Heritage Science

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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

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Abstract

Currently, the use of digital technology for the protection and research of cultural heritage has become a trend in this field. Rockeries in Chinese classical gardens have become an important cultural heritage type because of their unique shape, ingenious skills and rich connotations. Based on relevant historical information and 3D digital technology, this paper puts forward a multi-level quantitative analysis method on the scale, shape and quantity of rockeries in Chinese classical gardens, aiming at exploring the objective description and quantitative analysis path of rockeries at different levels. This method develops four levels: overall, regional, hierarchical, and individual and their corresponding quantitative contents, which in turn enable data extraction and analysis of the rockery through the different levels. The proposed method was applied to seven different Chinese classical garden rockeries, and taking Wanfang Anhe Rockery in the Old Summer Palace as an example for objective and comprehensive quantitative analysis and verification. The results show that this method is feasible and effective for quantitative analysis of the scale, shape and quantity of rockeries, which can help understand the basic background of stone rockeries and enhance a refined understanding of stone rockery construction, thereby providing data for preventive protection and informatization management of stone rockeries. The 3D rockery model database based on the overall, regional, hierarchical and individual quantitative analysis and numbering method brings a good application prospect for preventive protection and informatization management of the rockery.

Keywords Chinese classical garden, Rockery, Quantitative analysis, Method, Old Summer Palace, Wanfang Anhe

Introduction

Chinese classical gardens, as an important and special type of cultural heritage, are composed of a variety of elements including rockeries, water bodies, buildings and plants. The rockery, as the most important and distinctive element of the Chinese classical garden, needs to be treated separately. Related scholars from Tsinghua University [1], Tianjin University, Southeast University, Tongji University, etc. have made long-term photography, drawing and literature search records on the cultural heritage of Chinese classical gardens [2, 3]. In addition, the focus of rockery research has been on exploring the styles, types and skills of mountain stacking in the past. For example, Meng summed up the mountain stacking techniques and skills of rockeries in Chinese classical

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gardens, and also summarized the basic types and layout points of rockeries and arranged stones [4]; Cao put forward the basic laws of the development and evolution of ancient Chinese mountain stacking styles [5]; Fang, Han et al., as inheritors of the intangible cultural heritage of mountain stacking skills, summarized the skills and key points of mountain stacking in Chinese traditional gardens [6, 7]; as well as Zhang, Jia, Wang et al. sorted out the types and characteristics of rockeries in these royal gardens in Beijing [8, 9].

In recent years, benefiting from the development of digital technology and the abundance of information means, the research on rockery has developed rapidly in terms of digital surveying and mapping, analysis of rockery features, information management, etc. For example, Zhang Bo first proposed to adopt 3D technology to carry out 3D surveying and mapping of rockery elements in classical gardens [10]; the Zhang Qingping team collected and integrated data about rockeries and arranged stones at Jiangnan private gardens like Zhan Garden, Ou Garden and Huanxiu Villa [11, 12]; based on the "hole" characteristics of rockeries, Yang Chen proposed a method to extract and classify point cloud cave characteristics [13]; as well as the Qin Ke team carried out long-term research on digitalization of Chinese classical gardens [14, 15], especially rockery digitalization and quantitative analysis; for example, Wen adopted spatial syntax to analyze the accessibility and connectivity of rockery space in Jingyi Garden [16], Chen adopted finite element analysis to statically analyze and simulate the typical cases of rockeries and their skills [17]. However, Along with the development of cultural heritage protection to digitalization and refinement, the quantitative analysis and research of rockeries have become an important issue to be urgently solved.

