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Digital preservation of classical gardens at the San Su Shrine

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Abstract

Chinese classical gardens, an essential part of World Cultural Heritage, are well exemplified by Xishu Garden as a notable branch of this tradition. This research focuses on the San Su Shrine—a quintessential example of Xishu Garden—and explores the application of digital technologies in the commemorative research and quantitative preservation of these gardens. By integrating terrestrial laser scanning and terrestrial digital photogrammetry, we acquired quantitative data and constructed digital models to innovate upon the methodological approach to garden conservation. The innovation of this study is its analysis of Xishu Garden's commemorative spaces through both temporal and spatial dimensions. 1) Temporally, this study examines the evolution and stratification of the garden's commemorative elements across various historical periods. 2) Spatially, it explores the interconnectedness of commemorative elements within the garden's buildings, rockery stones, water landscape and plant landscape. This dual-faceted approach yields novel insights and methods for assessing the universal value of the commemorative aspects of Xishu Garden. Moreover, it promotes the application of digital technology in the study and preservation of Xishu and other Chinese classical gardens.

Keywords World Cultural Heritage, Landscape Architecture, Xishu Garden, San Su Shrine, Commemorative Space, Digital Preservation

Introduction

The Chinese Classical Garden is known as "the mother of gardens in the world" [1] and holds immense cultural and historical significance in world cultural heritage [2, 3]. Geographically, the Chinese Classical Garden can be classified into several distinct categories, including the Northern Garden, Jiangnan Garden, Lingnan Garden and other gardens [4], as well as their various branches, such as the important Xishu Garden centred around the Chengdu Plain in China [5]. Since ancient times, many Chinese literati have settled on the Chengdu Plain [6], such as the two generations of the Su family, Xue Tao and Du Fu. To commemorate these historical figures, later generations created a cluster of memorial gardens in Sichuan [7]. In this study, the San Su Shrine, a representative of the Xishu Historical and Cultural Celebrity Memorial Garden, was selected as the research object. This garden is famous for commemorating Su Xun, Su Shi and Su Zhe, famous literary scholars of the Northern Song Dynasty. In 2018, the United Nations Educational, Scientific and Cultural Organization (UNESCO) awarded San Su Shrine a Certificate of Appreciation for Cultural Heritage Protection [8]. The Lushan earthquake on April 20, 2013, caused damage to the buildings, walls and roads of the San Su Shrine, leading to the closure of the garden for two years for repairs [9]. Therefore, the restoration and digital preservation of classical gardens face new challenges. On the one hand, due to natural erosion and disasters [10], the Chinese Classical Garden faces increasingly

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severe damage each year, so there is an urgent need to record and preserve authentic data. On the other hand, traditional techniques such as photography and manual drawing cannot comprehensively and accurately replicate the intrinsic information associated with landscape elements and spatial characteristics [11], making the preservation of cultural heritage more difficult. With the rapid growth of computer processing and storage capacities, three-dimensional digital imaging technology can perform tasks such as acquisition and recording and complete remote operations [12]; subsequently, such technology has been gradually applied to the preservation of cultural heritage [13–15], making it possible to overcome the abovementioned challenges.

In recent years, digital technology has become a major means of preserving cultural heritage [10]. The potential of digital technology has gradually been recognized internationally [16] and has been widely applied in cultural heritage research, covering multiple aspects such as digital surveying [17], digital reconstruction [17–19] and simulation [20, 21]. In the past few decades, digital surveying technology, especially that integrated with terrestrial laser scanning (TLS) technology, has been increasingly applied in the fields of architecture and archaeology [11]. Moreover, digital preservation of garden heritage has made certain progress in terms of both technology and content: 1) The technology used has evolved from traditional methods such as sketching, photography and videography to include TLS combined with terrestrial digital photogrammetry (TDP) [22] and recording methods that integrate different laser scanning devices with drone photography sensors [15, 22–25]; additionally, there has been further development of 3D models and virtual reality, augmented reality and mixed reality (3R) technologies for reconstruction [26, 27]. At the macrolevel, in-depth studies of large-scale geospatial data collected using drones and TLS combined with geographic information systems (GIS) [28, 29] have indicated that digital collection and recording methods and reconstruction technology for landscape heritage are now being applied. 2) In addition, TLS technology has been widely applied in studies of rockery stones [30–34] and building structures [34–37] due to its flexibility and high precision. For example, Huilin Liang and others used various digital technologies to investigate, measure, display and analyse various landscape elements, especially rockery stone elements, at Huanxiu Shanzhuang [31–33]. Shizhen Jia and others constructed a three-dimensional digital information model of the Chinese Royal Garden considering its topography and stone elements [38]. Li Guo, Jiao Xu and others digitized the Du Fu Thatched Cottage in Xishu Garden by deconstructing it at three levels: dots, lines and surfaces [7].

However, as shown in Table 1, existing research primarily concentrates on analysing the present state of garden elements with notable gaps in two areas. On the one hand, the landscape elements (including rockery stones, buildings, and water and plant landscapes) and the spatial sequence relationships between them need to be further analysed. Chinese classical gardens differ from other types of heritage because they emerge from the synergistic interplay of diverse garden elements [42]. Their morphological characteristics are complex and multifaceted, forming

Table 1 Literature review analysis

Paper title	Research Domain	Research method	Research content
Huilin Liang [31]	Chinese Classical Garden (Jiangnan Garden)	TLS,TDP,Semantic-based analysis	Single garden element analysis(rockery)
Huilin Liang [32]	Chinese Classical Garden (Jiangnan Garden)	TLS,TDP	Single garden element analysis(rockery)
Qianli Dong [34]	Chinese Classical Garden (Jiangnan Garden)	Target-free 3D scanning method,3D printing	Single garden element analysis(rockery)
Mingjing Ding [39]	Chinese Classical Garden (Jiangnan Garden)	Digital imaging technology,Fractal dimension	Single garden element analysis(rockery)
Chen Yang [33]	Chinese Classical Garden (Jiangnan Garden)	TLS,PCVA	Single garden element analysis(rockery)
Shizhen Jia [40]	Chinese Classical Garden (Royal Garden)	TLS, photogrammetry, BIM, GIS	Digital deconstruction
Li Guo [7]	Chinese Classical Garden (Xishu Garden)	TLS,panoramic camera	Digital deconstruction
Shizhen Jia [38]	Chinese Classical Garden (Royal Garden)	TLS, photogrammetry, BIM, GIS	Whole garden element analysis, digital deconstruction
Huilin Liang [30]	Chinese Classical Garden (Jiangnan Garden)	TLS,TDP,UAVP	Methods of surveying, 3D modeling and digital documentation
Yuyang Peng [41]	Chinese Classical Garden (Jiangnan Garden)	TLS,photogrammetry, GIS	Garden spatial characteristics, preserving strategies

a unique spatial sequence and theme and cultural connotation [43, 44]. Accordingly, research dedicated to the preservation of classical gardens should transcend the analysis of individual garden elements to encompass a broader scope that includes landscape patterns, spatial sequences, cultural and historical attributes, and the overall artistic milieu. On the other hand, these studies ignore the generation process of memorial gardens in the temporal dimension. The cultural and historical landscape is an expression of the long-term interaction between natural and cultural forces. It can reflect the continuous reorganization of land and changing social needs [45, 46]. It serves as a pivotal site for activities of a commemorative nature. Commemoration is an act of seeking historical continuity through the orderly organization of material constructions or spiritual continuities [47, 48], representing the sequence and themes of objects in a spatiotemporal context. Thus, the commemorative nature of the Xishu Garden landscape is reflected mainly in the three target levels of orderly organization: space, time and the sequence and theme expressed by the two. The orderly organization of space refers to the commemorative space unit sequence of material construction. The orderly organization of time refers to the stratification of historically representative cultural relics, buildings, and ancient and famous trees in a time series. Sequence and theme refer to the common characteristics of the orderly organization of time and space, as well as the cultural connotations ultimately expressed.

In summary, the research and preservation of Xishu Garden should not be limited by its current material composition; rather, the garden should include a commemorative spatial sequence and theme composed of all the elements and the process of generating commemorative gardens. This is another innovation of this study. This study not only analyses the current spatial configuration but also examines the characteristics of various historical stratifications, thereby forming three progressive analytical dimensions—space, time and sequence theme—to elucidate the commemorative aspects of the Xishu Garden.

This study specifically focuses on the San Su Shrine, a renowned garden within the Xishu Garden, as its primary research subject. The objective is to utilize three-dimensional digital technologies in conjunction with relevant landscape architecture to explore the application of digital assistance in information collection and deconstruction analyses of gardens and to develop digital protection methods and technical paths for the Xishu Historical and Cultural Celebrity Memorial Garden. The research objectives of this article are as follows:

(1) To employ three-dimensional laser scanning and close-range photogrammetry techniques to acquire quantitative data and to construct a digital model of the San Su Shrine to preserve the information model of the San Su Shrine Garden;
(2) To quantify and analyse the expression ideas of the memorial core of the San Su Shrine, including landscape elements (rockery stones, buildings, water and plant landscapes), landscape sequences, spatial unit associations, and the generation process and stratification characteristics of memorial gardens;
(3) To explore the commemorative protection methods of the Xishu Historical and Cultural Celebrity Memorial Garden represented by the San Su Shrine;

By using three-dimensional laser scanning technology combined with close-range photogrammetry technology to obtain quantitative data, the overall layout, constituent elements and landscape sequence of the San Su Shrine were analysed to gain a deeper understanding of the artistic conception and connotations behind the material composition, thereby providing a scientific basis and effective method for researching, protecting and restoring garden heritage [30].

