Heritage Science

RESEARCH

Open Access

Digital improvements in the design and construction process of classical Chinese garden rockeries: a study based on material digitization

Zhe Wang[1], Penghao Song[1], Qingping Zhang[1*], Tianheng Wei[1] and Ben Pan[1]

Abstract

Rockeries have a complex and significant role in classical Chinese garden designs. They present distinct artistic characteristics and spatial hierarchies and are crucial to garden heritage conservation. Craftsmanship in rockery construction is a significant part of China's intangible cultural heritage. Rockeries are primarily composed of naturally occurring rocks chosen for their uniqueness and complex shapes and textures. These rocks present challenges as nonstandard elements within the traditional Chinese garden context, as it is not easy to depict them using conventional blueprints and models. This complicates the design, adjustment, display, and construction of rockeries, which lacks tangible bases for reference. Consequently, the preservation and restoration of garden rockeries is difficult, and the perpetuation and dissemination of rockery construction skills face numerous challenges. This study introduces a method that combines laser scanning and photographic measurements to digitize precisely nonstandard elements of rockery stones. This approach presents an innovative design and construction workflow for rockeries by refining design processes, showcasing real effects, and resolving assembly issues. The results demonstrate that the combination of three-dimensional laser scanning and close-range photogrammetry can accurately replicate the complex forms and textures of these nonstandard elements. The stone coding and digital management system devised based on the logic of construction effectively satisfies the design and building requirements of rockeries. Correspondingly, the proposed digital construction workflow enhances the accuracy of rockery design, presentation, and evaluation, thereby contributing to the protection and restoration of rockery heritage sites and the transmission of rockery construction techniques.

Keywords Rockery, Irregular heritage objects, Construction workflow, Chinese classical gardens, Digitalization

Introduction

Rockery, an integral element of Chinese garden heritage, is one of the most distinctive features that differentiates Chinese gardens from those of other countries and regions [1–3]. This traditional art form is featured in numerous world cultural heritage sites such as the Summer Palace and the classical gardens of Suzhou, where extensive rockery relics can be found [4]. The history of constructing rockeries in Chinese classical gardens dates back over 2000 years to the Qin and Han dynasties. Among the various aspects of Chinese garden construction, rockery construction is recognized as the most complex, challenging to learn, and difficult to replicate. Rockeries can be categorized into earthen, mixed stone and earth, and stone types, with the latter being particularly challenging to construct [5]. These artistic creations

*Correspondence:
Qingping Zhang
qpzh@njfu.edu.cn
[1] College of Landscape Architecture, Nanjing Forestry University, No. 159, Longpan Road, Nanjing 210037, Jiangsu, China

are meticulously designed and organized from naturally sourced stones with irregular geometrical shapes and complex surface textures and colors. They are assembled according to the principles of color homogeneity and pattern matching, forming elaborate, planned structures. This sophisticated skill is mastered by only a few; as a result, traditional rockery construction techniques have been designated as part of China's intangible cultural heritage [6].

The construction of traditional rockeries distinctly differs from conventional building and landscaping processes in several critical respects. Unlike the regularity, standardization, and replicability of most building or planting materials, rockery construction utilizes non-standard, unique, and irreplaceable natural stones [7–9]. Each stone features unique geometric and surface characteristics, essential for the artistic expression of rockeries. These unique attributes cannot be captured through traditional documentation methods, thus precluding the possibility of drafting preliminary design plans. Additionally, while modern design practices typically distinguish between design and construction phases [10], the specific nature of rock materials means that rockery design and construction continue to be deeply interwoven in a traditional artisan mode. The entire process is heavily reliant on the designer, who often also acts as the craftsman. This individual directly engages in the creative process on-site, orchestrating the placement of stones. This approach results in a one-time artistic creation; once the stones are positioned, further modifications to the design are not feasible. Consequently, the designer must possess an intimate knowledge of each stone's characteristics and be adept at applying the principles governing their assembly [11]. Furthermore, the designer needs to be capable of mentally visualizing the optimal arrangement of all materials involved. This expertise requires extensive practical experience and accumulated knowledge, underscoring the need for sustained traditional apprenticeship and training in this field.

The unique properties of the materials and workflows in rockery construction pose significant challenges to the preservation and restoration of rockery heritage, as well as to the transmission and protection of associated construction techniques.

(1) Heritage Conservation: Existing rockery sites are increasingly vulnerable to structural failures such as cracking, tilting, and collapsing attributed to factors like human activity, subsidence, and climatic variations, thus necessitating the implementation of urgent protective measures and repairs [12–14]. The lack of advanced three-dimensional (3D) stone-fitting simulation technology and visual presentation methods severely limits the ability to preplan restoration efforts. It becomes challenging to document and assess the interlocking relationships and structural features of rockeries [15–17] This gap in technology hinders comprehensive analysis and complicates stakeholder communication and decision-making, thereby impeding effective repair and reconstruction initiatives.
(2) Intangible Cultural Heritage Preservation: The perpetuation of stone-interlocking techniques, which are essential for rockery construction, is paramount [18, 19]. However, traditional transmission methods reliant on master-apprentice relationships are ill-equipped to meet modern needs owing to the absence of detailed 3D recordings and simulations of these techniques. Artisans typically convey complex construction concepts and techniques orally and through hands-on demonstrations, processes that are not only difficult to document but also challenging to learn efficiently. Learners require prolonged exposure and multiple practical experiences to grasp these skills [20–22]. This method of transmission is not only slow and inefficient but also risks the loss of these intricate techniques.
(3) Rockery Construction: The current practice of rockery construction continues to operate within a traditional framework, where a single artisan manages both design and construction. This method struggles to align with contemporary professionalized, standardized, and segmented construction processes. The absence of precise visualization tools for design and the lack of detailed material specifications hamper effective communication during the design phase, oversight and safety management during construction [12, 23]. Consequently, several rockery projects suffer from prolonged construction times, leading to deviations from intended outcomes, and potential safety hazards.

The majority of previous studies on classical Chinese garden rockeries have focused on historical, cultural, and aesthetic analyses and appreciation, which are predominantly qualitative and descriptive [24–27]. Although some scholars have recognized the importance of studying rockery construction techniques from a construction perspective, thereby improving traditional construction methods [28–31], only a few studies have been conducted on the construction processes and techniques of rockeries. Consequently, it is imperative to develop an enhanced rockery design and construction process that not only respects traditional techniques and artistry but also addresses the current requirements for heritage rockery restoration, the transmission of intangible cultural heritage, and the demands of modern design and construction practices.

The development of digital technologies offers innovative solutions and insights for addressing the issues outlined above. In the field of architecture digital and intelligent technologies play a crucial role throughout the entire lifecycle of projects [32–35], and in recent years they are also applied in the field of landscape [36–39]. During the digital design phase, adjustments and simulations are typically conducted based on parametric modeling [40–42]. In the architecture construction phase, reverse modeling techniques utilizing 3D laser scanning technology are extensively applied for deformation monitoring [43, 44], and quality monitoring of building components [45–47]. While these studies provide valuable insights into workflow improvements, the specific methods employed in each phase are not directly applicable to the digitalization of stone components or the simulated construction of rockeries. This limitation necessitates further exploration and adaptation of these digital techniques to suit the unique requirements of digital rockery design and simulated stacking.

In the domain of heritage conservation, digital technologies play a crucial role in various aspects such as the collection of artifact and heritage information [48–52], the establishment and classification management of heritage archives [53–57], the heritage assessment and monitoring [58–60], and enhancement of immersive heritage experiences [61–64]. Various methods, such as 3D laser scanning and photogrammetry, are employed to create digital archives for artifacts, historical buildings, and archaeological sites, to facilitate feature recognition [65, 66], and to simulate restorations [67, 68]. These innovations have introduced new methods and perspectives for protecting and managing irregular cultural heritage and immovable artifacts. While some scholars have applied 3D digitalization methods to conserve rockery heritage sites, their research has primarily focused on existing large rockery sites [53, 69–72]. Their objectives often include the quantitative identification and analysis of the spatial information and heritage value of constructed rockeries, as well as the creation of digital archives for these heritage sites.

Rockeries, as a unique type of structure, are a crucial component of cultural heritage, embodying conventional construction techniques and artistic value that are integral to intangible cultural heritage. While rockery construction shares certain similarities with architectural practices, it involves unique materials and a more complex design and construction process. Existing digital methods in the construction industry and reverse modeling techniques for cultural heritage do not directly align with the specific needs of digital design and construction for rockeries. Consequently, the digital design and simulated construction processes for rockeries require further exploration and adaptation to meet their unique demands.

Research aim

The aim of this research is to develop an efficient methodological framework for the digital design and simulated construction of rockeries that ensures the precise digital replication and systematic management of rock materials as non-standard components. The study focuses on achieving accurate 3D simulations of rock assembly, allowing for the visualization of the authentic sequence of rock stacking, interlocking features, and the overall construction outcomes. This project seeks to innovate the construction, restoration, and preservation of traditional rockery heritage by integrating digital methodologies into conventional rockery building practices. The research will be pursued based on four specific objectives:

(1) Integration of 3D laser scanning and close-range photogrammetry to devise a precise method for digital replication of rockery rock materials.
(2) Development of a systematic coding system for rock components that is tailored for use in simulated rockery stacking, facilitating the classification and management of these components.
(3) Utilization of digital design and simulated construction techniques for rockeries to visualize traditional craftsmanship and enhance the precision of construction quantification.
(4) Establishment of an optimized workflow for digital rockery design and simulation construction processes, promoting efficiency and accuracy in heritage conservation efforts.

Rockery construction techniques in traditional Chinese gardens

Rockery landscapes in classical Chinese gardens aim to emulate natural mountain and water scenes, striving for an art style that appears naturally formed despite its human-crafted nature. The construction of rockeries is predominantly guided by skilled artisans who use various natural and unordered rock materials. These materials are meticulously designed, combined, and assembled into works that capture both the essence of natural beauty and ingenuous human artistry. The materials for rockery construction are sourced from nature, with each rock being unique and irreplaceable and characterized by complex forms, colors, and textures. This uniqueness leads to a construction process for traditional rockeries that is distinct from that of regular buildings or structures, giving them unique characteristics.

Rock materials

In contrast to the traditional Chinese timber structures and other regular stone buildings, the rock materials used in constructing rockeries are naturally formed and unaltered by human hands. These materials are characterized as follows:

1) Natural formation and uniqueness: The stones used in rockeries are maintained in their natural state—unsculpted and unpolished—making each piece unique and irreplaceable.
2) Complex shapes and rich textures: The stones vary significantly in shape, containing many cavities and uneven surfaces, and exhibiting a diverse range of colors and textures.

In classical Chinese gardens, these stones are categorized into four main types: lake stones, yellow stones, blue stones, and bamboo shoot stones, each with distinctive characteristics (Fig. 1). Lake stone—the most used stone in classical Chinese gardens—is formed from limestone and shaped by the action of waves or the dissolution effects of acidic substances. These stones have intricate crisscrossed textures with numerous holes. Their surface textures include pitted, rugged, layered, and blocky patterns, predominantly in shades of gray and white, cyan-gray, dark gray, yellow-gray, brownish-yellow, and charcoal black. Yellow stone—a type of fine sandstone—has a regular shape and thick, dense body with nearly vertical joints, creating strong light and shadow effects. The surface textures are chiseled, blocky, layered, and smooth. The predominant color of the stone is yellow, with shades ranging from light yellow to brownish-yellow and orange-yellow. Blue stones and fine sandstones differ in their less regular joints and are often cross-weaved with slanted patterns. Common textures include chiseled, piled, and rugged, primarily showing as cyan-gray, yellow-blue, and yellow-gray. Bamboo shoot stones resemble slender bamboo shoots and are typically used to detail smaller rockery scenes rather than as the main structural elements. The surfaces of these stones often have a speckled appearance and may include vertical stripes. The colors primarily include shades of white, cyan-gray, black-gray, and yellow-gray.