For a long time, the quantitative research on stone masonry [18] by related scholars tends to qualitatively evaluate its performance and structure under certain loading conditions [19–21], while objective and quantitative research on the global characterization of masonry is more lacking [22]. In the identification and classification of masonry and walls, Giuffre [23] developed a study on the behavioral characterization of stone masonry, where various parameters are analyzed based on the brick facade and cross-section texture, such as transverse connections, the form of the stone arrangement, the size of the stones as well as their number. Almeida [22] proposed an irregular index method focused on analyzing masonry wall facade textures, defined by quantitative geometric parameters for identifying and classifying masonry phenotypes, with different wall types determining the corresponding indices. The applications of these studies range from a variety of stones composed of regular geometric patterns to irregular textures [24], helping the research objects to carry out some analysis, diagnosis and damage detection, and providing assistance for masonry construction practice, quality assessment and structural damage, so as to help assess and reduce the vulnerability of masonry buildings. The Minimum Trace Line (LMT) is a method to detect the interlock of stones and evaluate the masonry quality by analyzing the elevation and cross-sectional texture of masonry [25]. At the same time, more and more research in cultural heritage preservation applications focuses on the use of digital technology [26] and computer technology. The combination of these digital technologies with on-site investigations to represent heritage objects through 2D images, 3D point cloud and mesh models provides new ideas for the preservation and analysis of cultural heritage and historical sites and facilitates the making of correct decisions on the preservation of cultural heritage. Image analysis techniques based on Machine Learning (ML) and Deep Learning (DL) algorithms [27] have opened up more possibilities for quantitative studies of heritage objects of the type of rockeries, ancient rocks, natural elements, city walls, and so on.

The existing quantitative research on rockeries in Chinese classical gardens mainly quantifies and analyses rockeries in terms of external features such as quantitative evaluation perspective [28–30], shape contour and aesthetic perspective [31], and rockery space and path perspective [16, 32]. There is a lack of quantitative research on the rockery ontology and its constituent rocks. Therefore, with the help of digital technology, this paper puts forward a quantitative analysis method for the scale, shape and quantity of rockeries, aiming at exploring the objective description and quantitative analysis path of rockeries at different levels. Meanwhile, the relevant data will be recorded and managed to solve the problem of mixed information and data and difficult to query, which will be conducive to the later repair and preventive protection of the rockery.

Research ideas and methods, research objects

Research ideas and methods

How to objectively describe, quantitatively analyze and evaluate such rockeries is a long-standing research difficulty. 3D digital mapping and model reconstruction provide fine basic data for quantitative analysis. We care how to establish a targeted quantitative analysis method to carry out comprehensive and in-depth quantitative analysis of rockeries from the whole to the details, so as to objectively describe and summarize its inherent construction law. For example, how is the overall scale of a rockery determined? How to locate, describe and evaluate its function and shape? How to organize and analyze the morphology of different functional areas in a more detailed way? Are there any selection criteria and basic rules for individual rocks in scale? How to build a digital model or database of rockery for its preventive protection and informatization management?

Based on the above, this paper attempts to propose a multi-level quantitative analysis method for rockeries in Chinese classical gardens and intends to analyze and verify them using Wanfang Anhe Rockery in the Old Summer Palace as an example. The technical route is as follows (Fig. 1):

Before conducting quantitative analyses of rockeries, it is necessary to obtain records of information about the study object, including basic information and digital information. The collection of basic information mainly focuses on the historical documents, archives, photographs and images of the rockery. Such as Yangshi Lei Archives, Qing Palace archives, the Old Summer Palace paintings, historical images, etc., and analyzes, judges and summarizes the relevant information, so as to have a comprehensive and deeper understanding of the rockery. Based on the different shapes of the rockery, complex texture, flexible modeling, rich in changes and other characteristics, digital information acquisition is generally used in combination with 3D laser scanning and close-range photogrammetry, the acquisition of content including the rockery body and its surrounding environment, data processing and model reconstruction to obtain the 3D point cloud model, mesh model and other contents of the object rockery.

The multi-level quantitative analysis method refers to the quantitative extraction and analysis of rockeries based on four levels: overall, regional, hierarchical, and individual in terms of scale, shape, and quantity. Firstly, the quantitative content of the rockery (Table 1) is clarified, the numbering rules applicable to the quantitative analysis of the rockery are proposed, and then the extracted quantitative data are statistically and analytically analyzed. The relevant quantitative contents and key technical methods at different levels are as follows:

1. Overall. Using historical documents and field research methods to obtain the overall scale of the object of the rockery, the surrounding environment, the best viewing position, viewing line of sight and viewing angle and other content, such as the best viewing position is the center of the main building, stopping points of the Qing Emperor's living and activities in the garden, etc. Viewing line of sight extracts the distance from the viewing point to the vertical or horizontal line of sight of the object rockery, viewing angle extracts the angle from the viewing point to the vertical or horizontal line of sight of the object rockery, etc., to analyze the interrelationship between the viewing line of sight and the surrounding environment through the quantitative results.