Research location

The San Su Shrine is located on Shahuhang Street in Dongpo District, Meishan city, Sichuan Province, China. The 2018 UNESCO evaluation revealed that "the San Su Shrine is the birthplace of Dongpo culture and the ancestral hall embodies the charm of Chinese classical gardens, presenting the living environment and lifestyle of the Su family which is sacred, solemn and symbolic." [49]. San Su Shrine is a representative, commemorative and narrative example of Xishu Garden [50]. It has gone through four development stages: the courtyard, the Shrine, the San Su Garden and the garden-style museum [49]. After the Song, Yuan, Ming and Qing dynasties, it became one of the representative gardens of the Xishu Historical and Cultural Celebrity Memorial Garden (Figs. 1, 2).

Following the "4.20" Lushan earthquake in 2013, numerous historic edifices inside the San Su Shrine experienced structural impairment. This included the development of cracks in certain walls, damage to roof ridges and displacement of columns. The duration of the postdisaster reconstruction spanned two years. The restoration efforts primarily encompassed the preservation and maintenance of 16 key structures,

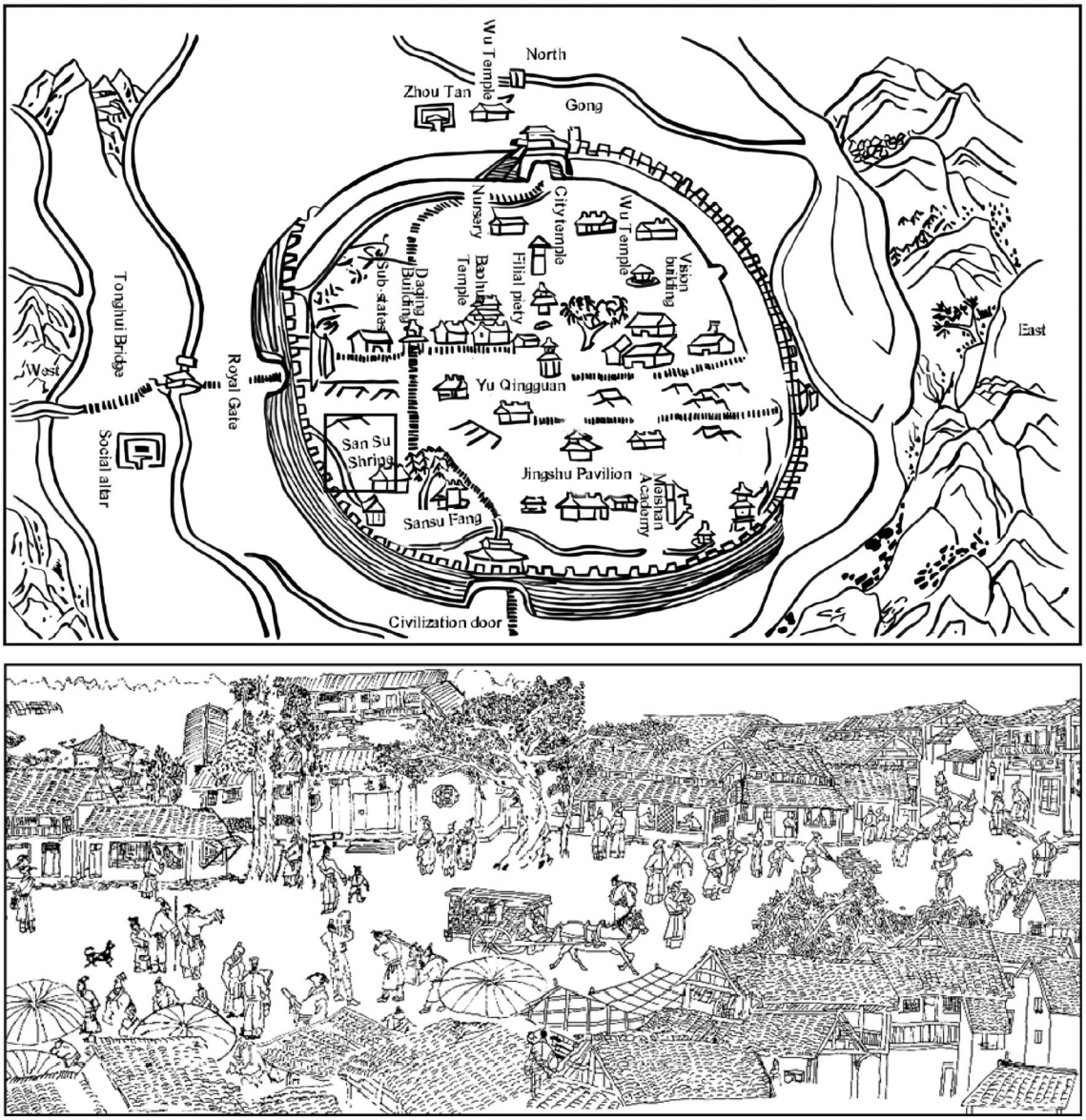


Fig. 1 Ancient Meizhou city map and Su Residence diagram (self-painted according to the exhibition data of the San Su Shrine)

the restoration of surrounding gardens and the establishment of a clear-water ecosystem (Fig. 3).

The digital research conducted on the San Su Shrine encompasses the eastern memorial ancestral hall area as well as the western garden area. The boundaries of the study area extend from the South Gate to the south to the Half Autumn Water Pond to the north and from the West Gate to the west to the Stele Pavilion to the east. The primary area of focus inside the garden is the memorial ancestral hall region. Consequently, the three-dimensional laser scanner primarily targets the eastern ancestral hall area (see Fig. 4).

Materials and methods

Information collection equipment and methods.

The digital information gathering on the San Su Shrine encompasses three distinct components, namely, data collection, data processing and digital results. Figure 5 illustrates the technical methods used. The objective of this digital study is to conduct a quantitative assessment of the memorial space, garden features and landscape

Fig. 2 Photograph of the San Su Shrine Ancestral Hall Area (provided by the San Su Shrine Museum)

Fig. 3 Signs of damage at the San Su Shrine (Provided by the San Su Shrine Museum)

Fig. 4 Aerial photo of the San Su Shrine (2021)

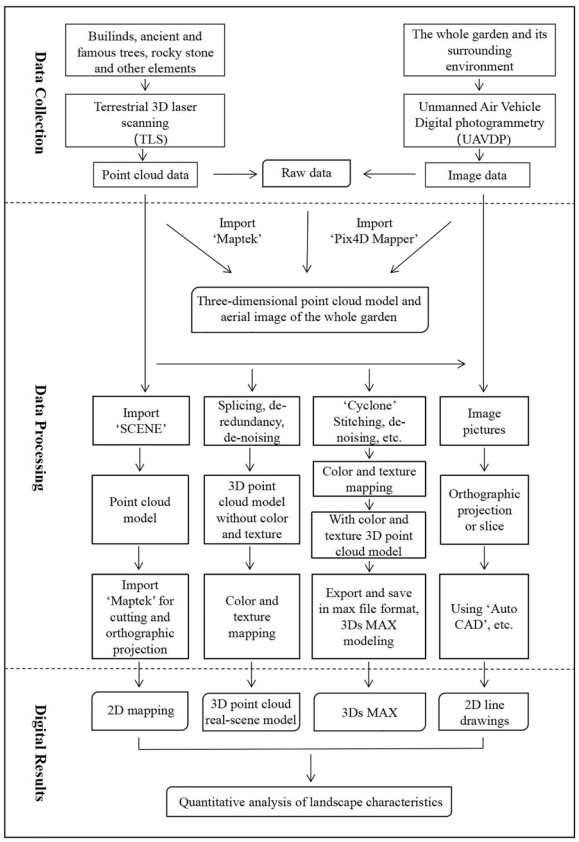


Fig. 5 Technical methods

characteristics of the San Su Shrine by acquiring three-dimensional spatial data.

Three-dimensional laser scanning has advantages in terms of measurement accuracy and ease of implementation and can be effectively used to describe the overall structure and morphological characteristics of a target [51]. It has the characteristics of high data collection efficiency, high resolution and high accuracy [52]. Typically, short-range distance measurements and static data collection methods are employed to acquire point cloud data for garden element surfaces [26]. Subsequently, professional software is used to process the collected data, resulting in a measurable point cloud model, which provides the foundational data for the next step of constructing a three-dimensional model [53]. However, when facing a large garden space, due to blockage by trees, the installation and operation of 3D laser scanners are relatively difficult and complicated. The utilization of flexible drone photography has emerged as a viable supplementary option. Today, digital measurements of cultural heritage are widely conducted using close-range photogrammetry and laser scanning technologies [31]. In this study, we employ a combination of three-dimensional laser scanning and unmanned aerial vehicle (UAV) photography technology to conduct a comprehensive assessment and map the San Su Shrine. The 3D laser scanner employed in this study utilizes the FARO Laser Scanner Focus S350 (manufacturer's name: FARO; hardware: FARO Focus Premium; software: FARO SCENE software). 1) This technology incorporates a spherical digital camera lens inside its design. Additionally, UAV photography utilizes the Pegasus D2000 UAV aerial survey system (D2000GLS20130094) (manufacturer's name: Pegasus). 2) This system is equipped with a SONY A6000 camera, which boasts an effective pixel count of approximately 24.3 million pixels. The camera sensor size measures 23.5 × 15.6 mm (aps-c) and is configured with a fixed focus of 25 mm.