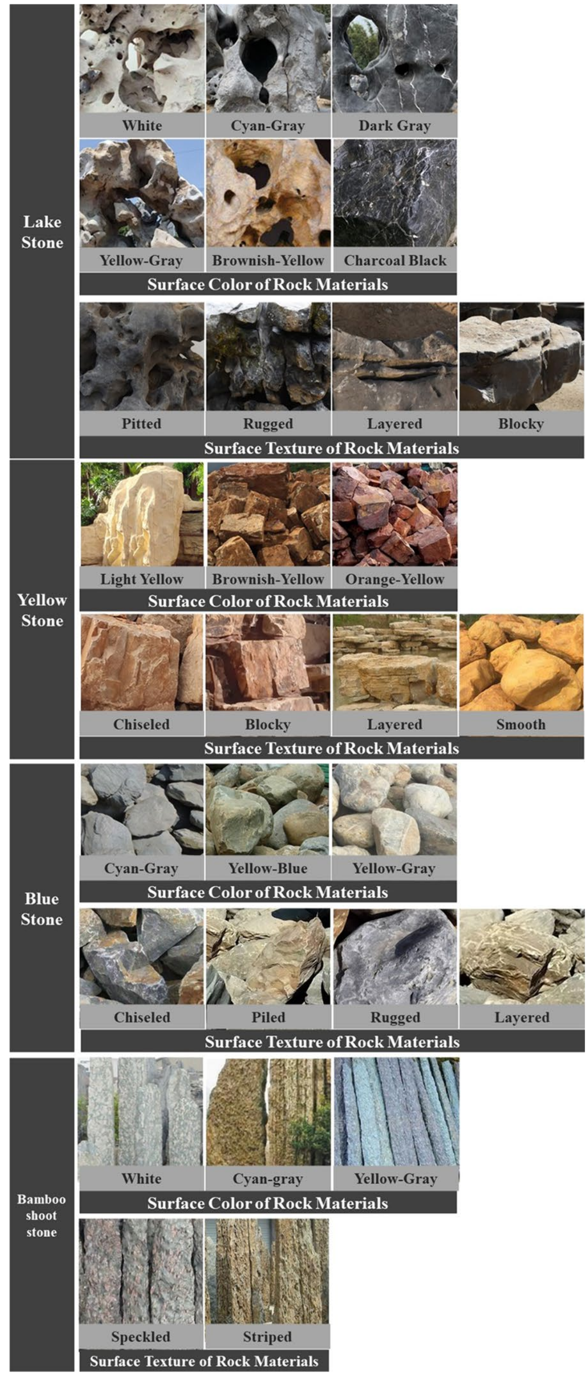

Fig. 1 Classification and characteristics of rock materials

Traditional rockery construction process

The construction of rockeries involves a sequence of fundamental steps: site surveying, stone selection and transportation, foundation construction, rockery body stacking, and stone embedding to fill gaps [11, 73, 74] (Fig. 2). In traditional rockery construction, the craftsman, who serves as the project leader, plays a pivotal role. He/She bears direct responsibility for overseeing the entire construction process. The critical phase of rock stacking presents unique challenges; due to the stones' intricate geometric shapes and varied surface textures,

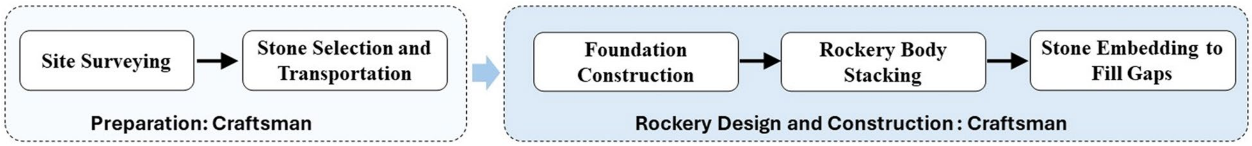

Fig. 2 Traditional rockery construction process

which cannot be adequately captured or conveyed through images, the designer must rely on mental simulations to arrange the stones. This mental visualization cannot be easily shared or visualized, complicating the ability to communicate design intentions, make adjustments, or conduct quantitative structural analyses with others. Following the mental simulation, the designer instructs craftsmen to place the stones in their intended positions, a process that is iteratively repeated until the rockery's completion. This method demands considerable expertise from the project leader and incurs significant time and cost, with the leader holding sole accountability for the rockery's aesthetic and structural integrity.

Challenges with rock materials and traditional processes

Owing to the distinctive properties of rock materials and traditional construction processes, the building of rockeries faces several significant challenges:

(1) Visual Representation Challenges: Rockery materials are inherently complex, making them difficult to represent with traditional two-dimensional (2D) techniques. Furthermore, rockery designs lack concrete blueprints and exist solely in the imagination of the craftsmen, who convey their design intentions through the meticulous assembly of rocks during construction. This limitation prevents the clear visual presentation of rockery plans to non-technical stakeholders, clients, and builders, complicating accurate design presentations, communications, and guidance for construction. Until a rockery is completed, no one apart from the craftsmen can fully understand, analyze, or evaluate the design.
(2) Difficulty in Design Adjustment: Once assembled, the substantial weight of the rockery stones and the complex, interconnected nature of their arrangement significantly restrict any modifications to the design. This inflexibility poses challenges when changes are required after the initial construction phases.
(3) Inefficiency and Unpredictability in Construction Management: The construction process begins with the transportation of a large volume of stones to the site, where craftsmen select only a part for the rockery construction. The surplus stones must then be removed from the site, leading to waste. Additionally, the unpredictable quantity of stones needed and the scope of the construction work complicate the precise calculation of foundational support and interlocking structures. These calculations are typically based on experience, and inaccuracies in these estimates can introduce safety risks and potential losses.

Given the complexity and unique characteristics of rock materials, as described in previous sections, traditional construction methods face inherent challenges that prevent them from potential adaptation to modern design and construction practices. Moreover, these challenges extend to the conservation and restoration of rockery heritage within garden landscapes, as well as the transmission of intangible cultural heritage associated with these structures. This highlights a critical need for innovative approaches to preserve effectively both the physical and cultural aspects of rockeries.

Materials and methods

Overview of methods and design

Advancements in 3D digital technology and computer graphics have introduced new methods to address the challenges in traditional rockery construction. These technologies enable the precise replication of rockery materials and the optimization of construction processes, thereby enhancing the preservation and transmission of rockery heritage and skills [75–77].

The traditional rockery construction process has been traditionally classified into two main phases: the preparation stage and the rockery design and construction stage. The proposed digital workflow refines this approach by dividing the process into three distinct phases: preparation, digital design for rockeries, and the rockery construction (Figs. 3, 4). This paper focuses primarily on the digital design phase of rockeries, structured into three key segments:

1) The first part, Digital Replication of Rock Material, employs an integration of 3D laser scanning and close-range photogrammetry. This approach facilitates the digital capture of rock components and uses

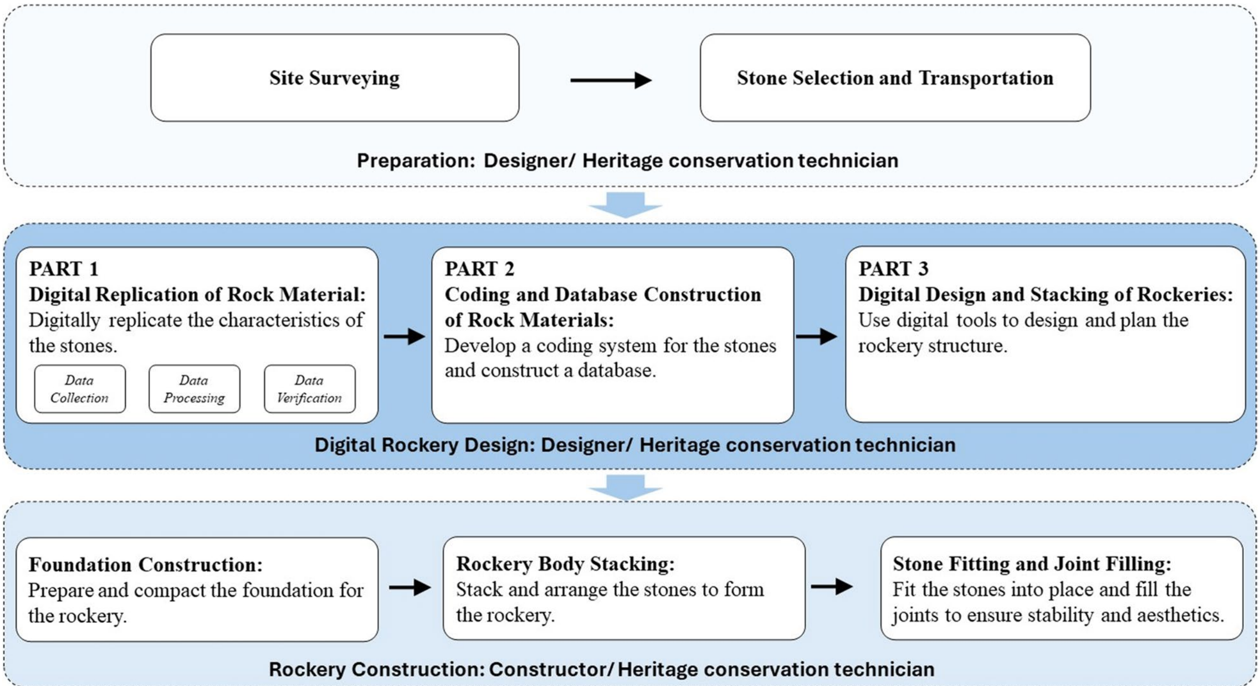

Fig. 3 Digital rockery design and construction workflow

3D mesh models to replicate the geometric forms and surface details of the stones, providing a robust foundation for subsequent digital design efforts.

2) The second part, Coding and Database Construction of Rock Materials, develops a systematic coding protocol for rock materials tailored to meet the logical and practical needs of construction. This coding, coupled with a comprehensive database, enables systematic management of a vast inventory of rock components, substantially enhancing the efficiency of both design and construction processes.
3) The third part, Digital Design and Stacking of Rockeries, executes the design and virtual assembly of rockeries within a simulated environment. This innovative process not only visualizes traditional rockery construction techniques and structures but also facilitates thorough evaluation and analyses of rockery designs. Subsequently, it allows for precise calculation of construction volumes and provides accurate, two-dimensional construction drawings derived from three-dimensional models to guide on-site work. Moreover, this digital approach greatly enhances the efficiency of communications among all stakeholders involved, including heritage managers, craftsmen, constructors, and designers.

By adopting this digital methodology, the article advocates for an enhancement of traditional cultural heritage construction practices. It not only ensures the preservation and visualization of historical and traditional construction techniques but also aligns these practices with modern design and construction management standards, thereby supporting the evolving needs of contemporary heritage conservation and restoration.

Digital replication of rock materials

Three key aspects must be considered when digitally replicating the complex and varied rock materials used in traditional rockery construction. First, the capturing of the intricate surface characteristics of the rocks, including their varied textures, colors, and contours, must be considered; these are essential for the accurate modeling of the appearance of the rock. Second, precise measurements of rock dimensions are considered, as this directly influences the accuracy of the assembly. Finally, the logistical challenges associated with the management of heavy and numerous rocks during data collection must be addressed.

Previous studies on architectural and archaeological heritage have demonstrated the feasibility of integrating multisource data to reconstruct complex heritage structures digitally [78–81]. This background supports the current study's use of both Terrestrial Digital

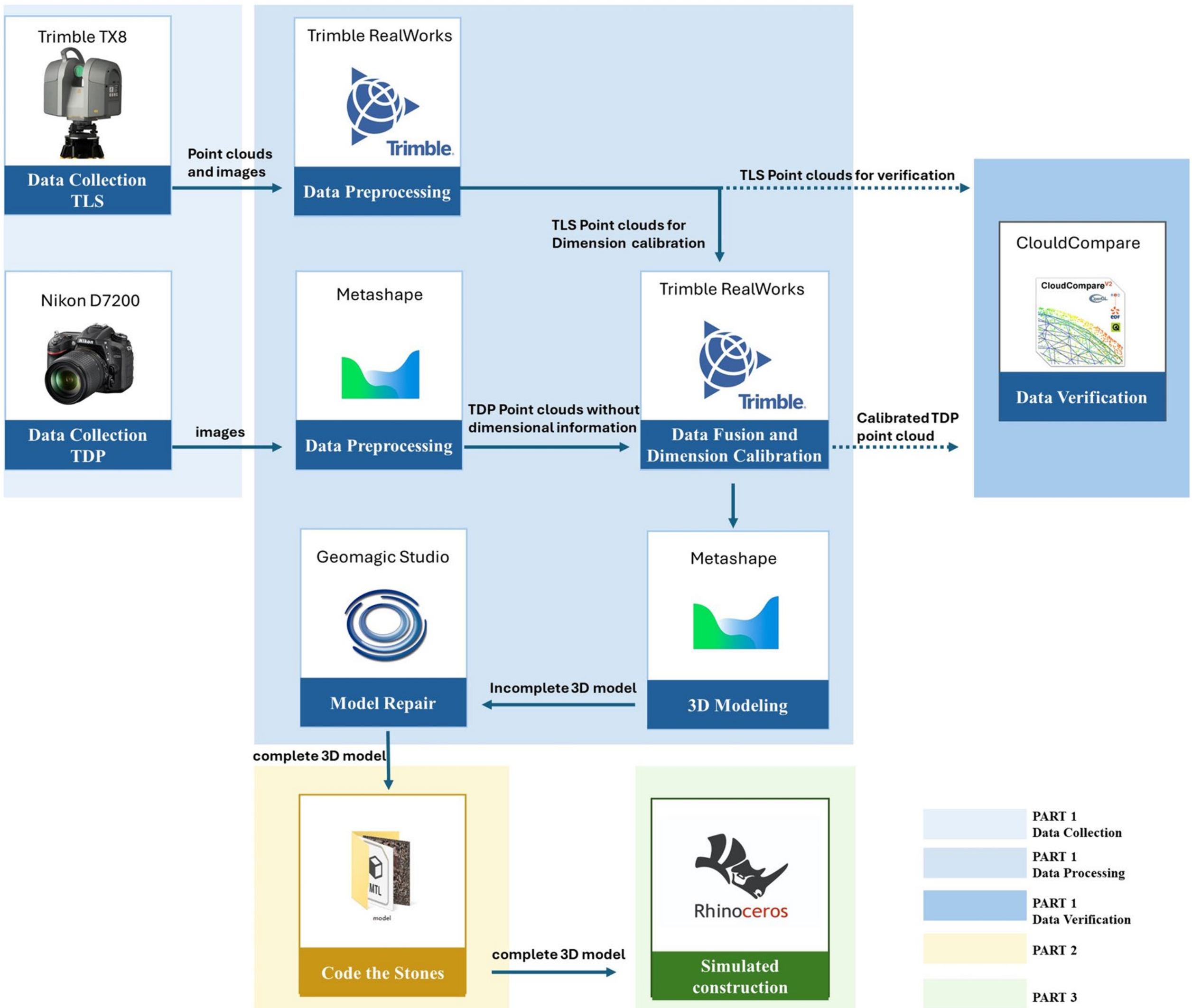

Fig. 4 Implementation details of the workflow

Photogrammetry (TDP) and Terrestrial Laser Scanning (TLS) to gather data efficiently (Table 1). The TDP is used to capture the authentic colors, textures, and physical details of rock materials at a low cost and with high efficiency, whereas the TLS is utilized to record the precise dimensional data of rocks, which is useful for detailed analysis and calibration.