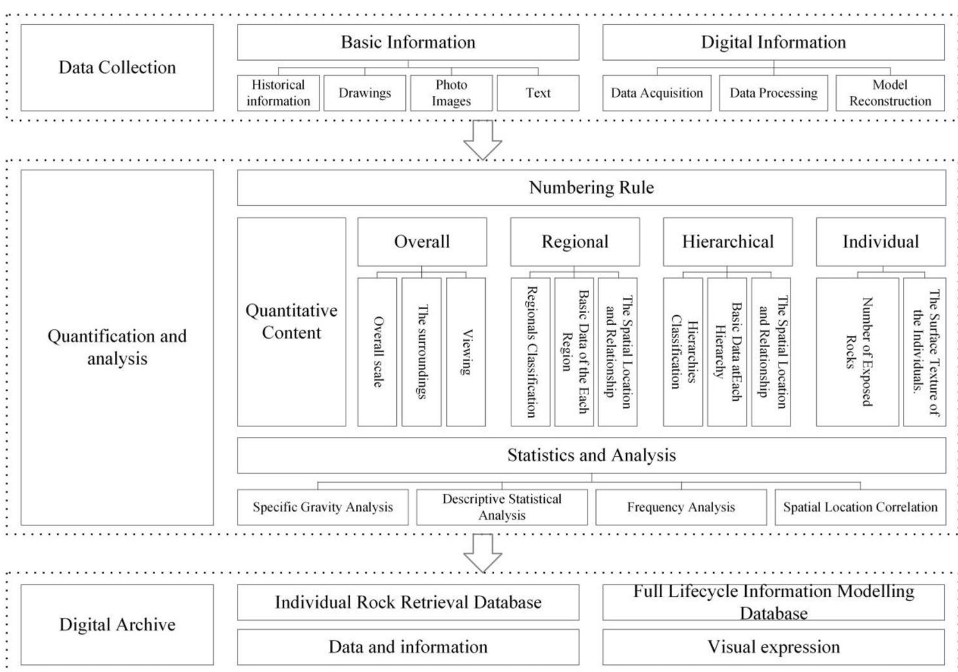


Fig. 1 Technical route

Table 1 Multi-level quantitative analyses of rockery scale, shape and quantity

Level	Description	Quantified contents
Overall	Overall scale and surroundings of the rockery	• Overall scale of the rockery • The surroundings • Viewing: best viewing position, viewing line of sight, viewing angle
Regional	According to different functions partitioned rockery	• Rockery regionals classification • Basic data of each region: projected area, surface area, volume, etc. • The spatial location, and relationship of each region within the overall
Hierarchical	Hierarching and interrelationships of the various regionals of the rockery from the foot to the top of the mountain	• Rockery hierarchy classification • Basic data at each hierarchy: scope, volume • Distances, heights, and areas of typical sections and elevations at each hierarchy, etc. • Interrelationships between the hierarchies
Individual	An individual of rock on the surface of a rockery	• Number of exposed rocks in overall, in regional, and in hierarchical • The length, width, ratio of short and long sides, area, and spatial location of the surface texture of the individuals