The surveying and mapping domain includes a comprehensive overview of the garden and its horticultural components. The various landscape components are categorized as buildings, water landscapes, plant landscapes and rockery stones, as shown in Table 2.

Data collection

The data collection process encompasses several activities, including on-site surveys, the establishment of control networks and target layouts, building scanning and the acquisition of textural data [31]. First, a comprehensive point cloud model and aerial image of the garden are achieved via three-dimensional laser scanning in conjunction with unmanned aerial vehicle (UAV) photography [54]. The diagram depicted in Fig. 6 illustrates the arrangement of the 115 scanning stations for 3D laser scanning. To obtain comprehensive data on the San Su Shrine, employing a spherical digital camera lens capable of capturing 8 photographs at each site is recommended. These photographs should have a resolution of 1920 × 1920 pixels and be able to capture RGB colour, texture and other pertinent information. Simultaneously, the combination of terrestrial laser scanning (TLS) and drone-captured image point clouds provides a complete geometric representation of the point cloud scanning process [55]. One unmanned aerial vehicle (UAV) is deployed to conduct an aerial survey. The average ground resolution is established at 5 cm, while the shooting height is approximately 180 m. A total of 395 photographs are acquired, with each individual photograph encompassing an approximate area of 2.22 hectares. Fourteen flight routes are constructed, consisting of five routes that run in an east–west direction and nine routes that run in a north–south direction. These routes are shown in Fig. 7.

Table 2 Surveying and mapping components of the San Su Shrine

Information category	Surveying and mapping components
Overall layout	San Su Shrine TLS plane layout, aerial photography, etc
Buildings	Building layout, planes, facades, sections, structure, size, etc
Water landscape	Water landscape plane layout, scale and shape, etc
Plant landscape	Plant TLS overall layout, green area, plant monomer TLS point cloud, façade and location, etc
Rockery stones	The overall layout of the rock, rock monomer TLS point cloud model, plane, façade and size, etc

Fig. 6 Distribution of scanning stations for TLS in the San Su Shrine

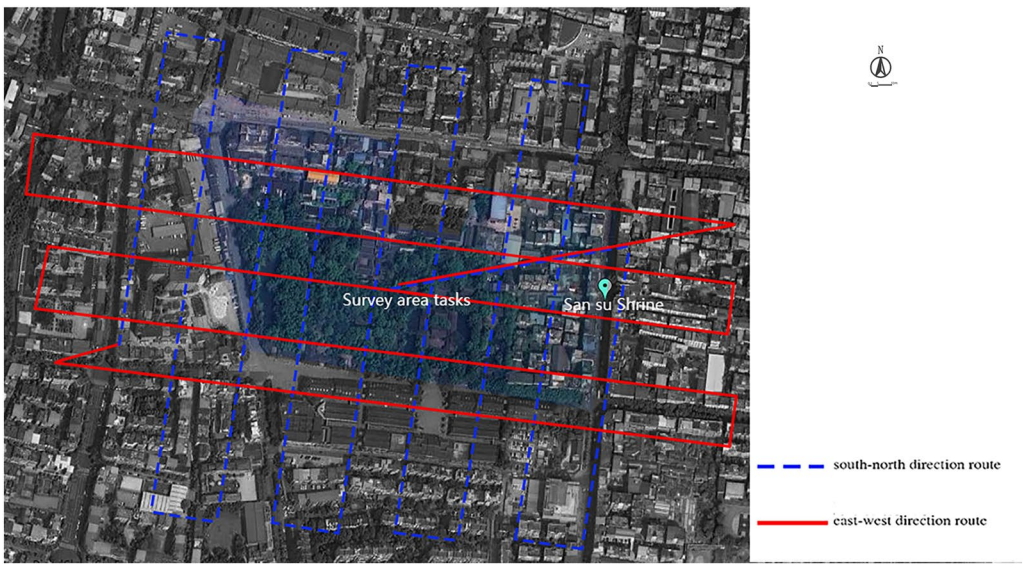


Fig. 7 Route map of the UAVDP in the San Su Shrine

Data processing

Data processing includes splicing, removing redundancy, denoising and correcting all types of source data and may also include manual or automatic filtering to delete unnecessary data [56]. The processed source data in this study were imported into the software “Maptek” (manufacturer: Maptek) to initially form a complete point cloud model of the entire San Su Shrine Garden. Next, the image data obtained by drones were sorted and summarized, and the positional data and source images were sequentially imported into the software "Pix4D Mapper” (manufacturer: Pix4D China Technology Co., Ltd.) for preliminary splicing. Finally, an aerial photograph of the entire San Su Shrine Garden was obtained.

Digital results

Digital results serve as the foundation for quantitative analysis, encompassing two-dimensional photographs, three-dimensional real-scene models and 3D MAX models. Two-dimensional images include line drawings and surveying drawings, and three-dimensional real-scene modelling is based on high-precision point cloud data. Through colour and texture mapping, a point cloud real-scene model with a 1:1 correspondence with the measured objects is obtained, as shown in Fig. 8. A 3D MAX model based on point cloud data is processed and exported to MAX format files through Cyclone software (manufacturer: Leica), and a realistic three-dimensional point cloud model file of the target object is initially obtained. Next, using 3D MAX modelling software (manufacturer: Autodesk), a 3D model of the target object is constructed, resulting in the final 3D MAX model of the object.

Discussion

Memoriality of the time dimension

The development of the San Su Shrine profoundly reflects the evolution of Chinese garden art and the accumulation of cultural value. From the Song Dynasty to the present, the San Su Shrine has experienced various stages of development, including the formation of the courtyard, the initial expansion of the Shrine, the maturation of the Shrine and the modern development period. Each period presents unique characteristics in terms of landscape design, architectural style and cultural connotation and leaves representative historical relics, as shown in Fig. 9. In the courtyard formation period (1009–1142), the San Su Shrine was closely related to the lives and artistic work of the three literati, Su Xun, Su Shi and Su Zhe, and its garden design successfully incorporated both natural landscape and cultural elements. In the initial expansion of the Shrine (1142–1665), the area underwent a significant transformation, evolving from a private residence into a public memorial space. The shrine maturation period (1665–1898) signifies the zenith of the garden art at the San Su Shrine, with the design and architectural developments of this era reflecting the pinnacle of Chinese classical garden art. The modern development period (1898-present) signifies the conversion of the San Su Shrine from its original shape as a traditional garden to its current state as a modern park. Furthermore, the stratigraphic map in Fig. 10 demonstrates that over the course of four periods, the San Su Shrine experienced continual growth and the integration of buildings, structures, and ancient trees. This has ultimately resulted in the

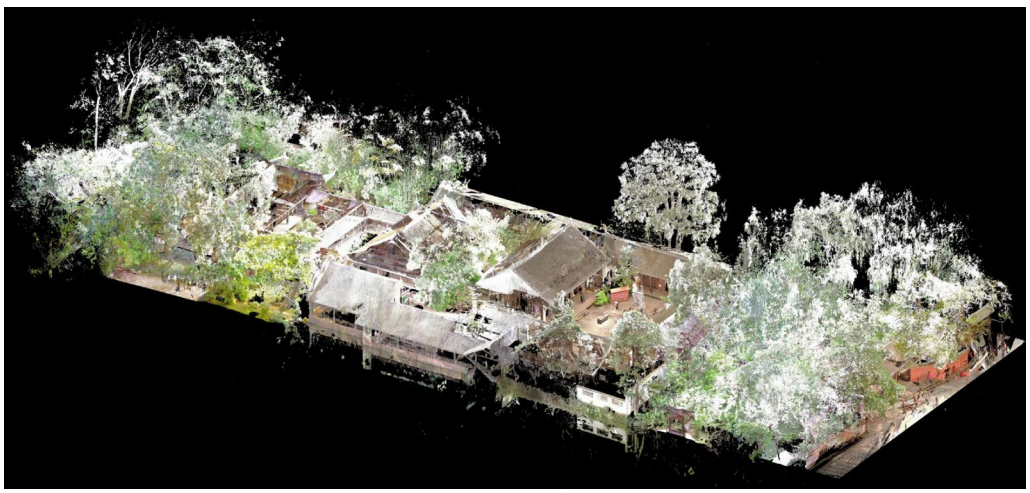


Fig. 8 TLS point cloud model of the San Su Shrine commemorative axis

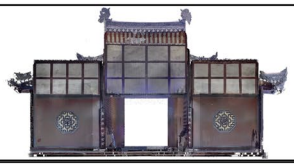
Development stage	Typical example	Section of point cloud	Scene photo
Courtyard formation period (1009-1142)	Su Residence Old Well		
Initial expansion period of the Shrine (1142-1665)	Worship Hall		
Shrine maturation period (1665-1898)	Lobby		
Modern development period (1898-present)	South Gate		

Fig. 9 Representative historical relics of each period

Fig.10 The Historical relics of the San Su Shrine in four periods

complete commemorative connotation of the San Su Shrine seen today.

