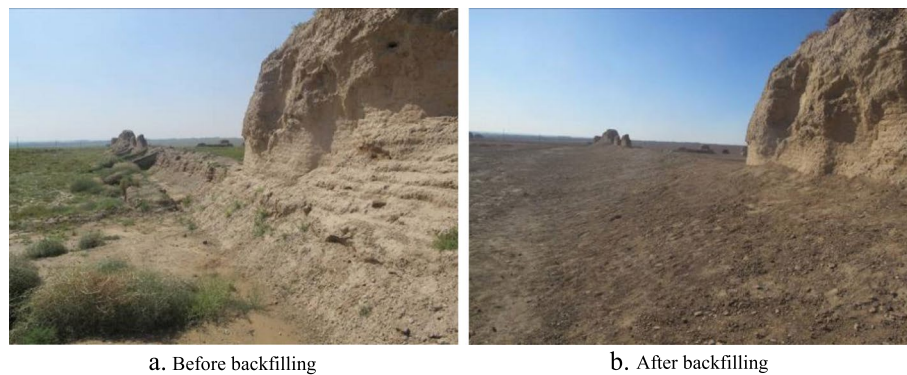
utilisation conditions. According to the Principles for the Conservation of Heritage Sites in China (ICOMOS China 2015), the construction of protective structures should consider changes in the structure. The structure should be unobtrusive and, as much as possible, should retain the original physical characteristics of the site. The primary consideration in the design and function of such a building or shelter is its protective function. In addition, the design of protective structures should follow certain principles. First, a detailed survey of the site should be performed. The investigation of weathering characteristics to determine the factors causing site weathering and blocking of weathering factors are the primary goals. Second, preliminary research must be conducted before the construction of protective structures. Through this work, possible problems can be corrected in time. The obtained research results could guide the design of protective structures. Finally, permanent monitoring is also needed after construction. Effective maintenance and management can prevent the occurrence of secondary decay.

### 3.5 Backfilling protection

Backfilling protection, which is often used in the conservation of archaeological excavation sites, is also a commonly employed weather-resistant measure at earthen sites. Soil is a very good buffer material with a low thermal conductivity and low water permeability. Backfilling protection can effectively block or reduce the impact of external environmental factors. Before archaeological excavation, the site occurred in a relatively stable environment. After excavation, the site became directly

exposed to the external environment, which is extremely vulnerable to exogenic forces. Under the combined action of the ambient temperature and solar radiation, the extreme surface temperature could exceed 50 °C. The surface daily temperature difference could reach much larger than 20 °C. Precipitation could also directly erode the site surface. Under the action of drying–wetting cycles, the site surface could increasingly become loose. Surface weathering could be further intensified by freezing and thawing. Under the action of temperature and water, the salinity on the surface could increase, which could accelerate weathering. Once the site is exposed to the external environment, it could be impacted by various environmental factors. Since the soil thermal conductivity is very low, the site could be protected via backfilling, and the daily temperature difference could remain very stable. The temperature below the surface could vary only annually with the ambient temperature. Even considering the influence of groundwater or capillary water, due to the low permeability coefficient of soil, the water-bearing state of the site would not change drastically within a short period, thus not causing great damage. The No. 6 Western Xia Mausoleum in Yinchuan was protected via backfilling after archaeological excavation. This method eliminated various weathering elements, such as rainfall and standing water. The site remained well preserved after backfilling (Fig. 10).

Backfilling protection is a relatively reversible process. This method can be used as a temporary or permanent protection measure. Backfilling protection is mainly used for non-exhibition archaeological sites. Backfilling



**Fig. 10** No. 6 Western Xia Mausoleum site protected by backfilling (Source: the authors)

protection should be implemented in conjunction with hydrogeological investigations. In principle, a stable environment should be ensured at the treated backfilling sites.

#### 4 Discussion and analysis

In China, the preservation of earthen sites began in the 1980s. First, a series of measures, such as penetrating consolidation, roof support reinforcement, and anchorage grouting, were implemented to solve weathering and collapse problems at earthen sites. These studies focused more on the site safety but gave less attention to site landscape improvement and environmental protection. With the continuous development of protection concepts and technology, especially the promotion of site protection engineering practices represented by the Jiaohe Ancient City at the beginning of this century and the key technology research project of earthen sites in arid areas, a complete set of key technologies was formed, mainly including anchor bolt anchoring, rammed roof-propping, fissure grouting and surface weathering prevention (Wang et al. 2013). In recent years, in view of the deterioration in the surface of earthen sites in different occurrence environments, measures were implemented to prevent weathering of earthen sites, such as penetrating consolidation, sacrificial layers, soft capping, protective structures and backfilling protection. These techniques must be comprehensively applied via in-depth research to obtain satisfactory results.