2. Regional. According to the different functions and shapes of each region of the rockery, the point cloud model of the object rockery is divided into regions using the point cloud classification technique. The projected area, surface area, and volume of the point cloud model of each region of the rockery are then quantitatively extracted through the region growth filtering algorithm to analyze the spatial position and relationship of each region in the whole.
3. Hierarchical. Contour line extraction of the rockery mesh model by combining the outer contour lines of the rocks and the volume of the rockery. The contour distance is set according to the height of the rockery and the quantification goal, and divide each region of the rockery from the foot to the top of the mountain in a hierarchy, so as to quantify the number of hierarchies and the interrelationships that exist in each region of the rockery. The point cloud slicing technique is used to obtain the typical cross-section slices, important elevations, and elevation unfolding diagrams of the target rockery. When obtaining the slices, the direction of the slices is set as longitudinal, transverse, or circular according to the object rockery and the content to be quantified, e.g., when longitudinal slices are made, we need to pay attention to the viewing points and rockery shape; when transverse slices are made, we need to pay attention to the hierarchical relationship of the rockery; and when circular slices are made, we need to pay attention to the viewing points and the rockery shape. The spacing of the slices is affected by the overall shape of the object rockery and the typical shape characteristics of the rockery and other factors, to the typical rockery or the key regions of corresponding to the rockery slices outline clearly and completely is appropriate. Finally, the obtained point cloud slices are used to extract the data such as hierarchical distances, hierarchical height, and hierarchical area of the target rockery.
4. Individual. Firstly, the number of individual rocks of the object rockery, especially those that can be viewed, are numbered and counted by rule. Secondly, two-dimensional vectorization and mathematical statistics methods are used to extract the key shape values such as the length of the long side, the length of the short side, the ratio of the long side to the short side, and the area of the surface texture of the individuals in the elevation unfolding diagram, and then explore the relationship between the long side, the short side and the area of the individuals of the object rockery through the specific gravity analysis, the descriptive statistical analysis, the frequency analysis and the correlation of spatial location, etc., to understand the selection of the individuals and the stacking rules in the object rockery construction.

In addition, in order to facilitate a clearer description, marking and positioning of the rockery, as well as the subsequent refined management of such rockery heritage, this paper proposes an overall, regional, hierarchical and individual numbering method to quantitatively mark the objects of this type of research as well. The specific rules are as follows:

1. Overall. It is the first level marked for the rockery case. According to the scenic spot to which the rockery belongs and its location in the scenic spot, the overall name can be adopted, and the numbering can be in the form of "capital pinyin initials of the involved garden + capital pinyin initials of the scenic spot name + orientation + two-digit serial number".

For example, the rockery on the west side of Wanfang Anhe can be named "YMY-WFAH-W-01".

2. Regional. It is the second level internally marked for the rockery case. By rockery function, the numbering can be capitalized pinyin initials that constitute the name, for example, the revetment numbering can be marked as B, and the tread numbering can be marked as T. If there are multiple areas in the same function, Arabic numerals can be added after the initials to distinguish them, such as B1 and B2.
3. Hierarchical. It is the third level internally marked for the rockery case. By order of the rockery in the area from bottom to top, the numbering can be marked with Roman numerals, for example, the first layer of revetment can be marked as B-I.
4. Individual. It is the fourth level internally marked for the rockery case, and also the ultimate goal of marking. According to certain sequence rules, these individual rocks in the hierarchy are separately marked with Arabic numerals, for example, the numbering of the third rock in the second hierarchy in the drop area can be marked as D-II-3.

After quantitative extraction and analysis of the rockery, all of the above were digitally archived, and the individual rockery rock retrieval database and the whole-life-cycle 3D digital information model database were established, facilitating refined management such as monitoring and repair of the rockery in the later stage.

Research objects

This paper focused on the rockery, one of the traditional gardening elements in Chinese classical gardens. The multi-level quantitative analysis method is applicable to this unique and complex element. Meanwhile, according to the specific research object, the content of each level of analysis can be updated accordingly. The application of the multi-level quantitative analysis method of rockery is shown in Table 2:

Furthermore, in this paper, Yuanmingyuan Wanfang Anhe Rockery is selected for example analysis and verification.

The Old Summer Palace, as a model of flat gardening among the three mountains and five gardens, has 137 stacked mountains in its heyday [33], among them, the most distinctive one is a type of rockery called "Tinkling Water" in the archives about style houses in the Qing Dynasty, and such Tinkling Water rockery is made of artificially piled rocks and forms sounds when water falls from the rocks, thus having both a visual and auditory appreciation value. Emperors of the Qing Dynasty were very fond of this type of rockery, which led to such rockeries mostly being built in the three mountains and five gardens, with those situated in the Wanfang Anhe scenic area being the most famous. The Tinkling Water rockery in Wanfang Anhe is located on the lake embankment to the west of Wanfang Anhe (as shown in Fig. 2), meaning a metaphor for Western celestial mountains in the ideal world. The basic structure of this rockery is well preserved and still in normal operation to this day. This rockery is specifically on the other west side of the "swastika"-shaped building, where there is a road on the west of the rockery, and a long and narrow earthen mountain running from north to south on the west of the road. The earthen mountain and plants form a slight embrace around the rockery, thereby becoming a good background for the rockery.