The courtyard formation period (1009–1142)

The establishment of the courtyard is intricately linked to the development and trajectory of the 'San Su' (Su Xun, Su Shi, Su Zhe), which provides a deep cultural basis for the 'San Su Shrine'. From the Shenlong period of the Tang Dynasty to the second year of the Dazhongxiangfu period of the Northern Song Dynasty (1009), the Su family's ancestors relocated to Meizhou and initiated the construction of the initial version of the courtyard. Subsequently, Su Xun, Su Shi and Su Zhe sequentially resided here [57], and during this period the residence saw gradual enhancements and development. Also during this period, both the Su Residence Old Well and the Premier Tree of Meizhou (*Ficus virens*) were established [58]. The overall style of the courtyards is discernible within Su Shi's poetry collection. For instance, in "Dong Po Zhi Lin" (东坡志林), Su Shi mentions, "In the past, my ancestors lived in Meishan, running a silk business (昔吾先君夫人宅于眉，为纱行) " [59]. This reference to the silk business in Meishan City's Su residence is indeed the present-day San Su Shrine. Additionally, in "Yi Que" (异鹊)) and "Dong Po Zhi Lin" (东坡志林), the poet vividly portrays elements such as paulownia flowers, vegetable gardens, bamboo and wild birds within the residence, collectively depicting a pastoral and idyllic scene of the estate [60].

The initial expansion period of the Shrine (1142–1665)

In the Shaoxing era of the Southern Song Dynasty (1142), in order to commemorate the ancestors of the San Su and their outstanding cultural contributions, the descendants transformed the old courtyard of the Su family into a shrine and began to repair and initially expand. The construction work during this period not only involved the physical extension of the Su family's courtyard but also served as a means of preserving and passing down the rich cultural heritage of San Su. In the fourth year of the Kangxi reign in the Qing Dynasty (1665), Huiya Zhao oversaw the reconstruction of the main buildings of the San Su Shrine, including the Worship Hall, Sage Hall, Mujiashan Hall and Ruilian Pavilion, which initially formed the commemorative axis pattern of the central axis of the San Su Shrine. The buildings of this period are still the earliest architectural relics in the San Su Shrine and have high historical and cultural value. To accentuate the commemorative significance of the central axis, six old and notable tree species, including *Ginkgo biloba, Cycas revoluta, Osmanthus fragrans*, and *Phoebe zhennan* were planted in the garden. Among them, *Ginkgo biloba* and *Phoebe zhennan* located near the south gate, have evolved into prominent landscape symbols within the entrance area of the San Su Shrine.

The shrine maturation period (1665–1898)

Amidst the flourishing era of Chinese classical garden art, the San Su Shrine underwent a series of extensive expansion projects based on inheriting and developing its previous characteristics, thus forming a unique and complete garden pattern and system. Between 1806 and 1898, eight significant structures were added, comprising the East and West Chambers, Square Wall Gate, Kuaiyu Pavilion, Lobby, Yunyu Building (Dongpo Building), Baoyue Pavilion, Oasis Pavilion and Pifeng Waterside Pavilion. Additionally, the expansion of the garden was not only by the increase in buildings but also by the expansion area, as *Ginkgo biloba, Lagerstroemia indica, Malus spectabilis, Osmanthus fragrans, Dalbergia hupeana, Podocarpus macrophyllus, Ulmus pumila* were added along the water, forming the island residence characteristics of "three parts water and two parts bamboo". For more than two hundred years, the present appearance of the San Su Shrine gradually formed during the Qing Dynasty. The Qing Dynasty not only was the main construction period of the existing relics of the San Su Shrine, but also marked the transformation of the San Su Shrine from a simple former San Su residence to an important cultural site with public memorial significance. The construction and expansion activities in this era were indicative of the advanced state of garden artistry at that time and underscored the San Su Shrine's prominent role in the annals of Chinese cultural history.

The modern development period (1898-present)

In the Republican era, the San Su Shrine underwent a significant transformation, initially taking on the existing appearance pattern and gradually being valued and protected at the national level. During this time, the primary emphasis of the San Su Shrine's development turned towards enhancing the functional amenities within the park to cater to the needs of the wider public. Therefore, a series of renovations were carried out on buildings and structures, including the South Gate, canopies, bridges, west garden, Sansu Memorial Hall, cultural relics exhibition hall, visitor centre and parking lot. Simultaneously, an array of plant species, including *Osmanthus fragrans, Celtis sinensis, Lindera megaphylla, Albizia julibrissin, Bischofia polycarpa, Triadica sebifera, Koelreuteria paniculata*, and *Phoebe zhennan* were strategically planted in key node areas of the garden. Over time, the San Su Shrine has changed from an unopened office area to a ' Sansu Park ' for the public.

The period of metamorphosis gave rise to the distinctive style known as the 'garden-style ancestral hall' at the San Su Shrine.

The San Su Shrine was included in China's National Cultural Relic Protection Unit in 2006. In 2018, UNESCO awarded Meishan the San Su Shrine Museum a Certificate of Appreciation for Cultural Heritage Protection. These accolades not only affirm the cultural significance of the San Su Shrine but also mirror the evolving trajectory of the protection and utilization of Chinese cultural heritage.

Memoriality of the spatial dimension

Garden layout

The San Su Shrine adeptly integrates the memorial ancestral halls and the narrative garden, resulting in a distinctive layout characterized by a harmonious arrangement of eastern and western elements, as well as a fusion of structured and organic design styles. The eastern ancestral hall region mostly comprises a regular pattern, with a total area of approximately 21,600 m^2. It follows a three-courtyard plan design. The western region is enhanced by the presence of natural gardens, spanning approximately 33,220 m^2. These gardens effectively depict vibrant living scenes in San Su. The characteristics of the garden layout can be summarized by analysing two-dimensional mapping and three-dimensional point cloud real-scene models. The diagram in Fig. 11 illustrates the presence of three courtyards, three axes, one island and one garden. The initial courtyard comprises the Lobby, East Chamber, West Chamber and Worship Hall. The second courtyard includes the Mo Pavilion, Kuaiyu Pavilion, Sage Hall and West Chamber. Finally, the third courtyard consists of Sage Hall, Laifeng Pavilion and the left and right hallways. The amalgamation of the aforementioned three configurations yields an architectural arrangement of ancestral halls featuring three courtyards, characterized by a balanced and symmetrical design on both the left and right sides, with carefully proportioned dimensions. The garden pattern consists of the central line and subcentral line, which are formed by three axes: an axis extending from the South Gate to the Laifeng Pavilion, an axis extending from the Ruilian Pavilion to the Dongpo Sculpture and an axis extending from the Oasis Pavilion to Yunyu Building. The island is a commemorative temple formed by three academies in a waterfront island-style residence. The garden exhibits a naturalistic design within the western region characterized by meandering and meticulously arranged pathways and interconnected water features that form a circular pattern.

Memorial elements

The garden surrounding the San Su Shrine consists of both constructed and natural environments. Commemorative elements encompass many components, such as buildings, plants, water and rockery stones. Their locations are shown in Fig. 12.