To validate the effectiveness of these methods, a verification step was added; in this step, both techniques were employed to capture comprehensively stone materials, ensuring the reliability and accuracy of the data. The procedures for rock data collection, processing, and verification are detailed in subsequent sections.

Data collection

Considering the unique properties of rock materials and the specific demands of rockery construction, alongside the strengths and limitations of various surveying techniques, this study employs an integrated approach utilizing TDP and TLS for the collection of 3D digital data. Given the substantial volume and weight of the rocks used in construction, which complicate handling, cranes are typically employed for their lifting and placement. To enhance efficiency and reduce repetitive handling, conducting surveys during crane operations proves advantageous. This methodology is tailored to address the unique collection requirements of rock materials while navigating challenges such as the extensive number of rocks

Table 1 Comparison of terrestrial digital photogrammetry (TDP) and Terrestrial laser scanning (TLS)

	Terrestrial Laser Scanning (TLS)	Terrestrial Digital Photogrammetry (TDP)
Measurement	Large Measurement Range	Small Measurement Range
Measurement Accuracy	Measurement of actual size of target object without requiring size calibration	Measurement of relative size of target object requiring size calibration
Accuracy of Color Texture Reproduction	Deviation exists	High level of fidelity
Work Efficiency	Speedy data acquisition; High fieldwork efficiency; High automation level; Large data volume; High redundancy	Convenient image acquisition; High fieldwork efficiency; Low automation level; High manual workload
Working Conditions	Can operate in all weather conditions	Affected by external conditions such as weather and lighting
Equipment Costs	High	Low
Original Data	Point cloud data, color images	Color images

and potential physical obstacles. To ensure efficient and accurate data gathering, several strategic approaches are formulated: one-time comprehensive collection, multiple partial collections, and calibration collection (Table 2).

(1) One-time Comprehensive Collection: Ideal circumstances allow for the one-time comprehensive collection, where rocks can be suspended for extended periods without time constraints or spatial limitations, in an environment free from obstructions. In this scenario, data are gathered by circumnavigating the suspended rock with a camera; without the need to reposition the rock. Care is taken to avoid overly bright or dark conditions; and adjust the rock's orientation as necessary to mitigate any shadow-induced color discrepancies (Fig. 5).

(2) Multiple Partial Collections: In situations characterized by limited time, restricted space, the presence of obstacles, or situations in which the rock cannot be lifted, multiple partial collections are necessary. Initially, data from the visible part of the rock are captured. The rock is then rotated or flipped to access additional angles, with each repositioning considered a separate data collection event. A mobile camera technique is employed, ensuring that the rock's spatial position remains constant. Photographs are acquired in a spherical pattern to cover comprehensively all visible facets, typically from top to bottom in a counterclockwise direction. More images are captured in areas with significant changes in form, and fewer in flatter areas, ensuring overlapping features in adjacent photos to aid in later data processing (Fig. 5).

(3) Calibration Collection: Depending on time availability and the operational setting, 3D laser scanning captures data from at least one position for dimensional calibration, referred to as calibration collection. In areas where the rock has a complex geometry with numerous concave and convex transitions, accuracy is enhanced by increasing the number of scanning stations. Care is taken to maintain an appropriate distance from the rock to ensure comprehensive data capture from multiple facets in a single session (Fig. 6).

Table 2 Collection scheme of rock materials

Elements	Data acquisition	Technical type	Acquisition method	Conditions of use
Rock materials	The precise dimensions of the rock materials	TLS	Calibration acquisition	All situations
	The form, color, texture, and texture of the rock materials	TDP	One-time comprehensive acquisition	Stone can be lifted and there are no obstructions around
			Multiple partial acquisitions	Stone cannot be lifted, or there are obstructions around the stone

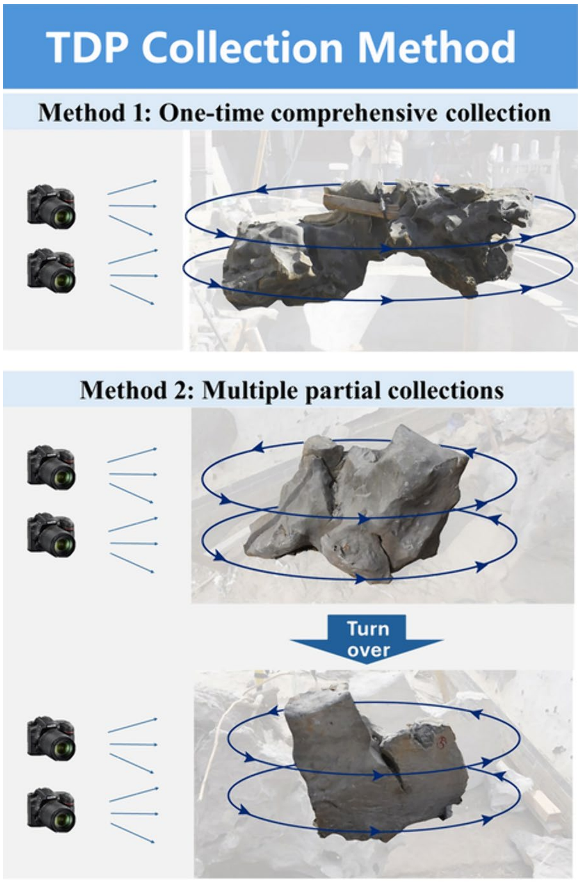

Fig. 5 Collection method of rock materials (Terrestrial Digital Photogrammetry (TDP))

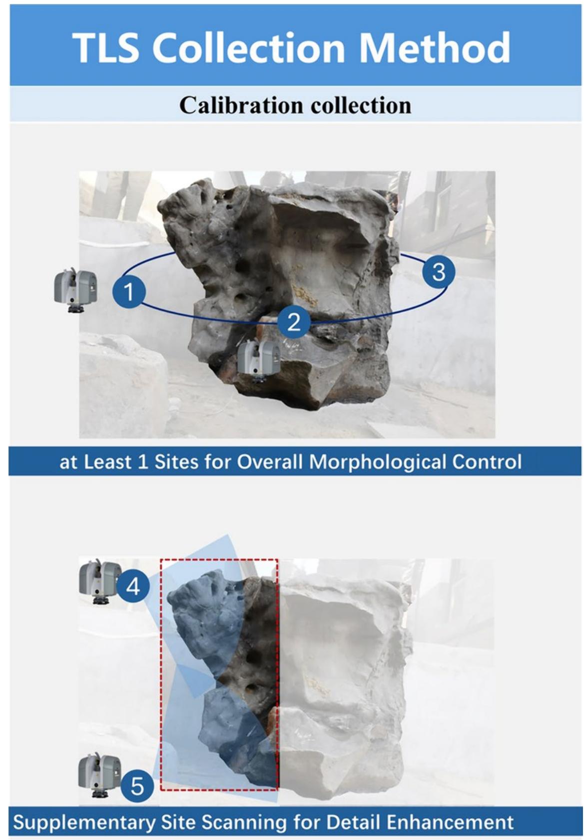

Fig. 6 Collection method of rock materials (Terrestrial Laser Scanning (TLS))

Regarding data verifications for stone labeled as LS-YG-L-001, data must be collected using the aforementioned methods. Additionally, comprehensive information on the stones was gathered using TDP, which requires multiple station setups to ensure data completeness. A complete TDP point-cloud model of LS-YG-L-001 was then developed through data integration. This model was used to verify the accuracy of the proposed dimensional calibration method.

Data processing

1) Data Preprocessing. The data obtained from terrestrial digital photogrammetry and laser scanning comprised point clouds and images, respectively. Preprocessing is necessary to make these data formats compatible with dimensional calibration and data fusion. The TDP data were processed using Agisoft Metashape, where photos accquired with a Nikon camera were grouped and aligned to create dense point clouds for each rock type. For TLS data, the RealWorks software program was used for preprocessing, beginning with target-free automatic stitching, followed by manual stitching and inspection, and then coloring and cleaning of the point cloud-model.
2) Data Fusion. The TDP data of rock materials obtained from one-time comprehensive captures can be directly used for dimensional calibration after cleaning. The results of multiple partial captures require fusion. The RealWorks software program was used to remove ineffective point clouds and perform automatic and manual stitching of multiple datasets to achieve a complete TDP point-cloud model of the rock.
3) Dimensional Calibration. TDP does not capture the true dimensions of objects, necessitating the calibration of the TDP point-cloud model to ensure accurate rock dimensions. After merging, the complete TDP point-cloud model was imported into the Realworks program for calibration against the TLS partial point-cloud model. Calibration was achieved by measuring the distances between multiple sets of characteristic points, calculating the scale ratio between the TDP

data and actual size data, and performing scaling adjustments to ensure that the rock model reflected the correct dimensions (Fig. 7).

4) Model Construction: The fused multisource point cloud models of the rockery stones and the 3D point-cloud model of the design site were imported into Agisoft Metashape for modeling. The models were then repaired using the Geomagic software program, resulting in 3D life-like models of the stones and the design site.

Data verification

To verify the effectiveness of the calibration methods discussed, we verified the calibrated results. A TDP point-cloud model of a rock, calibrated according to the workflow, was compared against a precise TLS point-cloud model obtained using laser scanning, and served as a standard-size reference.

By importing both the TDP and TLS models into the cloud for comparison and using the point-to-point distance calculation feature, we assessed the deviations between the TDP and TLS data. This comparison produces graphs illustrating the distribution and statistics of deviations, thereby assessing the completeness of photogrammetric measurements, dimensional accuracy, and accuracy of color and texture representations compared with actual photographs.

Coding and database construction of rock materials

To minimize confusion among rock materials and facilitate selection and pairing during rockery construction, it is essential to code each stone using a unique identification number. We proposed a coding rule based on the characteristics of rocks that aligned with the fundamental standards and logic of rockery design and construction.

In classical Chinese rocker gardens, stone assembly adheres to two principles: homogeneity in quality and color, and shape and texture alignment. The proposed coding system classifies rocks by type as a primary attribute, color and texture as secondary attributes, and individual numbers as tertiary attributes (Table 3). This systematic approach organizes rock components for better management, following the classifications introduced and summarized in Section Rock Materials.