The Wanfang Anhe rockery with the smaller volume and proximity to the shore, a more flexible close-range photogrammetric technique was chosen for digital acquisition. Acquisition device selected a 24.3 million pixels Sony A6000 camera. The acquisition routes form a closed loop from south to north from land to water. In order to ensure the accuracy of the collected data, a total of 5 control point positions are deployed so that 1–2 control point images can be collected from any angle (as shown in Fig. 3). The actual shooting of the main collection of subjects such as rockery cliff and other objects from top to bottom, to ensure the continuity of the collection of photographs and ensuring at least 70% overlap between adjacent photos.

Color digital photographs obtained from photogrammetry were imported into Context Capture software for aerial triangulation calculations and 3D point cloud model reconstruction. First of all, the lens correction is carried out, the connection point is set after the lens distortion is eliminated, and the proportion constraint is carried out according to the actual length of the target 0.08 m, and the relative coordinate system is finally established. A view acquisition report and quality report were generated, viewed to determine the completeness of the data (Fig. 4a), and 179 digital images of 6000×4000 pixels were captured, with an average ground resolution of 1.15999 mm/pixel and 17,339 connection points, with a median value of 356 points per image. The final 3D model was reconstructed based on the results of relative orientation. After acquiring the original 3D point cloud data, the Lidar360 software was used to process the original point cloud by denoising and smoothing to form reliable point cloud data of the research object. Finally, Geomagic Wrap and Cloud Compare software were used to obtain triangular mesh models (Fig. 4b) and point cloud slices of typical sections (Fig. 4c) for Wanfang Anhe rockery, respectively.

Table 2 The application of the multi-level quantitative analysis method of rockery

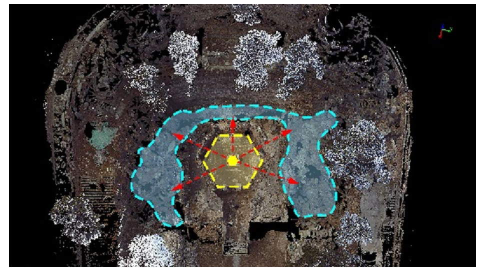
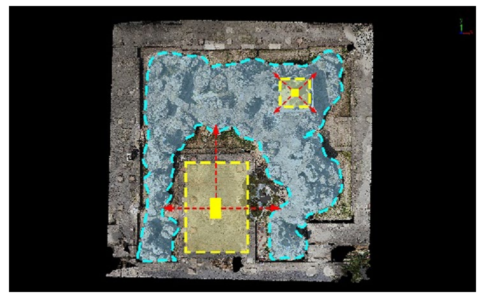
Level	Numbering	Quantitative Content	Application Cases of the Method
Overall	XS-XSS-N-01	• Overall scale of the rockery • The surroundings • Viewing line of sight, viewing angle	
	YMY-CHX-W-01	• Overall scale of the rockery • Viewing line of sight, viewing angle	
	YMY-WFAH-W-01	• Overall scale of the rockery • The surroundings • Viewing line of sight, viewing angle	

Table 2 (continued)