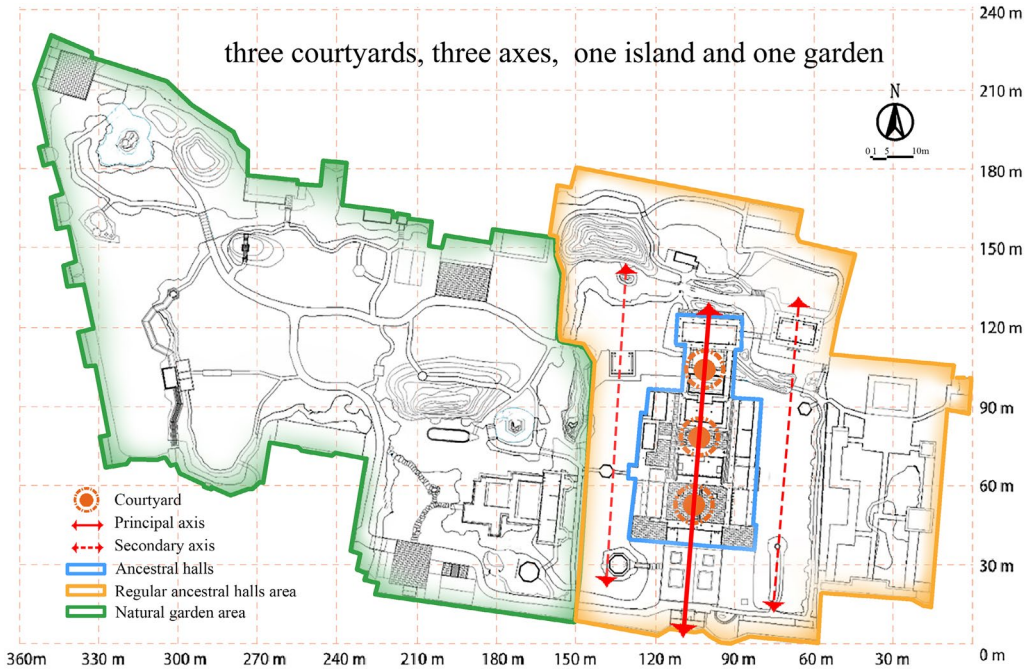


Fig. 11 Layout of the San Su Shrine

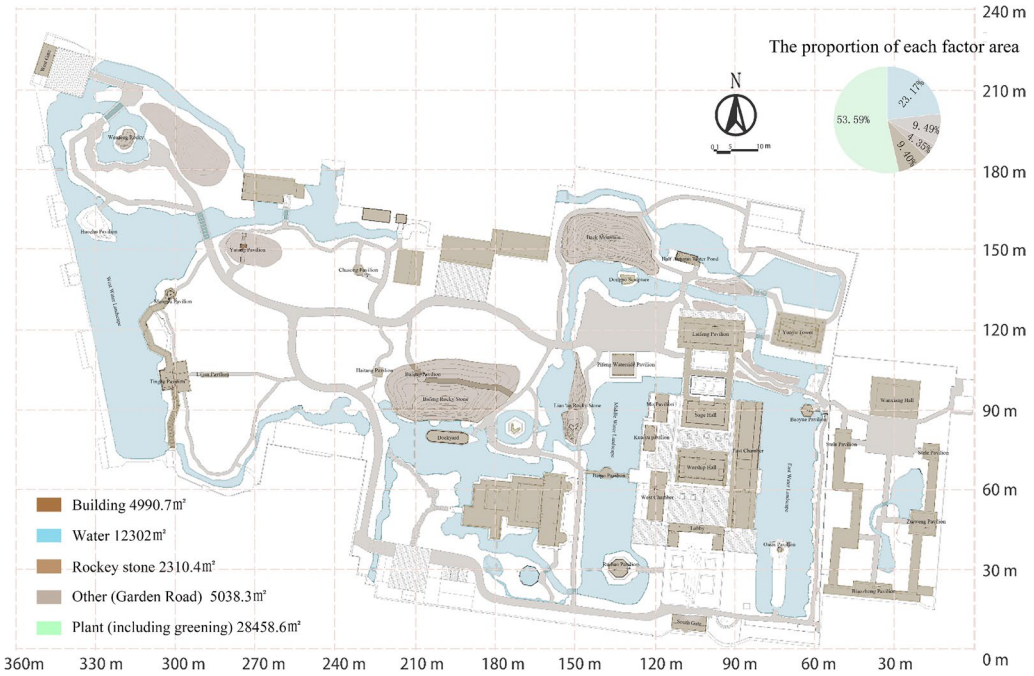
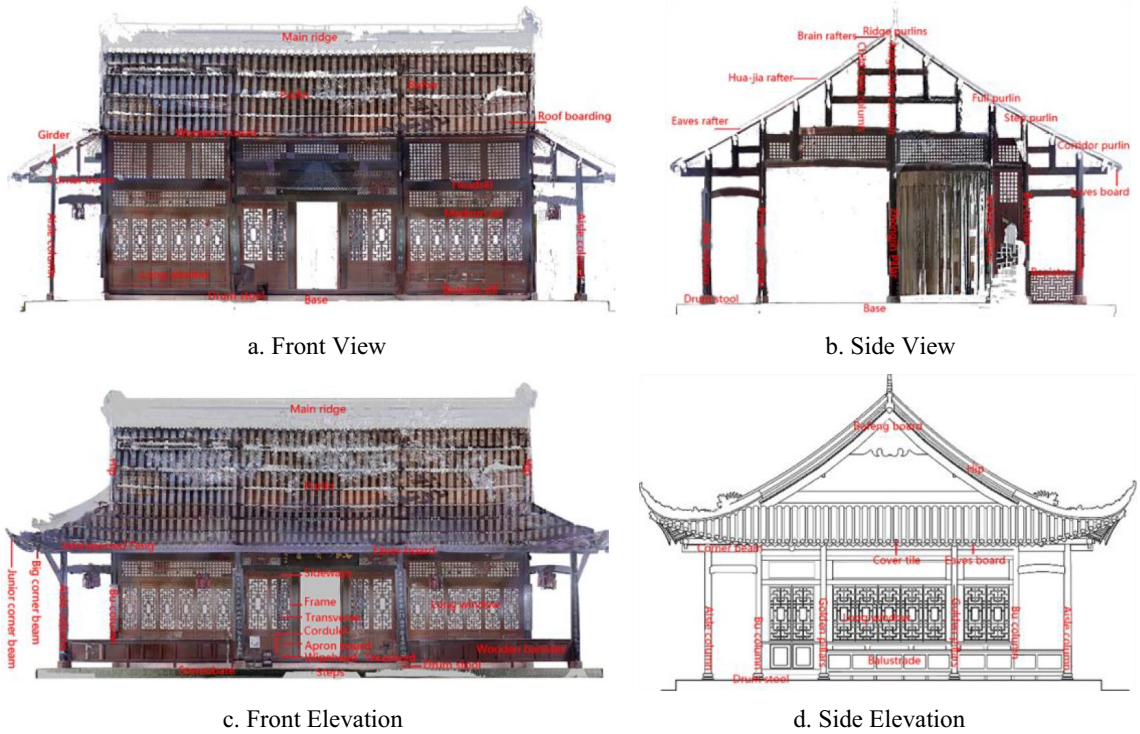


Fig. 12 The proportions of San Su Shrine landscape elements



a. Front View

b. Side View

c. Front Elevation

d. Side Elevation

Fig. 13 Building facade of the Sage Hall in the San Su Shrine (Fig. **a** ~ c are based on point cloud data from TLS, and Fig. **d** is redrawn with reference to the 'Ancient Temple Freshman')

Buildings The architecture of the San Su Shrine was derived from the Su Residence, predominantly incorporating elements of Xishu residential homes, as depicted in Fig. 13. Following the renovation and expansion efforts undertaken by previous dynasties, the architectural composition of the garden has evolved into a configuration that is characterized primarily by memorial ancestral halls, which occupy approximately 9.4% of the overall area. The arrangement of buildings typically involves positioning the windows of interior spaces to the south, optimizing exposure to natural light. The architectural arrangement principles governing the eastern memorial ancestral hall area adhere to a symmetrical structure, wherein the shrine, hall and pavilion are predominantly situated along a central axis. The grandeur of the memorial surpasses that of the building on all sides, effectively conveying a sense of solemnity and reverence. The Central Axis Building is encompassed by a series of smaller structures, including pavilions, on either side, resulting in the formation of island residences. The structures situated on each side of the central axis exhibit proximity and integration with the encompassing natural environment. The architectural arrangement of the western garden area exhibits greater

Table 3 Main plants in the San Su Shrine

Category	Number	Latin names	Genus	Family
Tree	1	*Ficus virens*	*Ficus*	Moraceae
	2	*Phoebe zhennan*	*Phoebe*	Lauraceae
	3	*Ginkgo biloba*	*Ginkgo*	Ginkgoaceae
	4	*Osmanthus fragrans*	*Osmanthus*	Oleaceae
	5	*Podocarpus macrophyllus*	*Podocarpus*	Podocarpaceae
	6	*Cycas revoluta*	*Cycas*	Cycadaceae
	7	*Camphora septentrionalis*	*Camphora*	Lauraceae
	8	*Salix babylonica*	*Salix*	Salicaceae
	9	*Firmiana simplex*	*Firmiana*	Malvaceae
	10	*Magnolia grandiflora*	*Magnolia*	Magnoliaceae
	11	*Metasequoia glyptostroboides*	*Metasequoia*	Cupressaceae
	12	*Ulmus pumila*	*Ulmus*	Ulmaceae
	13	*Acer palmatum* 'Atropurpureum'	*Acer*	Sapindaceae
Shrub	14	*Aucuba japonica* var. *variegata*	*Aucuba*	Garryaceae
	15	*Nandina domestica*	*Nandina*	Berberidaceae
	16	*Chimonanthus praecox*	*Chimonanthus*	Calycanthaceae
	17	*Juniperus sabina*	*Juniperus*	Cupressaceae
	18	*Lagerstroemia indica*	*Lagerstroemia*	Lythraceae
	19	*Camellia japonica*	*Camellia*	Theaceae
Herb	20	*Ophiopogon bodinieri*	*Ophiopogon*	Asparagaceae
	21	*Ophiopogon japonicus*	*Ophiopogon*	Asparagaceae
	22	*Salvia japonica*	*Salvia*	Lamiaceae
	23	*Oxalis triangularis* 'Urpurea'	*Oxalis*	Oxalidaceae
Hydrophyte	24	*Nelumbo nucifera*	*Nelumbo*	Nelumbonaceae
	25	*Phragmites australis*	*Phragmites*	Poaceae
	26	*Nymphaea tetragona*	*Nymphaea*	Nymphaeaceae
Bamboos	27	*Bambusa multiplex* f. *fernleaf*	*Bambusa*	Poaceae
	28	*Bambusa emeiensis*	*Bambusa*	Poaceae
	29	*Pleioblastus amarus*	*Pleioblastus*	Poaceae
	30	*Bambusa multiplex* 'Alphonse-Karr'	*Bambusa*	Poaceae
	31	*Bambusa multiplex*	*Bambusa*	Poaceae
	32	*Bambusa ventricosa*	*Bambusa*	Poaceae
	33	*Phyllostachys edulis*	*Phyllostachys*	Poaceae
	34	*Rhapis excelsa*	*Rhapis*	Arecaceae
	35	*Phyllostachys heteroclada*	*Phyllostachys*	Poaceae

Fig.14 Plane diagram of the central axis of the building and plants at the San Su Shrine

freedom and flexibility as one moves from east to west, with a gradual reduction in the variety of buildings.

Plant landscape The San Su Shrine boasts a diverse array of plant species and a substantial expanse of greenery, encompassing approximately 28,458.6 m^2, which corresponds to 53.6% of the entire garden area. A collection of approximately 49 ancient trees can be found at the shrine, including species such as *Ginkgo biloba, Lagerstroemia indica* and *Osmanthus fragrans*. The San Su Shrine boasts a diverse array of garden flora. Table 3 showcases the presence of trees, shrubs, herbs, hydrophytes and bamboos within the context of commemorative themes. These botanical elements are strategically mixed with structures, rockery stones and water scenes to create a harmonious planting layout. Su Shi, a renowned poet and scholar, expressed his preference for consuming bamboo over meat, stating "Better to eat without meat than live without bamboo". The exclusion of meat from one's diet affects one's weight, while the lack of exposure to refined cultural influences such as bamboo can change a person more profoundly. Furthermore, the presence of ancient ginkgo trees within the designated ancestral hall area serves as a representation of the Sansu period, emphasizing the commemorative and historical attributes of the Xishu Historical and Cultural Celebrity Memorial Garden (Fig. 14).