Digital design and stacking of rockeries

Digital information is transmitted through the entire cycle of digital design, facilitating seamless integration of the planning and design phases through data exchange across multiple software platforms. The foundation of this process is data interoperability. This study used the OBJ file format to export 3D rock material models, utilizing the Rhino software program as the platform for digital design and stacking. The OBJ file format, which is known for its excellent interoperability and comprehensive feature retention, also supports both normal and texture coordinates. This ensures that the textures and colors of the rock materials are well represented in the models. By importing the encoded rock material models into Rhino, designers and heritage restoration professionals can engage in digital design and stacking within virtual scenes. This approach enabled a comprehensive and accurate depiction of the postconstruction shape, spatial layout, and dimensional characteristics of a rock. It also facilitated adjustments and comparisons among different designs. The resulting 3D models, 2D drawings, and videos served as precise references for rockery

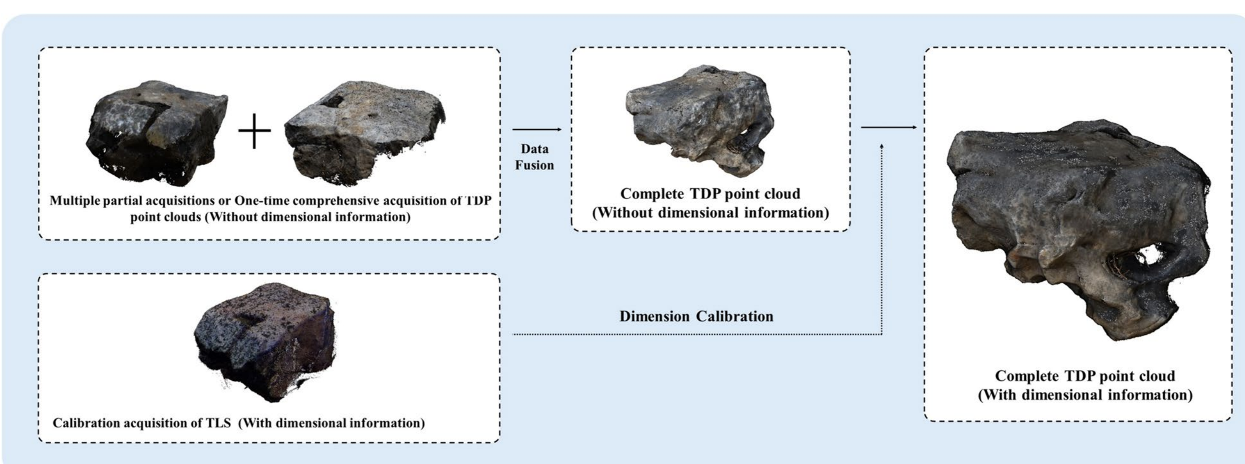

Fig. 7 Data fusion and dimensional calibration process

Table 3 Attribute characteristics of rock materials

Primary Attributes		Secondary Attributes		Tertiary Attributes
Types	Code	Types	Code	Number
Lake Stone	LS	Secondary Attributes 1: Surface Color		1 ~ 999
		White	W	
		Cyan-gray	CG	
		Dark grey	DG	
		Yellow-grey	YG	
		Brownish-yellow	BY	
		Charcoal black	CB	
		Secondary Attributes 2: Surface Texture		
		Pitted	P	
		Layered	L	
		Rugged	R	
		Blocky	B	
Yellow Stone	YS	Secondary Attributes 1: Surface Color		
		Light yellow	LY	
		Brownish-yellow	BY	
		Orange-yellow	OY	
		Secondary Attributes 2: Surface Texture		
		Chiseled	C	
		Blocky	B	
		Layered	L	
		Smooth	S	
Blue Stone	BS	Secondary Attributes 1: Surface Color		
		Cyan-gray	CG	
		Yellow-blue	YB	
		Yellow-gray	YG	
		Secondary Attributes 2: Surface Texture		
		Chiseled	C	
		Piled	P	
		Rugged	R	
		Layered	L	
Bamboo Shoot Stone	BSS	Secondary Attributes 1: Surface Color		
		White	W	
		Cyan-gray	CG	
		Yellow-grey	YG	
		Secondary Attributes 2: Surface Texture		
		Speckled	S1	
		Striped	S2	

construction and provided a reliable basis for decision-making in heritage conservation and restoration.

Study area and equipment

Study area

Yangzhou, China, located at the confluence of the Yangtze River and the Grand Canal, is renowned for its traditional garden artistry, particularly its advanced rockery construction techniques. This region houses numerous invaluable rockery heritage sites and maintains traditional rockery construction techniques and styles in modern garden settings. These techniques, recognized as part of China's intangible cultural heritage, have been continuously applied throughout the area.

The research site selected for this study is a private garden covering approximately 77.49 m^2, located at 1 Garden Road, Yangzhou. Surrounded by buildings to the north and walls to the east and west, a planned rockery

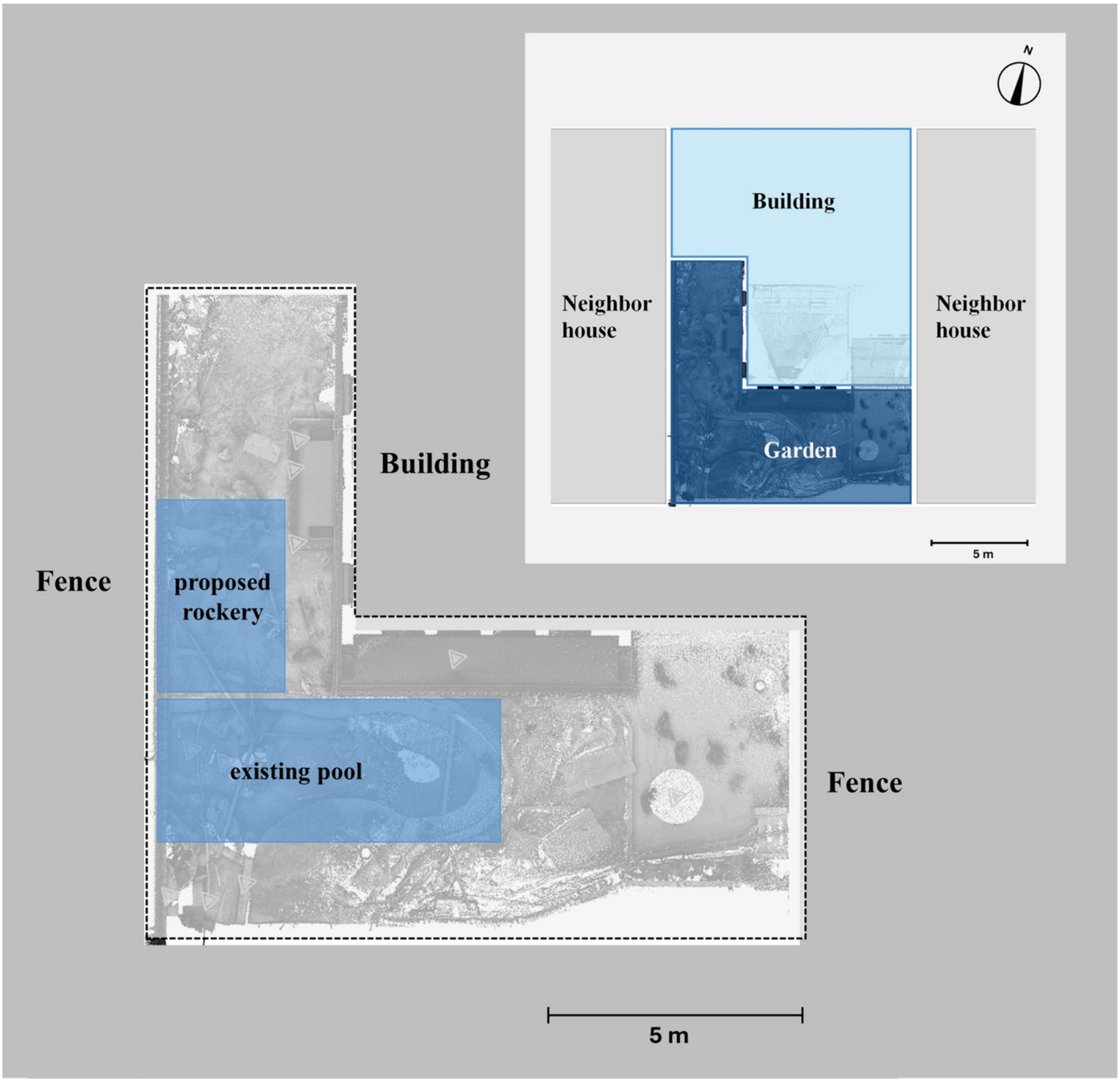

Fig. 8 Top views of the study area

was constructed on the western side of the garden, near the water (Fig. 8). The construction was completed under the guidance of Fang Hui, a bearer of intangible cultural heritage, and employed traditional gardening techniques and methods.

Equipment

In this study, the Trimble TX8 stationary 3D laser scanner was utilized, featuring a scanning speed of up to 10^6 points per second and supporting an extensive field of view of 360° × 317°, with a maximum range of 340 m. This scanner integrates an HDR panoramic camera to enrich the point clouds with true color fidelity. For thorough shape control, data were collected from at least three strategic stations surrounding each rock. Additional stations were deployed to improve accuracy in areas where rocks exhibited complex geometries and significant variations in surface contours. Photographic documentation was performed using a NIKON D7200 DSLR camera set to a resolution of 6000 × 4000 pixels, with a fixed focal length of 18 mm to maintain consistency throughout the data-collection process. The camera's shutter speed, aperture, and sensor sensitivity were automatically adjusted by the system, with the flash disabled and without the use of exposure compensation. The number of photographs and the overlap between them were determined by the geometric complexity and the textural and color variations of the rocks' surfaces. Regions with pronounced morphological changes required a higher number of photographs with an overlap of ~ 75%, while areas with minimal variation necessitated fewer photographs an overlap of ~ 60%, optimizing the coverage and accuracy of the 3D modeling process.

Using the specified equipment and methodologies, data were collected from 19 specimens; all the specimens were classified as lake stones, notable for their rich color palette and diverse textures, representing the entire color spectrum and texture variations typical of this stone type. A 3Dl laser scanning technique was employed to gather environmental data from 16 strategically positioned stations across the site. These data served to establish a virtual environment for subsequent design and simulations.

Results

Digital replication of rock materials

Accuracy of dimensional calibration

Using LS-YG-L-001 as an example rock material, data were collected and preprocessed to obtain the TLS-calibrated and TDP-fused point cloud rock models. Calibration involves the alignment of the six characteristic points between these models to produce a TDP model that includes accurate dimensional information (Table 4). The integrity of the calibrated model was verified using a comprehensive TLS point-cloud model. The deviations in the TDP model were analyzed, indicating an average deviation of 4.9 mm and a standard deviation of 6.1 mm (Fig. 9). These results confirm the high precision of the calibration process, suggesting the potential for this method to be widely applied in the calibration of other rock material data.

Comparison of color and texture fidelity

LS-YG-L-001, classified as "lake stone" (yellow-gray and layered), was used to validate digital replication techniques. Both the TDP-calibrated and TLS point cloud models of the rock were compared.

Table 4 Scaling ratio of LS-YG-L-001 TDP data size calibration

Target object	Characteristic points	Distance		Scale ratio
		TDP point cloud model (a)	TLS point cloud model (b)	
Stone LS-YG-L-001	Points 1- points 2	10,209	1575	0.154
	Points 2- points 3	7962	1234	0.155
	Points 3- points 4	9651	1505	0.156
	Points 4- points 5	7852	1240	0.158
	Points 5- points 6	5631	867	0.154
	Points 6- points 1	8450	1284	0.152

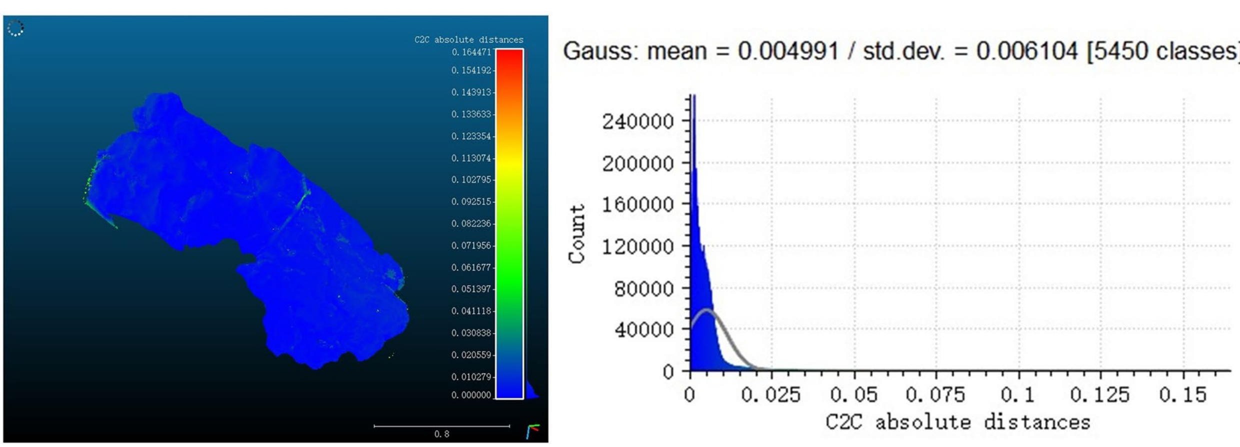

Fig. 9 Deviation distribution and statistical deviation of LS-YG-L-001 TDP and TLS point cloud model

The TDP method matched the actual surface characteristics of the rock more closely, capturing its color, texture, and physical nuances more accurately than the TLS method. The TLS model exhibited color shifts and failed to capture the gray tone characteristics of lake stones with a general reddish tint and poor texture detail. Overall, the point-cloud model generated by the TLS method significantly lacked both color fidelity and precision compared with the TDP method. Although the camera integrated within the laser scanner captured certain surface features of the stone, it failed to reproduce adequately the colors and textures necessary for detailed rockery stacking (Fig. 10).