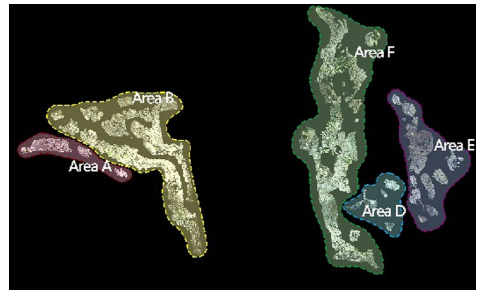
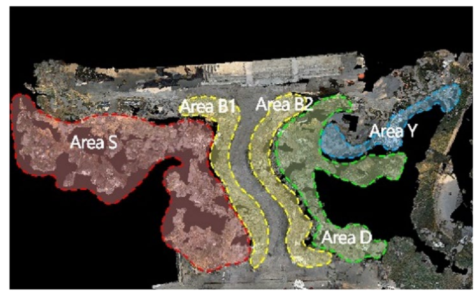
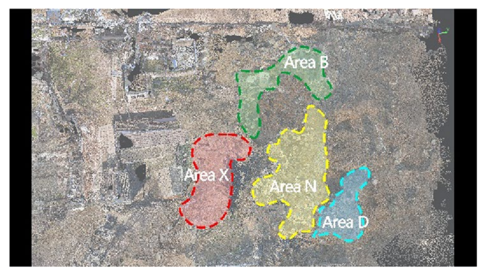
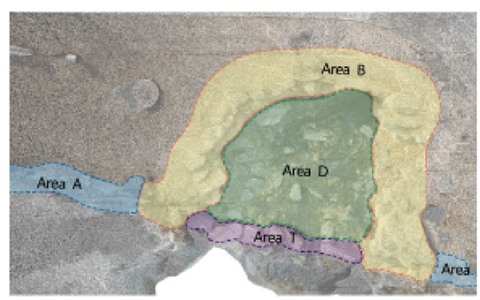
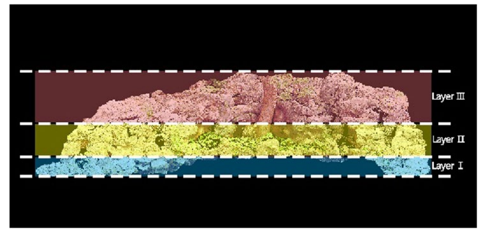
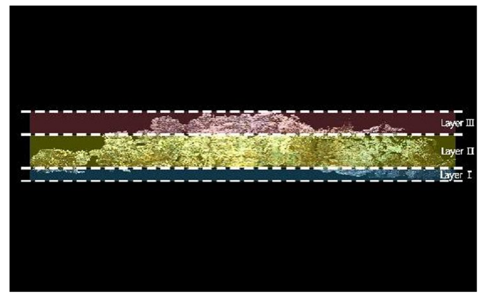
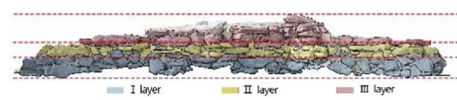
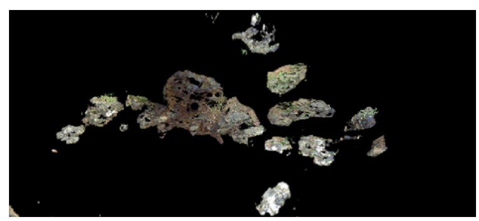
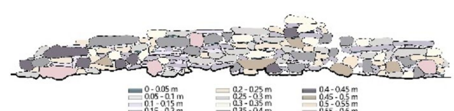
Level	Numbering	Quantitative Content	Application Cases of the Method
Regional	XS-JXZ-B XS-JXZ-E XS-JXZ-A XS-JXZ-F XS-JXZ-D	• Rockery regionals classification • The spatial location, relationship of each region within the overall	
	YHY-RSD-S YHY-RSD-B1 YHY-RSD-B2 YHY-RSD-D YHY-RSD-Y	• Rockery regionals classification • The spatial location, relationship of each region within the overall	
	YMY-ZBSF-D YMY-ZBSF-N YMY-ZBSF-X YMY-ZBSF-B	• Rockery regionals classification • The spatial location, relationship of each region within the overall	
	YMY-WFAH-A YMY-WFAH-B YMY-WFAH-D YMY-WFAH-T	• Rockery regionals classification • Basic data of each region: projected area, surface area, volume, etc. • The spatial location, relationship of each region within the overall	

Table 2 (continued)