Water landscape The San Su Shrine boasts a substantial expanse of water features, constituting approximately 23.17% of the overall garden area. The garden features a diverse array of water landscapes, including the central water landscape spanning 1900 m^2, the eastern water landscape covering 1950 m^2 and the western water landscape spanning 4010 m^2. These water landscapes constitute the primary components of the garden water,

Table 4 Water system in the San Su Shrine Garden (unit: m^2)

Name	Main water	Scattered water	Water body of the whole garden
Region	S1, S7, S14, S15	S2, S3, S4, S5, S6, S8, S9, S10, S11, S12, S13, S16	–
Area	7,899	4,514	12,413
Ratio	63.6%	36.4%	100%
	Scattered water area: Main water area ≈1:1.7		

while a meandering stream traverses the entire garden, forming an interconnected water network. The primary water landscapes near the memorial ancestral hall of the eastern region of the San Su Shrine are the middle water landscape and the west water landscape, both of which are expansive. The northern and southern dimensions measure 83 m and 84 m, respectively, while the eastern and western dimensions measure 19 m and 22 m, respectively. The area ratio is nearly 1:1, with a high degree of symmetry observed between the left and right sides. The ancient ancestral memorial hall is effectively encircled by the surrounding landscape, creating an island-like setting with three water sections interlaced with two bamboo sections (Table 4, Fig. 15).

Rockery stone The rockery stone at the San Su Shrine primarily consists of soil stone and stone piles, encompassing approximately 4.4% of the overall garden area. Rockery stone mostly utilizes indigenous red sandstone, blue stone, pebbles and other locally sourced stone materials, hence exhibiting a diverse range of literary features. The arrangement of rockery stones is closely interconnected with the order of the tour and the range of visibility, particularly exemplified by

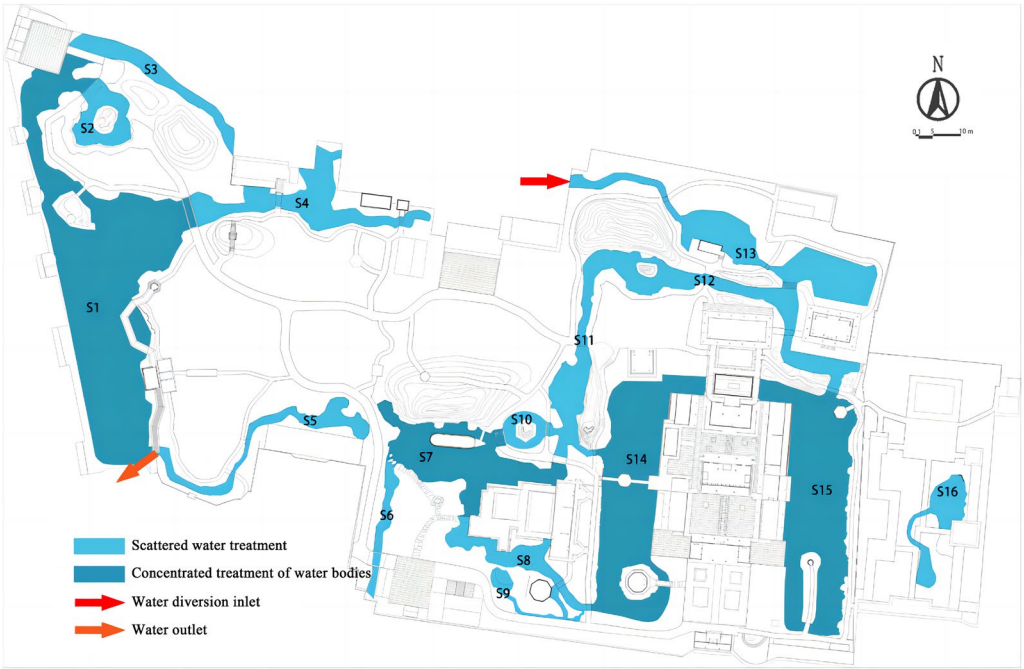
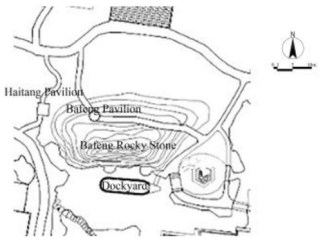
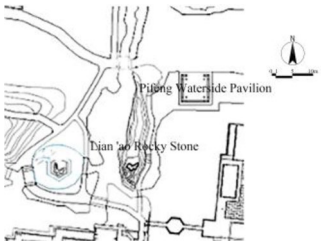
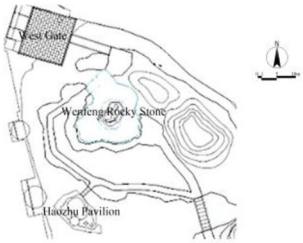


Fig. 15 Water landscape plan in the San Su Shrine Garden

Table 5 Rockery Stones in the San Su Shrine

Name	Bafeng rockery stone	Lian'ao rockery stone	Wenfeng rockery stone
Plane graph			
TLS elevation			
Characteristic	Bafeng Rockery Stone is 5.85 m high, 23.75 m wide, 58.36 m long on the north side and 23.2 m long on the south side. The material of the Rockery Stone is mainly natural soil stone in Xishu	Lian'ao Rockery Stone is 5.85 m high, 8.12 m wide and 33.25 m long. The material of the Rockery Stone is mainly natural red sandstone in Xishu	Wenfeng Rockery Stone is 6.39 m high, 7.74 m wide and 10.34 m long. The main material of the Rockery Stone is cement mortar and wood. After being damaged by the earthquake, it was repaired with natural red sandstone in Xishu

the Bafeng rockery stone, Lian'ao rockery stone and Wenfeng rockery stone, as depicted in Table 5. Further exmaination of the Lian'ao rockery stone reveals that this geological formation is situated on the western side of the Pifeng Waterside Pavilion. The Lian'ao rockery stone exhibits a topographical elevation of 5.85 m and spans a width of 8.12 m. When visitors pause to observe the scenery along the garden path, they can discern the

intricate features of the Lian'ao rockery stone. The Lian'ao rockery stone is situated at a horizontal distance of approximately 12.4 m from the overlook point. The ratio of the horizontal distance to the height (D/H) is greater than 1, indicating a generally broad spatial overview. The horizontal field of view measures 106°, while the vertical field of view measures 19°. These measurements fall within the optimal range for human perception, allowing individuals to effectively observe scenery. This approach effectively directs the attention of visitors to the three prominent figures of the Lian'ao rockery stone, creating an atmosphere that resonates with the historical and cultural significance of the San Su Shrine. With respect to the Lian'ao rockery stone in the Dockyard, the horizontal distance between the viewpoint and the stone is 17 m. The horizontal viewing angle is 88°, while the vertical viewing angle is 19°. From this perspective, one can obtain a comprehensive view of the Lian'ao rockery stone topography, enabling a deeper appreciation of the aesthetic essence conveyed through the interplay of the peaks, loops, rugged stones, and lush forests.

Commemorative axis landscape

The memorial hall area in the eastern part of the San Su Shrine has an obvious commemorative axis landscape. It is composed of four commemorative space units, which are marked in turn, by the South Gate, Lobby, Worship Hall, Sage Hall and Laifeng Pavilion, and these coincide with the main line in sight corridors and tour routes. Through the changes of plant height, building height and the distance between the two, a commemorative space sequence of ' starting - reinforcement - transition - conclusion ' is formed: starting space (S space), reinforcement space (R space), transition space (T space) and conclusion space (C space), as shown in Fig. 16.

The DH ratio reflects the degree of enclosure of the space. Through a comprehensive analysis of both vertical and horizontal elements within the landscape space, the "H" in D/H is indicatived by the vertical interface height, which is constituted by three-dimensional elements such as buildings, trees and walls. Meanwhile, "D" represents the width of the flat activity area where visitors are situated, thereby establishing the scale of the landscape space.

Memorial space unit Starting stage: South Gate—Lobby Four renowned and antiquated arboreal specimens, namely, *Ginkgo biloba* and *Phoebe zhennan*, are meticulously cultivated in the area spanning the South Gate to the Lobby. Based on empirical measurements, the horizontal visual distance between the South Gate and the ginkgo tree is estimated to be approximately 10.2 m. Furthermore, the ratio of the height of the *Ginkgo biloba* to the horizontal visual distance is estimated to be approximately 0.4. The *Ginkgo biloba* has a greater vertical stature than to the adjacent buildings, with a height ratio of approximately 2.75: 1 in relation to the lobby. Additionally, the ratio of the distance to height was less than 1 ($D/H < 1$). As a result, the area is perceived to have a cohesive and narrow ambiance, which results in a dignified and imposing entrance area [61]. The spatial distance between the South Gate and the Lobby is precisely 23.1 m. The vertical dimension of this space is 9.43 m and it offers a vertical field of vision spanning 27°. This falls within the optimal vertical viewing angle range. In addition, the ratio of the distance to height (D/H) exceeds 2, indicating a cohesive spatial arrangement that does not result in a sensation of dispersion [61]. This characteristic ensures the presence of adequate areas for both gathering and dispersing. Simultaneously, the presence of towering and old *ginkgo trees* within the Lobby serves the important purpose of obstructing the view, strategically setting the stage for the subsequent landscape and serving as the initial focal point of the commemorative landscape sequence.