Replicated rock material models

After calibrating the TDP point-cloud model of stone LS-YG-L-001, further cleansing, modeling, and repair were conducted to achieve a 3D triangular model of the stone. This fused model benefits from the advantages of both methods, capturing the stone's shape and size with precision while effectively restoring its textured surface and rich colors. This demonstrates the detailed and nuanced results of the digital modeling process.

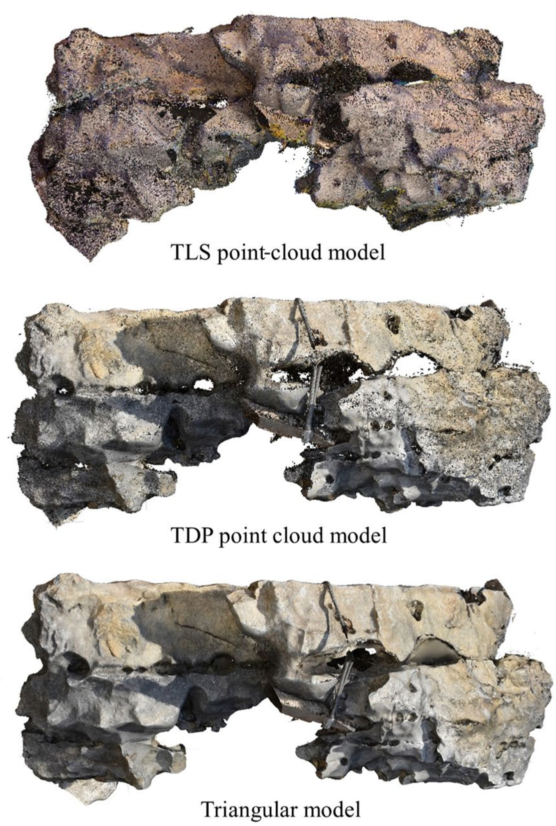

Fig. 10 Point-cloud and triangular models of stone LS-YG-L-001

The results on the accuracy of dimensional calibration and comparison of color and texture fidelity validate our TDP and TLS integrated approach. This underscores the necessity and feasibility of digitizing rock materials. The workflow was applied to an additional 18 rocks with varying surface textures, colors, and shapes, ultimately yielding 19 rock models suitable for digital rockery design and stacking. As shown in Fig. 11, all rock types, colors, and textures are identifiable.

Coding and database construction of rock materials

For the construction of the rock material repository, all 19 rocks were classified as lake stones (LSs). The palette primarily comprises gray shades encompassing five common hues of lake stone: dark gray (DG), cyan-gray (CG), white (W), charcoal black (CB), and yellow-gray (YG), with three, five, one, one, and nine stones in each category, respectively. The textures were pitted (P), layered (L), rugged (R), and blocky (B), with eight, four, five, and two rocks, respectively. According to the stone coding rules established in this study, the coding results for the 19 rocks used in the rockery stacking are shown in Fig. 11. The 3D models of the coded rocks generated after coding served as fundamental digital components for the construction and restoration of rockeries.

Digital design and stacking of rockeries

The 3D models effectively display design schemes and landscape spaces, visually demonstrating the techniques and principles used in rockery stacking. The 3D model of the site environment obtained using the TLS method retained intricate site details. This illustrates the crucial site features that influence rockery construction, such as the positions and appearances of buildings, ponds, and walls, enhancing visual comprehension of their impact on the rockery stacking process (Fig. 12). The 3D models of the base environment and the 19 stones were imported into Rhino for digital design, simulated stacking, scheme adjustment, and rockery display. Nine stones selected from the library were used to design and construct the rockery virtually. The subsequent sections provide an analysis of the outcomes of digital rockery stacking, focusing on the application of traditional techniques throughout the design process and the detailed visualization, computation, and analysis conducted postconstruction (Fig. 13).

Analysis and visualization of traditional techniques based on simulated stacking

3D modeling enhances the visualization of the stones' textures and colors, thereby facilitating more accurate and efficient design and virtual stacking of rockeries. Additionally, this approach allows the visual

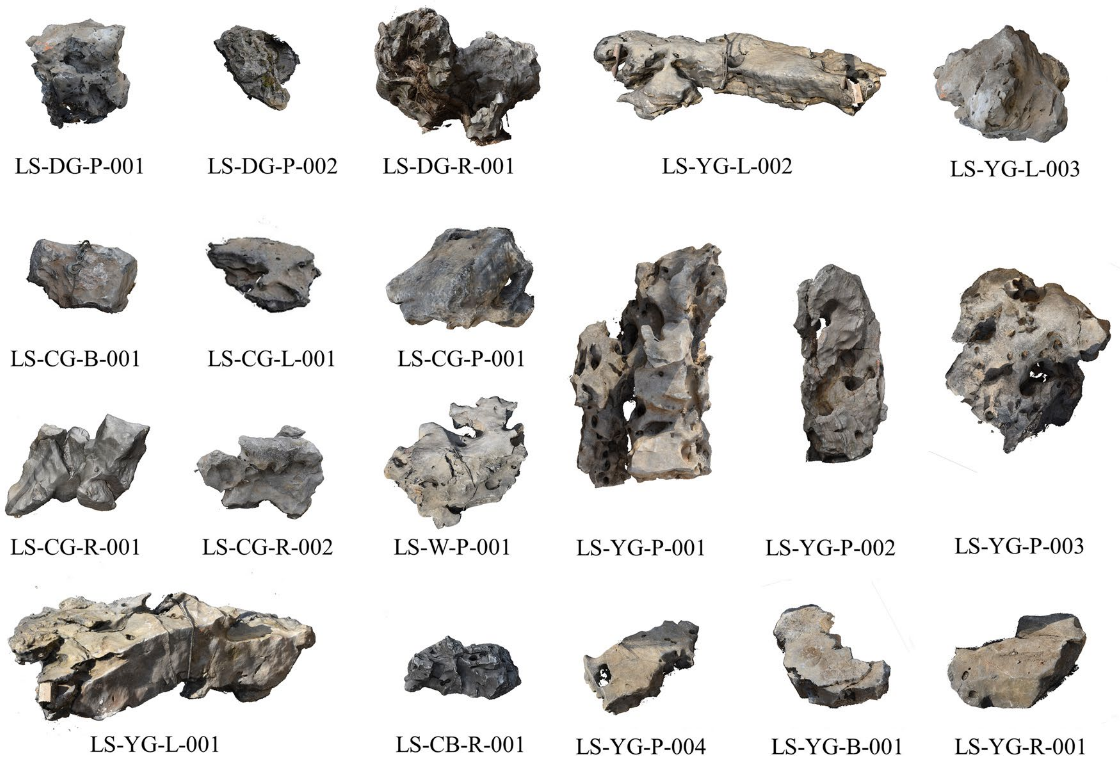

Fig. 11 Nineteen 3D models and coding of rock materials

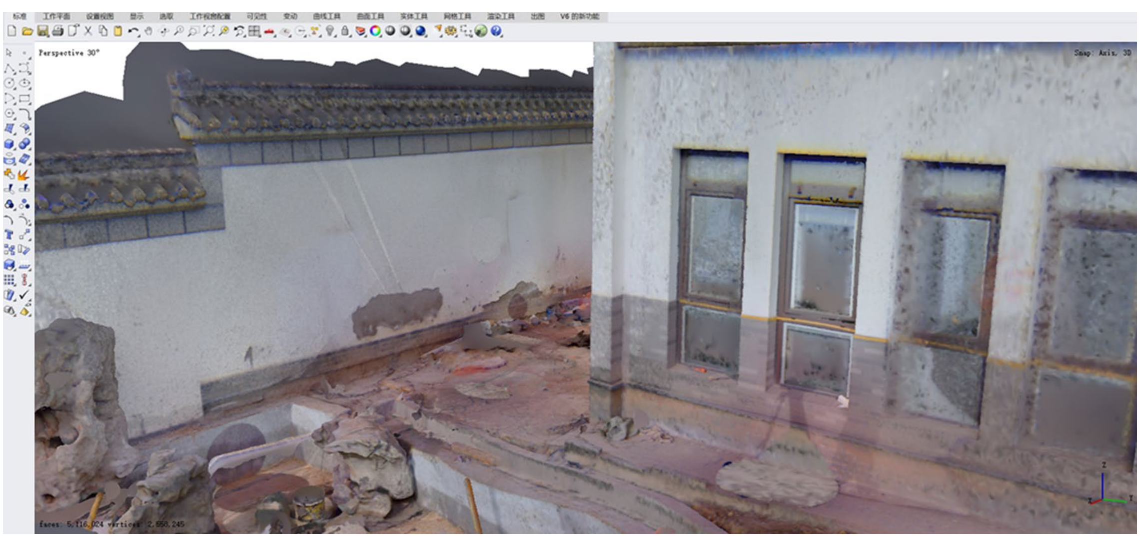

Fig. 12 Interface of digital rockery design and simulated stacking

documentation and preservation of the principles, artisanal skills, and experiential knowledge involved in rockery construction, thus bridging traditional practices with modern technological advancements.

Layered stacking principles of rockeries in the case study: The construction principles of the rockery as a whole involve the stacking of layers according to a basic logic that progresses from the bottom foundational layer [82], through the transitional middle layer, to the top pinnacle-forming layer. The geometric shapes of the stones used primarily for viewing are directly related to the functional and aesthetic requirements of each layer

Fig. 13 The simulated rockery

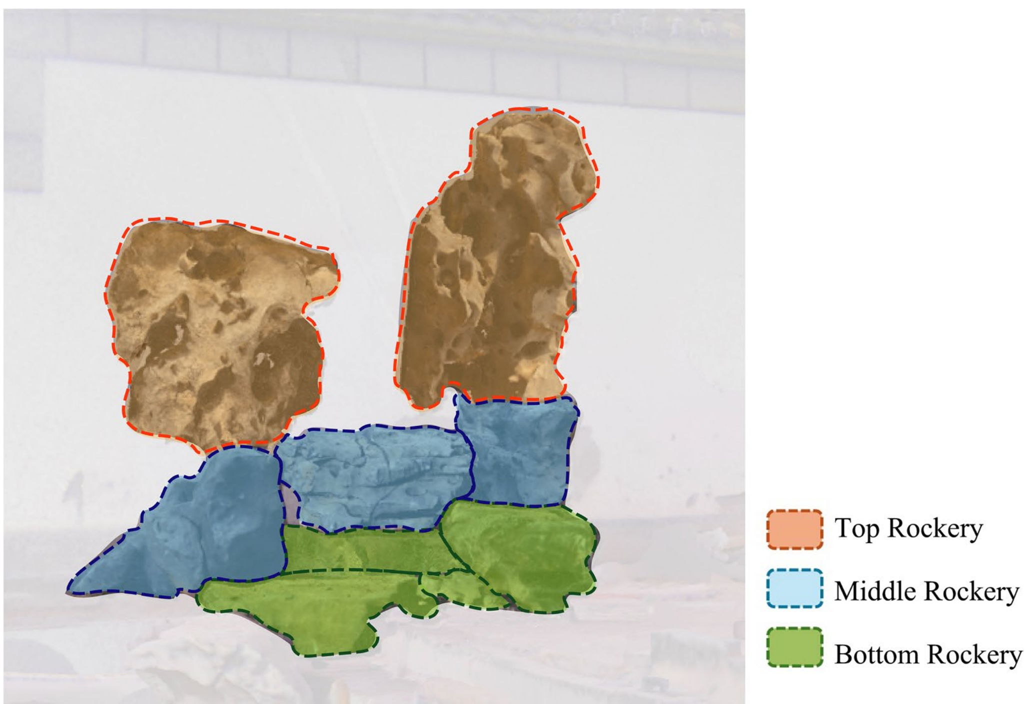

Fig. 14 Layered structure of the case study rockery

(Fig. 14). Initially, the bottom layer, which bears the greatest pressure, consists of natural rocks that must possess sufficient strength to support the weight of the layers above it. The stacking of this base layer is considered the core technical aspect of rockery stacking because the spatial changes in the middle and upper layers fundamentally rely on the foundation. Thus, the topographical variations of the base layer on the horizontal plane are crucial. The design and virtual stacking of the rockery in this study meet these requirements by selecting stones with flat upper and lower surfaces and relatively regular shapes for the base. Additionally, stones with irregular geometrical shapes are used on the sides that do not bear the weight of structures above them, thus creating a rich variety of forms. The middle layer, positioned between the top and bottom layers, determines the overall volume of the rockery. In smaller garden rockeries, the middle layer serves as a transition from the bottom to the top, providing linkage; in larger rockeries, this layer features a diverse combination of units and structural variations. In this study, the rockery is a small wall-attached type, where the primary function of the middle layer is to support the weight of the top layer and serve as a visual transition from the lower layers. Therefore, the stones in this layer also tend to have relatively regular geometric shapes with flat surfaces. Finally, although the top layer does not require a large number of stones, it influences significantly the silhouette, shape, and dynamics of the mountainous form; hence, careful selection of its form is necessary. The top layer stones do not need to bear much weight but must be stable on their own. They can be supported by rock slices and gravel spacers as supplementary structural elements. In this study, two uniquely shaped stones were chosen for the top layer to symbolize natural towering peaks.