The development and scientific research of earthen site protection technology originates from many engineering practices. Researchers encountered problems in practice, adopted problems as a guide, and continuously analysed site-specific decay processes. Considering weathering, penetrating consolidation was mainly used at the early stage. Under different environmental conditions, researchers gradually realised the limitations of penetrating consolidation and considered more suitable

protection technology for different environmental conditions. Especially in recent years, a series of weather-resistant technologies, such as penetrating consolidation, sacrificial layer, soft capping, backfilling protection, and protective structures, have been proposed according to different environmental conditions based on the understanding of the existing environment and site conditions. Penetration treatment can prolong the life of a given site by improving the mechanical strength and weather-resistant ability of the surface weathering layer. In arid areas, penetrating consolidation is preferred because this method slightly affects the overall appearance of the site. However, due to the influence of soil properties and climate environment, the applicable scope of penetrating consolidation is limited. The sacrificial layer and soft capping methods are conservation technologies formed after the ecological coordination concept of deep learning. These methods provide a notable environmental applicability but exert a certain impact on the site surface and overall appearance. Backfilling protection and protective structures are used for isolation or semi-isolation purposes from the environment in response to complex climatic conditions. This represents an important means to alter the existing site environment through intervention. The protective structure method could be adopted to meet site display needs, and its most notable disadvantage is that this approach greatly influences the style and features of the site. Therefore, penetrating consolidation, sacrificial layers, soft capping and backfilling protection provide a greater potential to be popularised and applied because of their economy and operability.

In addition, with the continuous progress of science and technology and the development of protection technology, site protection measures have begun to focus on historical information, architectural art and traditional technology at the considered sites. Research on weather-resistant technology for earthen sites started from the existing environment, weathering mechanism, protection

and reinforcement mechanisms, failure mechanism and other aspects of the site. The advantages and disadvantages of different protection measures were deeply examined. At the same time, researchers of cultural heritage protection accurately defined the applicable scope of different weather-resistant measures and proposed quantitative indicators for site surface weathering and reinforcement effect evaluation. This research could provide technical support for the standardised monitoring and scientific evaluation of earthen sites and could continuously realise and improve monitoring and early warning systems. The above measures promoted the development of earthen sites from rescue protection to both rescue and preventive protection.

At present, the development trend of earthen site protection has changed from single-site protection to comprehensive protection, including management, prevention, intervention, and utilisation. More attention should be given to the erosion process under the coupled action of water, heat, salt, and other factors. Various weathering problems in the shallow surface layer of sites should be further studied. It is also necessary to explore and study the surface weathering characteristics and degradation mechanism of sites under the action of multiple factors. Integrated prevention and site protection technology, considering the ecological and human environments, should be gradually established.

## 5 Conclusions

The weather resistance of earthen sites represents a notable problem in the protection of these sites. Under the coupling of multiple factors, it is difficult to define the environmental adaptability of different weather-resistant measures. On the premise of fully considering historical site information and effective protection of both architectural art and traditional craft, the selection of protection measures results in higher requirements for researchers. The above constitutes the development direction and trend of weather-resistant measures and reinforcement technology for earthen sites by organically combining various types of weather-resistant technologies and establishing a comprehensive weather-resistant technique. Based on the environmental adaptability of various weather-resistant protection measures for earthen sites in China, the following conclusions could be drawn in this paper:

(1) Penetrating consolidation is the most convenient to implement but is the most restrictive method. The thickness of the weathering layer, earthen site properties, penetration technology, and precipitation all affect the reinforcement effect. However, water is the most important factor determining the scope of application. In open

environments, this measure can provide a satisfactory effect in extremely arid and semi-arid areas.

(2) Sacrificial layers can effectively constrain the erosion effect of exogenic forces. The durability of sacrificial layers is affected by the nature of these sacrificial layers and environment. Sacrificial layers can attain a greater durability in arid and semi-arid areas and can generally be used at open earthen sites.

(3) Soft capping can not only strengthen the weathering layer but can also inhibit the erosion process due to exogenic forces. The adaptability of soft capping depends on the environmental adaptability of the selected vegetation. Through NDVI analysis, soft capping can potentially be used in humid and semi-humid areas.

(4) Protective structures can effectively block or reduce weathering. According to the existing environment, researchers can choose semi-open or fully enclosed protective structures. Researchers can control the micro-environment either passively or actively. Therefore, the scope of protective structures is very wide.

(5) As a buffer at earthen sites, backfilling protection can reduce the influence of exogenic forces. Therefore, backfilling protection can generally be applied at non-exhibition archaeological sites.

### Abbreviations

NDVI: Normalised Difference Vegetation Index; PS: High-modulus  $K_2SiO_3$ ; NCHA: National Cultural Heritage Administration; ICOMOS China: Chinese National Committee for the International Council on Monuments and Sites.

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### Authors' contributions

Xudong Wang: Ideas; formulation or evolution of overarching research goals and aims. Bo Zhang: Conducting a research and investigation process, specifically performing the experiments, or data/evidence collection. Qinglin Guo: Oversight and leadership responsibility for the research activity planning and execution, including mentorship external to the core team. Qiangqiang Pei: Development or design of methodology. All author(s) read and approved the final manuscript.

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### Availability of data and materials

Not applicable.

### Declarations

### Competing interests

The author declare that they have no competing interests.

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