Reinforcement stage: Lobby-Worship Hall

Four different individuals of *Podocarpus macrophyllus* are systematically planted in a symmetrical arrangement at the four corners of the front entrance located on the southern side of the Worship Hall. The height ratio between the trees and the Worship Hall is approximately 0.21:1, contributing to an expansive and panoramic view that enhances the solemn atmosphere of the hall. Based on the provided measurements, the distance between the Lobby and the Worship Hall is precisely 13.3 m. The height of the hall is 12.18 m, while the vertical angle of view is 36°. Additionally, the ratio of the distance to the height (D/H) falls within the range of 1 to 2. Furthermore, there is a steady decline in elevation between the building and the surrounding vegetation. The arrangement of space in this context creates a sombre and reverential ambiance, although it does not feel spatially confining [61]. It serves as a pivotal element within the overall landscape sequence.

Transition stage: Worship Hall—Sage Hall

Osmanthus fragrans, a traditional garden species, is strategically positioned in front of the entrance on the southern front of Sage Hall. The tree height is proportionally higher than that at Sage Hall, with a ratio of approximately 1.25:1. The height of *Osmanthus fragrans* is comparable to that of the Sage Hall roof, allowing *Osmanthus fragrans* to effectively keeping the mood light. Additionally, its stature serves to shield against adverse weather conditions, thus augmenting the

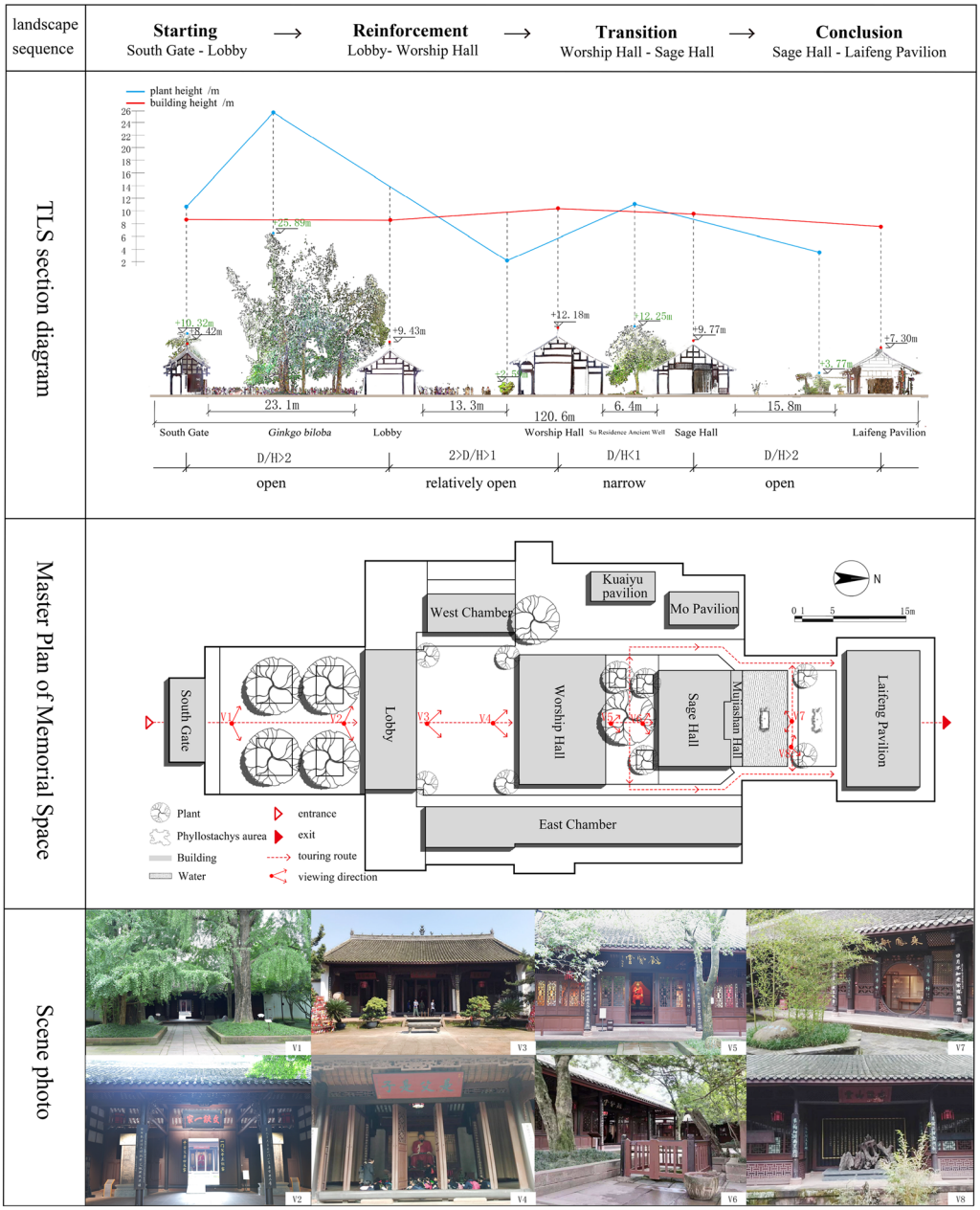


Fig. 16 Spatial sequence analysis of the central axis of the San Su Shrine

overall impression of solemnity and reverence around the main edifice. Based on the recorded measurements, the distance between the Worship Hall and the Sage Hall is precisely 6.4 m. Additionally, the height of the structure is 9.77 m, while the vertical viewing angle is 50°. Furthermore, it should be noted that the ratio of the building height to its distance from the ground (D/H) is less than 1. Additionally, the vertical dimensions of both the building and its surrounding plants are comparable, contributing to a compact spatial arrangement that feels confining [61]. Simultaneously, cultural artefacts and ancient and famous trees with commemorative significance, such as the Su Residence Old Well and the *Osmanthus fragrans* respectively, are strategically positioned in the area to augment the commemorative ambiance and achieve the pivotal juncture of the axial sequence.

Conclusion stage: Sage Hall—Laifeng Pavilion

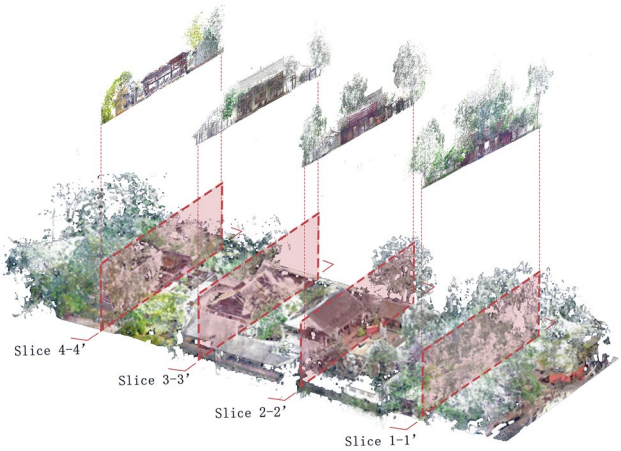


Fig. 17 Point cloud slice location map

The Laifeng Pavilion served as the place of study for the two brothers, Su Shi and Su Zhe. *Phyllostachys aurea* and *Cycas revoluta* are strategically planted within the tree pool near the entrance on the southern side. The height ratio between the tree and the Laifeng Pavilion is approximately 0.5:1, resulting in the creation of a serene spatial ambiance. Based on empirical measurements, the distance between Sage Hall and the Laifeng Pavilion is precisely 15.8 m. Additionally, the height of the Laifeng Pavilion is 7.30 m. The vertical angle of view, observed from a specific vantage point, is 17°. Furthermore, the ratio of the distance to the height (D/H) exceeds 2. Notably, the spatial arrangement between these structures exhibits a gradual opening, hence evoking a perceptible sensation of expansiveness [61].

Memorial space sequence As the D/H ratio increases, the enclosed space undergoes a transition from narrow to open, leading to three distinct perceptual stages for visitors: oppression, enclosure and openness. To delve deeper into the relationship between spatial sequences and their commemorative expressions, a line graph is presented in Fig. 18 based on the point cloud slice shown in Fig. 17 presents a line graph illustrating the variations in plant height, building height and the distances between them across four spatial cross-sections. Moreover, Fig. 19 provides an analysis of the distribution and variations in height within the D/H ratio for these four distinct spaces.

From the perspective of the changes in height shown in Fig. 18: 1) the height of plants has a significant change trend, showing a gradual decrease overall, transitioning from a layout of to a flatter trend. 2) The height changes between buildings are relatively small and show an overall trend of initially increasing and then decreasing, with the highest point in space T and the lowest point in space C. 3) There is a significant difference in the overall height between buildings and plants. In space S, plants are much taller than buildings and are located in the central area, emphasizing the symbolic entrance. Space R continues the layout of space S, but the difference in height between buildings and plants gradually decreases, serving as a transition. In space T, as the height of the plants gradually decreases, the buildings become slightly taller than the plants, creating a clear sense of transition. In space C, as the height of both buildings and plants gradually approaches a horizontal level, the difference in height between them is parallel to the horizontal sightline, creating an overall enclosed atmosphere.

Analysing the DH distribution and variations depicted in Fig. 19 reveals the following observations: (1) In space S, the DH values exhibit a consistent decreasing trend from left to right, consistently remaining below 1. This compact arrangement imparts a palpable sense of oppression. (2) Spaces R and C display higher DH values in the central area, contrasting with lower values on the sides. This configuration results in a spacious central zone, emphasizing the central building form while compressing the sides. (3) The T space has an overall more compact layout, contributing to a heightened sense of enclosure.