Interlocking principles among stones in the case study: The assembly of stones in rockery stacking adheres to four fundamental principles—homogeneity, uniform color, shape matching, and pattern integration—that are pivotal to China's intangible cultural heritage in rock stacking [18]. Homogeneity ensures that the rocks mimic the natural composition of mountainous terrains and maintain consistency in type and texture. Uniform color strives for coherence in hue across all stones, accounting for variations due to factors like age, weathering, and moisture content, even within the same stone type. Shape matching involves aligning the outer contours of the stones so that the seams and surfaces fit tightly, while pattern integration harmonizes textural patterns and variations in cavities, including those created by stone alignment. Among these principles, homogeneity and uniform color are the most basic and straightforward to implement. Conversely, shape matching and pattern integration have traditionally posed greater challenges in terms of understanding and application in heritage conservation efforts. This study's approach to rockery design and simulation adheres to these principles and effectively visualizes the assembly process based on 3D modeling.

(1) Homogeneity and Uniform Color: The rocks used in this study are exclusively Lake stones sourced from the same region, ensuring consistency in material properties. Color-wise, all the nine stones selected were predominantly gray; seven stones used fin the main structure displayed a YG hue, and two stones used for the external connections of the rockery exhibited a CG hue. This strategy ensures a harmonious overall color palette with nuanced local variations.
(2) Shape Matching and Pattern Integration: The 3D model accurately reproduces the precise geometrical shapes and surface textures of the stones. The connections and correspondences between the designed stone contours are well-delineated. By stacking, the contours of different stones are interconnected, effectively blurring the boundaries between individual stones. Visually, the originally separate pieces appear organized into a cohesive rock mass, achieving shape matching.

Each stone was selected for its unique surface texture based on the desired artistic effect. For the stacking of the rockery, four stones with pitted textures, two with layered textures, two with rugged textures, and one with a blocky texture were chosen. Stones that are focal points or are part of the primary viewing facade were selected for their representative pitted textures. For instance, two peak stones in the upper layer of the rockery, which serve as visual focal points, were chosen for their rich pocked surfaces, translucency, and high aesthetic value; stones positioned more prominently also featured pitted textures. On the left side of the rockery, which forms the external contour of the structure, stones with a rugged texture were used, while the mid-layer stones displayed layered textures. It is important to note that regardless of whether adjacent stones share the same texture, the transition at their junctions is seamlessly integrated, such as the connection between the lower part of LS-YG-P-001 and the top texture of LS-YG-L-003, the left side of LS-YG-L-003 and the right side of LS-YG-L-004, the left side of LS-YG-L-004 and the right side of LS-CG-R-001, and between LS-CG-R-001 and LS-YG-R-001, among others (Fig. 15).

In traditional rockery design and stacking, once stones are placed, adjusting them becomes very difficult. However, under the simulated stacking conditions described herein, optimal textural and form alignment between the stones can be achieved through multiple repositionings.

Computation and analysis based on 3D models

The rockery occupies an area of approximately 3 m^2 and has a height of approximately 3.6 m. Traditionally, estimating the weight of a rockery has been challenging owing to the irregularity of the stones and variability in the form of the structure. It has been particularly difficult to calculate accurately the rockery's weight before its completion, leading to significant uncertainties in weight estimations [82, 83]. There are two prevalent methods for estimating the weight of rockery projects:

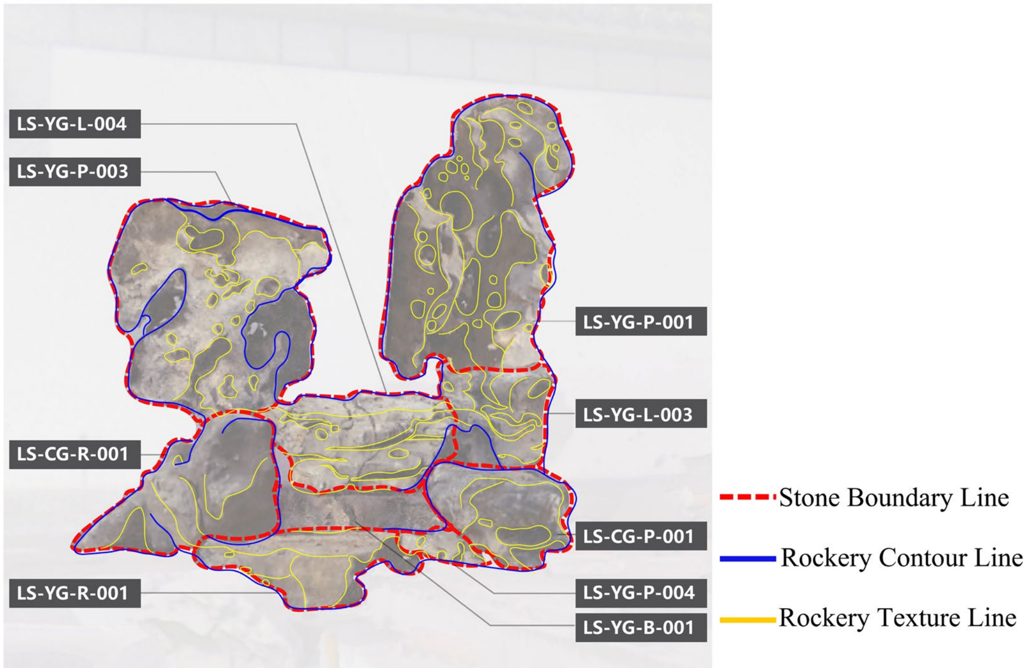

Fig. 15 Interlocking relationships and textural patterns of the case study rockery

Whole Estimation Method: This approach considers the rockery as a singular entity for estimation. Although this method is straightforward, it typically results in considerable errors. The weight of rockery can be estimated using Eq. (1):

$$W = A \times H \times R \times K \times K_n \tag{1}$$

In the formula, W represents the total weight of the rockery in tons. A denotes the horizontal projection area of the rockery's footprint in square meters. H is the vertical distance from the base to the highest point in meters. R stands for the density of the stone, typically assumed to be equal to 2.6 tons /m^2 for lake stones. K_n is a conversion coefficient, valued at 0.65 for rockeries up to 2 m in height and 0.56 for those up to 4 m.

Individual Block Addition Method: This method estimates the weight of individual stone blocks and then sums them up. This approach is suitable for smaller rockeries. The weight of rockery can be estimated using Eq. (2):

$$W = W_c + \sum_{i=1}^{n} L_i \times B_i \times H_i \times R_i \tag{2}$$

where W represents the total weight of the rockery in tons. W_C is the weight of the underlying regular padding stones or soil, in tons. L, B, and H are the average length, width, and height dimensions, respectively, in meters. R is the density of the stone material, typically equal to 2.6 tons/m^2 for lake stones.

In this study, a 3D virtual model of the rockery was developed to facilitate more precise geometric data calculations for irregular stones, which in turn enables more accurate weight estimations, aiding the subsequent construction, management, and safety calculations. The model-based weight estimation formula using Eq. (3):

$$W = W_c + \sum_{i=1}^{n} W_n \tag{3}$$

where W represents the total estimated weight of the rockery in tons, W_n indicates the calculated weight of the stones from the model in tons, and W_C denotes the weight of the internal padding stones or soil, also in tons.

This refined approach provides a significant advancement in the precision of rockery construction estimates, integrating traditional methods with modern technological tools. The encapsulation method was employed to calculate the total volume of stone used, estimated at 1.52 m^2 [84]. Given the density of lake stones at 2.6 tons/m^2, the total weight of the nine utilized stones was approximately 3.96 tons. Specifically, the base layer comprised stones weighing approximately 1.12 tons; elongated stones with flat surfaces were utilized for stacking, which provided a stable foundation. The middle layer, weighing approximately 1.1 tons, featured stones with complex shapes on the exterior to facilitate the transition to the peak stones above, while internally, stones with flat surfaces and fewer gaps were preferred for stacking. The top layer employed distinctively shaped stones to represent mountain peaks, with a total weight of approximately 1.74 tons. Given the substantial weight of the top layer stones, reinforcement was necessary; the study integrated regular cubic homogeneous stones within the rockery to bolster and stabilize the structure, thereby enhancing its overall stability and safety. The support stones used internally amounted to approximately 2.77 tons, bringing the total stone usage to 6.72 tons for the rockery.

Comparative weight estimations using the Whole Estimation Method resulted in 15.7 tons, whereas the Individual Block Addition Method yielded 9.68 tons. Both methods produced higher estimates than the model-based method; this is attributable to the porous characteristics of Lake stones (Table 5). The weight estimation of the rockery based on the model is more accurate compared to traditional methods, providing a robust data foundation for subsequent structural mechanics calculations.

After finalizing the design, the simulated stacking drawings and orthogonal views of the rockery were drafted (Fig. 16). The plan received approval from an inheritor of the intangible cultural heritage of rockery construction techniques. Under their guidance, the rockery was constructed, with the final outcome illustrated in the figures. An excellent correspondence existed between the physical stones and the 3D model (Fig. 17).

Discussion

This research integrates digital technology into traditional rockery construction, offering a novel approach to digital design and simulated stacking that diverges

Table 5 Rockery weight estimation table

Position	Stone identification number	Overall estimation method(t)	Individual block addition method(t)	Model calculation method(t)
Top	LS-YG-P-003	–	1.91	0.94
	LS-YG-P-001	–	1.56	0.81
Middle	LS-CG-R-001	–	0.71	0.47
	LS-YG-L-003	–	0.52	0.29
	LS-YG-L-004	–	0.53	0.34
Bottom	LS-YG-R-001	–	0.37	0.31
	LS-YG-P-004	–	0.84	0.39
	LS-CG-P-001	–	0.32	0.29
	LS-YG-B-001	–	0.16	0.13
Interior	Internal Foundation Stones/Soil	–	2.77	2.77
Total		15.7	9.68	6.72

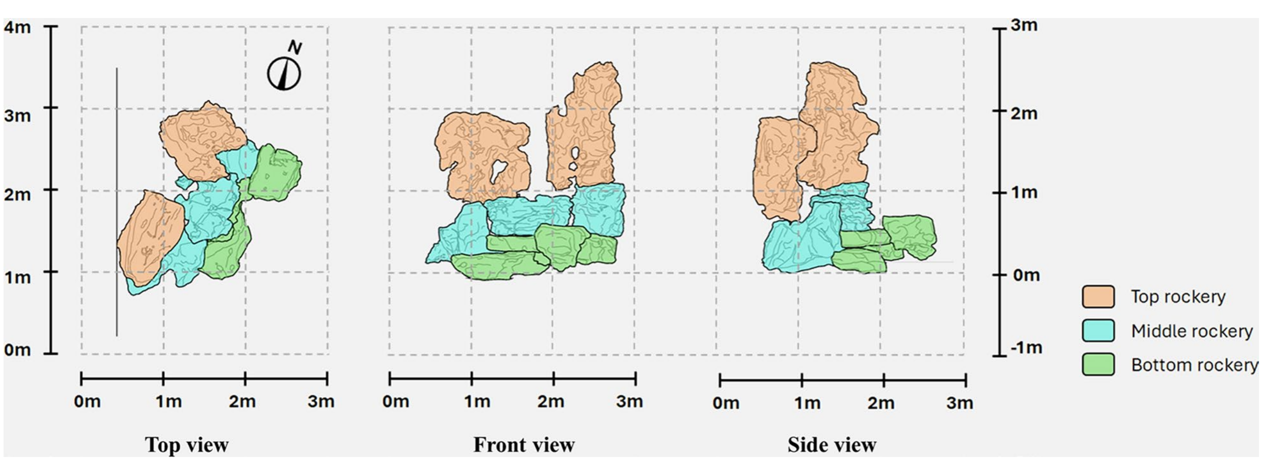

Fig. 16 Top view, front view and side view of the rockery

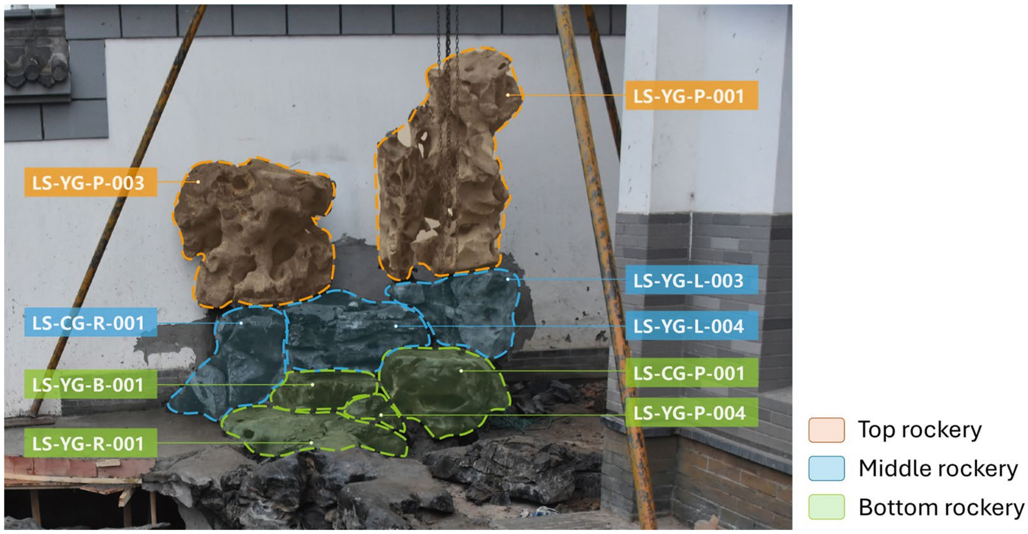

Fig. 17 Real stacking of the rockery

from previous studies centered on existing rockery sites [7–9, 53, 69–72]. The methodology is structured around three key components: Digital Replication of Rock Material, Coding and Database Construction of Rock Materials, and Digital design and stacking of Rockeries. This innovative process represents a departure from the traditional synchronous design and stacking methodologies employed in Chinese classical garden rockery creation, offering several advantages:

(1) Efficient Management of Stone Materials: Stone is the primary component of rockeries. Prior research typically overlooked stone management from a design and construction perspective, leading to unstructured and extensive management practices. While some scholars have proposed classification rules based on location or semantics and touring paths for established rockery sites [25, 85], these have generally analyzed the spatial characteristics of completed rockeries from a layout perspective, neglecting the construction logic and interlocking rules between stones. The stone coding method proposed in this article accounts for the form and surface characteristics of the stones, which are critical in determining the traditional techniques used during stacking. This coding system, rooted in construction logic and traditional craftsmanship, facilitates more scientific and efficient management of stone materials. It can be directly applied in rockery construction and repair, as well as in the visualization of traditional techniques, filling the gaps of previous research and practice and providing a direct methodological reference for heritage conservation management.

(2) Visualization of Traditional Techniques: Traditionally, rockery construction and repair were documented through textual descriptions and simplistic diagrams, which inadequately represented the intricate relationships between stones and traditional craftsmanship [12, 75]. This lack of precise visualization made it difficult for stakeholders to communicate and for traditional techniques to be accurately understood, learned, and transmitted, thereby impeding the preservation of rockery sites and the transmission of intangible cultural heritage. Unlike parametric methods [86, 87], which are unsuitable owing to the irregularity and uniqueness of stones, this study utilized integrated 3D laser scanning and photogrammetry technologies to capture accurately the detailed features of the studied stones. The 3D models facilitate easy identification of the rockeries' types, shapes, textures, and color characteristics, and display the interlocking relationships between stones, structures of various layers, and the external contours and internal textures. By digitizing traditional techniques, this method enhances our understanding of rockery cultural heritage and promotes the advancement of conservation efforts and the transmission of traditional skills.

(3) Enhanced Precision in Project Presentation: Plans for rockery construction based on digital modeling of stone materials are presented more tangibly, allowing for precise quantitative analysis of building materials and structures. This fosters improved

communication among designers, constructors, heritage managers, and other stakeholders. Moreover, digital design and simulated stacking provide greater flexibility for adjusting plans before actual construction begins, overcoming the traditional constraints of rockery construction in stones cannot be altered after they are placed. This separation of design and construction not only improves work efficiency but also aligns rockery building and repair practices with modern, standardized, and regulated management approaches.

The methodology proposed in this article was applied to the construction of a rockery, demonstrating its practical viability. This approach involved the digital replication of 19 lake stones using 3D laser scanning and photogrammetry, achieving dimensional deviations within 10 mm. The process accurately restored each stone's color and texture, validating the effectiveness of this replication method. Utilizing established coding rules, 19 stones were coded systematically, encapsulating their textural, color, and surface features. Nine of these stones were subsequently selected for digital design and the simulated stacking of the rockery. This digital approach vividly illustrated the rockery's spatial layers, enabling the visualization and analysis of traditional construction techniques and patterns used in building the rockery. Moreover, the model-based calculations and analyses provided essential data support for the construction phase. The final design, guided and approved by a national-level inheritor of intangible cultural heritage in China, was employed in the actual construction, marking a successful integration of digital technology with traditional building crafts. This trial confirmed the feasibility of the proposed methods and underscored the potential of digital tools in traditional construction contexts.

The digital design and simulated stacking processes for rockeries are of significant importance for the restoration of rockery sites, the preservation of intangible cultural heritage, and the construction of modern rockeries. In the realm of cultural heritage restoration, numerous existing rockery sites are plagued by structural failures, such as collapses and cracks. Addressing these issues effectively involves the utilization of original stone materials for precise assembly and restoration in a virtual environment, which clarifies the restoration plans and expected outcomes. The use of 3D models facilitates multifaceted communication and decision-making among stakeholders, allowing for iterative adjustments and evaluations of restoration plans, thereby minimizing potential restoration damages. In terms of preserving intangible cultural heritage, this methodology enables comprehensive documentation of the construction processes, creating a valuable database for the transmission of traditional techniques. This not only aids the preservation of cultural heritage but also promotes its dissemination. For modern rockery construction, the methodology introduces a novel approach that separates the design from the construction phase, enhancing communication among designers, constructors, and other stakeholders. This separation ensures that designs and construction processes are more precise and scientifically sound, aligning well with modern engineering management and practices, and thus meeting contemporary needs more effectively.

This study has certain limitations. It primarily focused on the critical components of rockery construction, particularly the unique and irreplaceable rock materials. Efforts were concentrated on digital mapping, modeling, and coding of these primary components, but the study did not extensively discuss auxiliary components such as joint fillers and stabilizing gravel, which could affect the accuracy of rockery volume calculations and structural mechanicals analyses. Future research could expand the examination of these auxiliary components to enable more detailed and accurate project evaluations and analyses. Additionally, this research was centered on achieving digital design and simulated stacking stages of rockeries. The approach to evaluating and analyzing plans was relatively simplistic. Given the complexity and irregularity of the rocks used in rockeries, analyzing their structural stability is inherently more challenging than for conventional structures with regular shapes. This study did not conduct a comprehensive examination of experimental investigations in this area. Future studies could delve deeper into methods for analyzing the structural stability of rockeries, such as employing structural inspections based on finite element analysis, to enhance their stability and safety. Moreover, this research was conducted on a small-scale rockery with a limited number of stones. In practice, the reconstruction or repair of large-scale rockery sites involves significant quantities of rock materials. Future efforts could benefit from utilizing Building Information Modeling (BIM) platforms to establish extensive databases of rock materials, which would facilitate the digital design and simulated, management planning, protection, and restoration of rockeries.

Conclusion

Rockeries, a significant component of classical Chinese gardens, have attracted global attention. However, research on rockery construction and restoration is limited. This study introduced a digital construction process for rockeries based on 3D digital mapping technologies and validated its feasibility. Compared with traditional methods that rely heavily on a craft's imagination and personal experience, the proposed method is more reliable and efficient. It integrates various digital mapping technologies to digitize irregular and nonstandard rock structures, thereby creating highly realistic 3D models and a systematic rock material database for digital rockery design and stacking. This approach allows for a precise, visualized simulation of rockery construction, facilitating effective communication and decision-making among heritage stakeholders.

This study provides new methods and insights for the protection and restoration of rockery heritage and promotes the transmission of rockery construction technique, a vital intangible cultural heritage.

Acknowledgements
We extend our sincere gratitude to Mr. Fang Hui and Mr. Yang Kaibo, esteemed inheritors of China's intangible cultural heritage, for their invaluable contributions in sharing expert knowledge and practical insights into the traditional craft of rockery construction. We thank the editor and anonymous reviewers for their helpful comments and valuable suggestions. Thanks are also due to Editage (www.editage.cn) for linguistic assistance during the preparation of this manuscript.

Author contributions
ZW designed the project and was the major contibutor in writing the manuscript. PS performed the data collection, and provided suggestions to the data analysis methodology. QZ was responsible for the review and revision of the article.TW and BP participated in the process of data collection. All authors read and approved the final manuscript.

Funding
This work was supported by the National Natural Science Foundation of China (No. 51878353), the Priority Academic Program Development of Jiangsu Higher Education Institutions (PAPD), Jiangsu Provincial Culture and Tourism Key Laboratory Research Project, and Jiangsu Province Science and Technology Program Special Funds (Key R&D Program for Social Development) Project (No. BE2023822).

Availability of data and materials
The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Competing interests
The authors declare that they have no competing interests.

Received: 4 May 2024 Accepted: 4 September 2024
Published online: 12 September 2024

References

1. Wilson EH. China, Mother of Gardens. 1st ed. Boston: The Stratford Company; 1929.
2. Sirén O, Xi R. Gardens of China. 1st ed. New York: Ronald Press; 1949.
3. Liang H, Li W, Lai S, Zhu L, Jiang W, Zhang Q. The integration of terrestrial laser scanning and terrestrial and unmanned aerial vehicle digital photogrammetry for the documentation of Chinese classical gardens–a case study of Huanxiu Shanzhuang, Suzhou. China J Cult Herit. 2018;33:222–30.
4. UNESCO World Heritage Centre–World Heritage List. https://whc.unesco.org/en/list/. Accessed 30 Apr 2024.
5. Zhou W. History of Chinese classical gardens. 3rd ed. Beijing: Tsinghua University Press; 2008.
6. National representative List of intangible Cultural Heritage-China Intangible Cultural Heritage Network China Intangible Cultural Heritage Digital Museum. https://www.ihchina.cn/project.html. Accessed 30 Apr 2024.
7. Lou L, Wei C, Wu H, Yang C. Cave feature extraction and classification from rockery point clouds acquired with handheld laser scanners. Herit Sci. 2022;10:177.
8. Yang C, Han X, Wu H, Han F, Wei C, Shutter L. Digital characterization of the surface texture of chinese classical garden rockery based on point cloud visualization: small-rock mountain retreat. Herit Sci. 2023;11:13.
9. Ding M, Zhang Q, Li G, Li W, Chen F, Wang Y, et al. Fractal dimension-based analysis of rockery contour morphological characteristics for Chinese classical gardens south of the Yangtze River. J Asian Archit Build Eng. 2023;22:2490–505.
10. Corsini L, Moultrie J. a review of making in the context of digital fabrication tools. 2018: 1021–30.
11. Gu K, Za W. Inheritance and development: inquiry into crafts and theory of traditional garden rockery making by contemporary craftsman Fang Hui. Landscape Architect. 2019;26:19–24.
12. Fu L, Pan J, Tang Y, Zhang Q. A multi-criteria decision-making approach to assessing the health risk of rockeries in Chinese classical gardens. Herit Sci. 2023;11:92.
13. Zhang Q, Chen F. The influence of plant root splitting on garden rockeries in Jiangnan: taking the Zhanyuan Garden as an example. J Nanjing Forest Univer. 2024;8:1–8.
14. Cheng H, Hu F. Research on the heritage monitoring of the rockery in the mountain villa with embracing beauty. Chinese Landsc Architect. 2021;37:139–44.
15. Zhang Q, Wang C, Zhang X. Research on disease monitoring and structural protection of garden rockery heritage based on finite element analysis. J Nanjing Forest Univer. 1–15.
16. Cheng H, Hu F, Xiao L, Gu M, Zheng Q. Research on preventive protection of historical garden rockeries and suggestions for countermeasures——a case study of Suzhou garden. Chinese Landsc Architec. 2023;39:57–63.
17. Li H, Zhang X, Li Z, Wen J, Tan X. A review of research on tree risk assessment methods. Forests. 2022;13:1556.
18. Fang H. The theory and technique of rock stacking and mountain building. Beijing: China Architecture and Architecture Press; 2005.
19. Gu K, Za W. "Exploration on garden rockery-making craftsmanship of "less exceeding more": taking small courtyard garden for example. Landsc Architec. 2022;29:12–8.
20. Gu K, Qian B. Scenery-realm value and the significance of master craftsman: tentative discussion on purposes and methods of artificial rockery reparation in the conservation of Chinese garden heritage. Heritage Architec. 2021;14:46–52.
21. Zu G, Yu W. Theoretical thinkings on the conservation of traditional garden heritage in China. Heritage Architec. 2021;3:1–8.
22. Lou J. Study on the inheritance path and countermeasures of Chinese garden rockery stone stacking technique. Chinese Landsc Architec. 2023;39:9–13.
23. Ciaffi M, Alicandri E, Vettraino AM, Paolacci AR, Tamantini M, Tomao A, et al. Conservation of veteran trees within historical gardens (COVE): a case study applied to *Platanus orientalis* L. in central Italy. Urban For Urban Green. 2018;34:336–47.
24. Gu Z, Zhang Q. Research status and future trends of domestic studies on suzhou classical gardens in the past two decades: bibliometric analysis based on CNKI. Chinese Landsc Architec. 2018;34:73–7.
25. Li X, He X, Xiao Y, Jia S, Qin K. A multi-level quantitative analysis method on the scale, shape and quantity of rockeries in Chinese classical gardens: taking Wanfang Anhe rockery in the Old Summer Palace as an example. Herit Sci. 2024;12:101.
26. Zhao D, Zhang L. Protection and utilization of Gaichun Garden ruins of the Summer Palace. In: Kao JCM, Sung WP, editors. Civil, architecture and environmental engineering, vols 1 and 2. Leiden: CRC Press-Balkema; 2017. p. 119–24.
27. Shao X. "Yellow Stone" and the aesthetic transition of literati gardens in late ming dynasty. Architec J. 2023; 89–94.
28. Jia X, Zhang Q, Yin X, Song P, Zhang X. A study on the rockery techniques in Yangzhou based on three-dimensional digitization. Chinese Landsc Architec. 2022;38:88–93.
29. Wei W. Research on the stacking method of Wenlange Rockery in Hangzhou based on 3D digital technology. M.S. thesis. Zhejiang Univer. 2023.