Upon horizontally comparing and analysing the four spaces, several key insights emerge. First, the DH distribution in each space aligns with the axial height, showcasing the most open area in space R and the narrowest in space S. This alignment corresponds with the narrative roles and functions assigned to each space sequence. Second, within the axial area, the DH variation across the four spaces follows a pattern of ascent, descent and then ascent again. This pattern forms a dynamic and rhythmic tour experience within the enclosed spaces, conveying a nuanced sense of a commemorative narrative.

In conclusion, the analysis of the landscape axis elucidates the height and scale trends within each space of the memorial sequence. The diminishing vegetation height in space contributes to a progressive sense, radiating from the interior outwards. Simultaneously, the alternating first and then descending building heights establish a spatial hierarchy within the transition and conclusion spaces. The alignment between height variations in the primary tour route area and the central axis underscores the significance of this region within the overall sequence. This nuanced examination of changes in height and scale enhances our understanding of the distinctive characteristics of each space, facilitating a deeper comprehension of the relationships and commemorative expressions embedded within them.

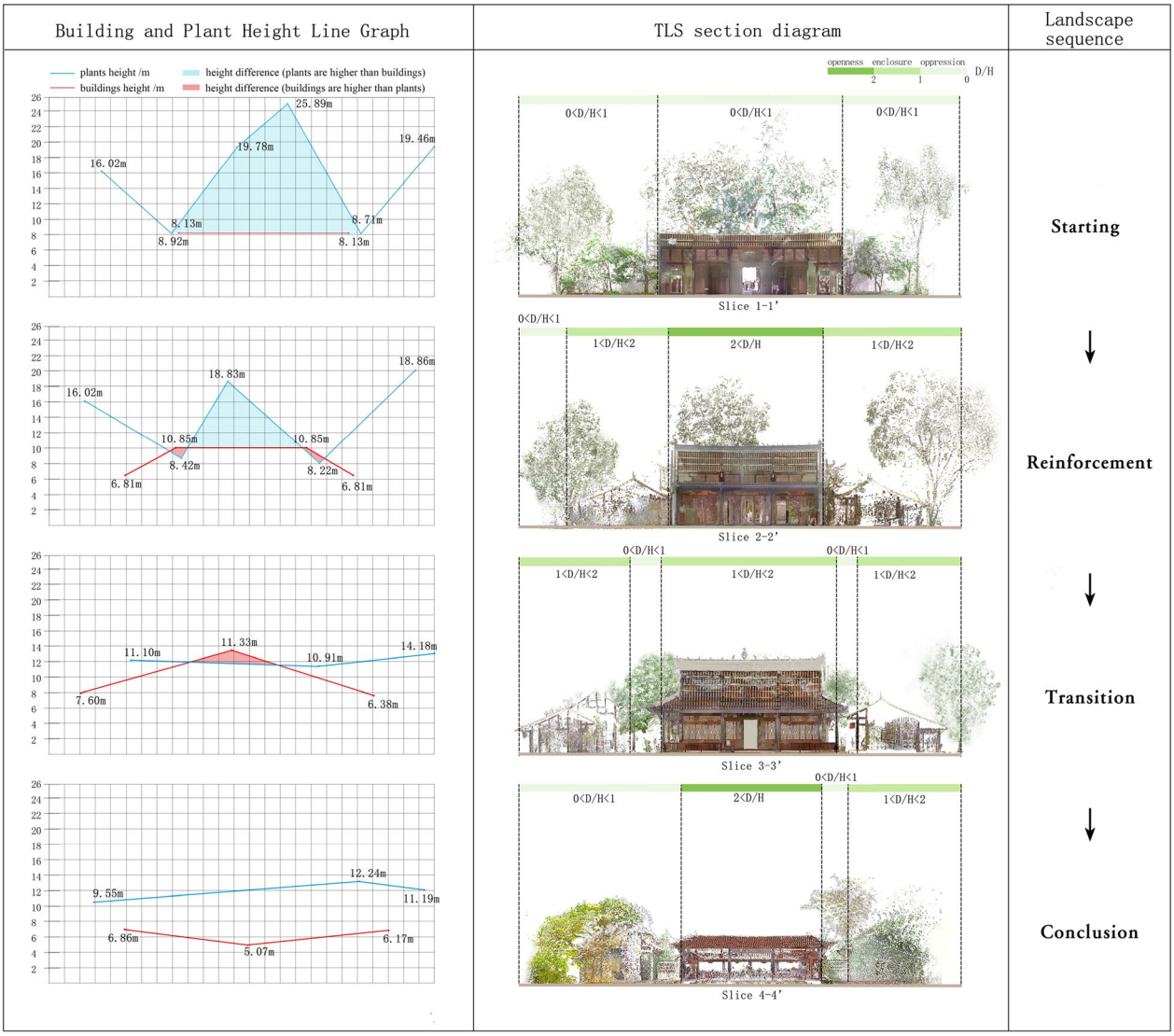


Fig. 18 Central axis section and height analysis diagram

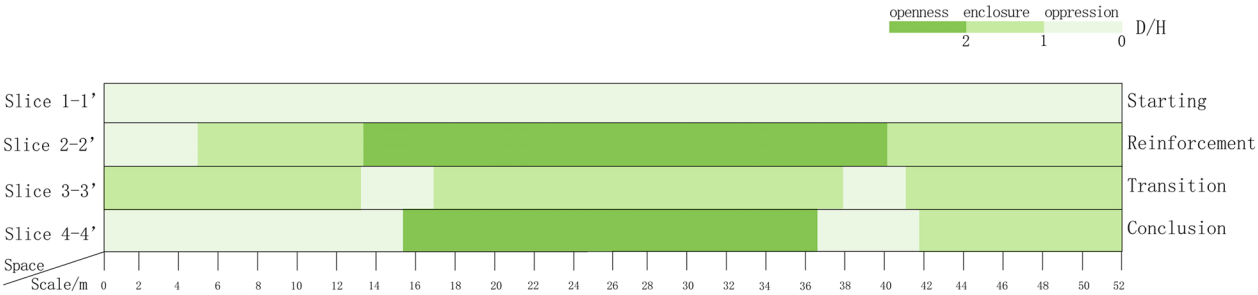


Fig. 19 Distribution map of DH values in the central axis space

Conclusions

This study, taking the San Su Shrine as a prototypical case, marks a breakthrough in research techniques and content within the field of landscape architecture. By integrating digital survey technologies (TLS, TDS, UA), we successfully acquired quantitative data on the garden landscape. These data enabled us to reconstruct models, extract key elements and identify characteristics, thereby dissecting the material composition and interrelations from both spatial and temporal dimensions. Our approach elucidates the formation logic of landscape features, filling a research gap in the digital preservation of Xishu Garden and offering new insights for the digital preservation of World Cultural Heritage landscapes.

The key findings are as follows: (1) The digitization of garden elements such as garden buildings, rocks, water landscapes and plants in the San Su Shrine, plays a pivotal role in the digital preservation of baseline data after earthquakes; (2) We reveal the spatial patterns of the memorial landscape axis in Xishu Garden through the analysis of landscape sequence slices, height variations and DH value distributions, providing a scientific basis for understanding the mechanisms of memorial expression in landscape design; (3) We provide a quantitative analysis of the memorial core of the San Su Shrine, constructing a memorial analysis framework encompassing both spatial and temporal dimensions and revealing the narrative axis of "starting-reinforcement-transition-conclusion" and the genesis of the Xishu Historical and Cultural Celebrity Memorial Garden, laying a foundation for further research in this area.

However, the study also identifies areas for improvement. The rich garden elements and complex spatial structures of the San Su Shrine, along with issues such as overlapping targets and spatial density variations, limit the visual representation of some plant landscapes and obstructions in 3D point cloud visualization. Additionally, while 3D laser scanning technology efficiently captures data with complex landscape and spatial features, it struggles to accurately record internal details such as branch morphology, branching patterns and leaf textures. The dynamic nature of plant changes across seasons and years further complicates this recording, leading to inaccuracies and challenges in verification.

Future garden heritage research should thus integrate digital technology optimization, dynamic monitoring, historical changes and universal aspects of cultural heritage protection. Indeed, constructing methods and approaches for garden heritage information protection not only aids in conservation research on Chinese classical gardens but also promotes diversified studies on World Cultural Heritage. With its significant universal value in cultural heritage protection and regional cultural value, this study not only advances the regional expression of the Xishu Garden in Chinese classical garden art but also contributes to the development of World Cultural Heritage protection.

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Author contributions

GL: (1) Project Leadership and Supervision; (2) Acquisition of Funding and Resources; (3) Research Design; (4) Writing and Revision. MWJ: (1) Research Design; (2) Data Collection and Manipulation; (3) Data Processing and Analysis. ZDS: (1) Technical Guidance; (2) Writing and Proofreading. GXQ: (1) Literature Review and Synthesis; (2) Full Manuscript Composition and Editing; (3) Data Interpretation and Discussion of Results; (4) Guidelines for Figures and Charts. Zhai ZG: (1) Figure and Chart Illustration; (2) Initial Drafting of the Discussion; (3) Reference Proofreading. LMJ: (1) Drawing the Technical Workflow; (2) Collaborative Chart Creation; (3) Drafting the Initial Research Methodology; (4) Formatting and Proofreading.

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Availability of data and materials

The datasets used and/or analysed in the current study are available from the corresponding author upon reasonable request.

Declarations

Competing interests

The authors declare that they have no competing interests.

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