30. Zhang B. Three-dimensional digital technology to promote the study of traditional Chinese landscape gardening method. Tradit Chinese Architec Gardens. 2010;14:36–8.
31. Bai X. Study on Digitalization of Chinese Rockery. M.S. thesis. North China Univer Technol. 2015.
32. Garavaglia E, Anzani A, Maroldi F, Vanerio F. Non-invasive identification of vulnerability elements in existing buildings and their visualization in the BIM model for better project management: the case study of Cuccagna farmhouse. Appl Sci. 2020;10:2119.
33. Khairadeen Ali A, Lee OJ, Lee D, Park C. Remote indoor construction progress monitoring using extended reality. Sustainability. 2021;13:2290.
34. Kim S, Kim S, Lee D-E. 3D point cloud and bim-based reconstruction for evaluation of project by as-planned and as-built. Remote Sens. 2020;12:1457.
35. Wang J, Zhang S, Teizer J. Geotechnical and safety protective equipment planning using range point cloud data and rule checking in building information modeling. Autom Constr. 2015;49:250–61.
36. Shan P, Sun W. Research on landscape design system based on 3D virtual reality and image processing technology. Ecol Inform. 2021;63: 101287.
37. Yu L, Zhang L, Gong Z. An optimization model for landscape planning and environmental design of smart cities based on big data analysis. Bin S, editor. Sci Programming-neth. 2022;2022:1–12.
38. Wu X. The digital landscape design and layout of wetlands based on green ecology. Energy Rep. 2023;9:982–7.
39. Wang H. Landscape design of coastal area based on virtual reality technology and intelligent algorithm. Guarda T, Lopes I, Rocha Á, editors. J Intell Fuzzy Syst. 2019;37:5955–63.
40. Abdelaal M, Galuschka M, Zorn M, Kannenberg F, Menges A, Wortmann T, et al. Visual analysis of fitness landscapes in architectural design optimization. Vis Comput. 2024;40:4927–40.
41. McClymonds AD, Asadi S, Leicht RM. Development of a Parametric Modeling Method for Masonry Wall Systems to Support Robotic Construction. In: Turkan Y, Louis J, Leite F, Ergan S, editors. Computing in civil engineering 2023-visualization, information modeling, and simulation. New York: Amer Soc Civil Engineers; 2024. p. 398–406.
42. Han Y, Zhang K, Xu Y, Wang H, Chai T. Application of parametric design in the optimization of traditional landscape architecture. Processes. 2023;11:639.
43. Jaafar HA, Meng X, Sowter A, Bryan P. New approach for monitoring historic and heritage buildings: using terrestrial laser scanning and generalised Procrustes analysis. Struct Control Health Monit. 2017;24: e1987.
44. Erdélyi J, Kopáčik A, Kyrinovič P. Spatial data analysis for deformation monitoring of bridge structures. Appl Sci. 2020;10:8731.
45. Xu Z, Kang R, Lu R. 3D reconstruction and measurement of surface defects in prefabricated elements using point clouds. J Comput Civil Eng. 2020;34:04020033.
46. Li H, Zhang C, Song S, Demirkesen S, Chang R. Improving tolerance control on modular construction project with 3D laser scanning and BIM: a case study of removable floodwall project. Appl Sci. 2020;10:8680.
47. Guldur Erkal B, Hajjar JF. Using extracted member properties for laser-based surface damage detection and quantification. Struct Control Health Monit. 2020;27: e2616.
48. Wang Q, Tan Y, Mei Z. Computational methods of acquisition and processing of 3D point cloud data for construction applications. Arch Comput Method Eng. 2020;27:479–99.
49. Alshawabkeh Y, Baik A. Integration of photogrammetry and laser scanning for enhancing scan-to-HBIM modeling of Al Ula heritage site. Herit Sci. 2023;11:147.
50. Golovina S, Kanyukova S. Photogrammetry and Laser Scanning for Reconstruction and Restoration of Historical Buildings. In: Maltseva T, editor. Xv International Conference Topical Problems of Architecture, Civil Engineering, Energy Efficiency and Ecology - 2016. Cedex A: E D P Sciences; 2016. p. 01008.
51. Priego E, Herraez J, Denia JL, Navarro P. Technical study for restoration of mural paintings through the transfer of a photographic image to the vault of a church. J Cult Herit. 2022;58:112–21.
52. Jin X, Wang X, Xue C. Nondestructive characterization and artificial intelligence recognition of acoustic identifiers of ancient ceramics. Herit Sci. 2023;11:144.
53. Jia S, Liao Y, Xiao Y, Zhang B, Meng X, Qin K. Conservation and management of Chinese classical royal garden heritages based on 3D digitalization-a case study of Jianxin courtyard in Jingyi garden in fragrant hills. J Cult Herit. 2022;58:102–11.
54. Liu Z, Zhang M, Osmani M. Building information modelling (BIM) driven sustainable cultural heritage tourism. Build-Basel. 2023;13:1925.
55. Santos B, Gonçalves J, Almeida PG, Martins-Nepomuceno AMT. GIS-based inventory for safeguarding and promoting Portuguese glazed tiles cultural heritage. Herit Sci. 2023;11:133.
56. Giuliani F, Gaglio F, Martino M, De Falco A. A HBIM pipeline for the conservation of large-scale architectural heritage: the city Walls of Pisa. Heritage Science. 2024;12:35.
57. Machete R, Silva JR, Bento R, Falcão AP, Gonçalves AB, Lobo de Carvalho JM, et al. Information transfer between two heritage BIMs for reconstruction support and facility management: the case study of the Chalet of the Countess of Edla, Sintra Portugal. J Cultur Herit. 2021;49:94–105.
58. Wang P, Ma X, Fei L, Zhang H, Zhao D, Zhao J. When the digital twin meets the preventive conservation of movable wooden artifacts. Herit Sci. 2023;11:54.
59. Garcia-Molsosa A, Orengo HA, Petrie CA. Reconstructing long-term settlement histories on complex alluvial floodplains by integrating historical map analysis and remote-sensing: an archaeological analysis of the landscape of the Indus River Basin. Herit Sci. 2023;11:141.
60. Yang J, You Y, Ye X, Lin J. Cultural heritage sites risk assessment based on RS and GIS-takes the Fortified Manors of yongtai as an example. Int J Disaster Risk Reduct. 2023;88: 103593.
61. Zhang R, Zhang C. Classification and application of digital technologies in landscape heritage protection. Land. 2022;11:1699.
62. Fu Y, Guo T, Zhao X. Intelligent splicing method of virtual reality lingnan cultural heritage panorama based on automatic machine learning. Mob Inf Syst. 2021;2021:8693436.
63. Zhong H, Wang L, Zhang H. The application of virtual reality technology in the digital preservation of cultural heritage. Comput Sci Inf Syst. 2021;18:9–9.
64. Dang X, Liu W, Hong Q, Wang Y, Chen X. Digital twin applications on cultural world heritage sites in China: a state-of-the-art overview. J Cult Herit. 2023;64:228–43.
65. Mustafa MH, Ali M, Has Yun Hashim KS, MohdSuhaimi MS. Recreating historical malay architecture with BIM process. Int J Built Environ Sustain. 2020;7:79–89.
66. Mustafa MH, Ali M, Mohd Ismail K, Has Yun Hashim KS, Mohd Suhaimi MS. BIM backed decision support system in the management of heritage building. Int J Built Environ Sustain. 2019;6:63–71.
67. Thamir ZS, Abed FM. How geometric reverse engineering techniques can conserve our heritage; a case study in Iraq using 3D laser scanning. IOP Conf Ser: Mater Sci Eng. 2020;737: 012231.
68. Biagini C, Capone P, Donato V, Facchini N. Towards the BIM implementation for historical building restoration sites. Autom Constr. 2016;71:74–86.
69. Liang H, Li W, Lai S, Jiang W, Zhu L, Zhang Q. How to survey, model, and measure rockeries in a Chinese classical garden: a case study for Huanxiu Shanzhuang, Suzhou. China Landsc Res. 2020;45:377–91.
70. Yang C, Han F. Digital heritage landscape: research on spatial character of the grand rockery of Yuyuan garden in shanghai based on 3D point cloud technologies. Chinese Landsc Architec. 2018;34:20–4.
71. Dong Q, Zhang Q, Zhu L. 3D scanning, modeling, and printing of Chinese classical garden rockeries: Zhanyuan's South rockery. Herit Sci. 2020;8:61.
72. Jia S, Liao Y, Xiao Y, Zhang B, Meng X, Qin K. Methods of conserving and managing cultural heritage in classical chinese royal gardens based on 3D digitalization. Sustainability. 2022;14:4108.
73. Wang J. Study on Rockery of Chinese Imperial Gardens. Ph.D. thesis. Tsing Hua or Qinghua University. 2009.
74. Dai W. making stone into mountain: research on the rockery techniques of craftsman fang hui by simulating operation. M.S. thesis. Southeast University. 2022.
75. Cai L. The concept hierarchy and procedure diagram of digital planning and design for landscape architecture. Landsc Architec. 2013;1:48–57.
76. Łabędź P, Ozimek A, Ozimek P, Skabek K. Digital modelling and accuracy verification of a complex architectural object based on photogrammetric reconstruction. Buildings. 2021;11:206.
77. Arbace L, Sonnino E, Callieri M, Dellepiane M, Fabbri M, Iaccarino Idelson A, et al. Innovative uses of 3D digital technologies to assist the restoration of a fragmented terracotta statue. J Cult Herit. 2013;14:332–45.

78. Martínez S, Ortiz J, Gil M. Geometric documentation of historical pavements using automated digital photogrammetry and high-density reconstruction algorithms. J Archaeol Sci. 2015;53:1–11.
79. Gonzalez-Aguilera D, Munoz-Nieto A, Rodriguez-Gonzalvez P, Menendez M. New tools for rock art modelling: automated sensor integration in Pindal Cave. J Archaeol Sci. 2011;38:120–8.
80. Ciaffi M, Vettraino AM, Alicandri E, Tomao A, Adducci F, Kuzminsky E, et al. Dimensional and genetic characterization of the last oriental plane trees (*Platanus orientalis* L.) of historical sites in Lazio (central Italy). Urban Forest Urban Green. 2022;69:127506.
81. Jo YH, Hong S. Three-dimensional digital documentation of cultural heritage site based on the convergence of terrestrial laser scanning and unmanned aerial vehicle photogrammetry. ISPRS Int Geo-Inf. 2019;8:53.
82. Cui X, Shang Y. Garden Engineering. Wuhan: Wuhan University Press; 2018.
83. Ministry of Housing and Urban-Rural Development of the People's Republic of China: Standard method of measurement for landscape works. https://www.mohurd.gov.cn/gongkai/fdzdgknr/zqyj/201910/20191022_242353.html. Accessed 30 Apr 2024.
84. Wang Y, Ding M, Zhang Q, Zhang X, Qu Z. Volume calculation methods of irregular stone artifacts based on 3D laser scanning technology. J Asian Archit Build Eng. 2023;22:3386–402.
85. Liang H, Li W, Zhang Q. Semantic-based 3D information modelling and documentation of rockeries in Chinese classical gardens: a case study on the rockery at Huanxiu Shanzhuang, Suzhou. China J Cult Herit. 2019;37:247–58.
86. Lee C, Shin S, Issa RR. Rationalization of free-form architecture using generative and parametric designs. Buildings. 2023;13:1250.
87. Wu S, Lu W-Z, Qin C, Wen B, Wu D, Xiang Y. A goal-oriented planning approach for two-dimensional cutting components in architectural design: coupling BIM and parametric design (PD). J Build Eng. 2023;76:107156.

Publisher's Note