Level	Numbering	Quantitative Content	Application Cases of the Method
Hierarchical	XS-SQY-S-I XS-SQY-S-II XS-SQY-S-III	• Rockery hierarchy classification • Interrelationships between the hierarchies	
	XS-JXZ-E-I XS-JXZ-E-II XS-JXZ-E-III	• Rockery hierarchy classification • Interrelationships between the hierarchies	
	YMY-WFAH-B-I YMY-WFAH-B-II YMY-WFAH-B-III	• Rockery hierarchy classification • Basic data at each hierarchy: scope, volume • Distances, heights and areas of typical sections and elevations at each hierarchy, etc. • Interrelationships between the hierarchies	
Individual	XS-JXZ-D-I-1 XS-JXZ-D-I-2 XS-JXZ-D-I-3 ……	• Number of exposed rocks in overall, in regional and in hierarchical	
	YMY-WFAH-B-I-1 YMY-WFAH-B-II-1 YMY-WFAH-B-III-1 ……	• Number of exposed rocks in overall, in regional and in hierarchical • The length, width, ratio of short and long sides, area, and spatial location of the surface texture of the individuals	

Results

Overall data results and analysis

Based on measurement results with the digital model, the overall straight line length of the rockery is about 20.997 m, the width is about 7.395 m and the height is about 2.604 m. The straight line distance between the viewing point of "Swastika-shaped House" and the rockery is about 45.580 m. From a horizontal perspective, the angle between the viewing point and the line of sight of the buildings on both sides is 30°, and the rockery can be fully within the range of visibility of the viewer (i.e. emperors of the Qing Dynasty). From a vertical perspective, the vertical angle of view from the viewing point of the "Swastika-shaped House" to the rockery is 3.5°. It is worth noting that there is an earthen mountain about 4 m high behind the rockery, where trees of 6–8 m high are planted. Combined with the background environment, the vertical line of sight angle is expanded to around 15° (Fig. 5).

Regional data results and analysis

In this case, the rockery can be divided into four regions at the regional level, i.e. drop (D), precipice (B), tread (T) and revetment (A). Region D is composed of drop water as well as water-bearing stone and water-dividing stone distributed in water, and is the main area of rockery waterscape; and region B represents the precipice on the side of Wanfang Anhe Rockery, which imitates the natural waterfall scene in combination with water flow, and is the core area of rockery rocks. In addition, there is a

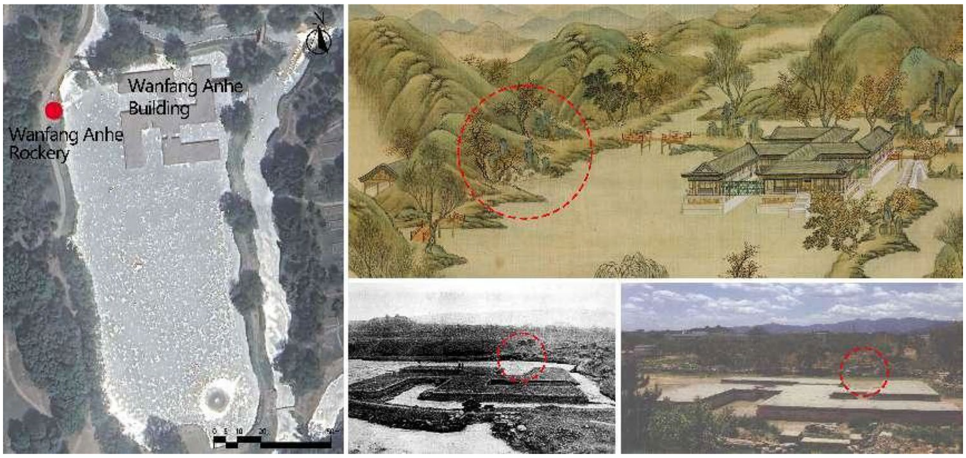


Fig. 2 Location map of Wanfang Anhe in the Old Summer Palace (bottom-right corner image from Hundreds of scenes of the Old Summer Palace [34])

Fig. 3 Live photos and panoramic images of Wanfang Anhe Rockery

water outlet of the Wanfang Anhe Rockery at the junction of the bottom of region D and region B. Region T is at the junction of the lake surface and rockery, and is composed of stepping stones (i.e. stepping stones in water) and rocky ledge, and region A is the transitional rock revetment area between Wanfang Anhe Rockery and land (Fig. 6).

Constructing an irregular triangular mesh from laser point cloud data based on the regional growth filtering algorithm to measure each partition, the basic data about the projected area, surface area, and volume of regions D, B, T and A are measured (as shown in Table 3).

Those with projected areas in the rockery from large to small are region D, region B, region A and region T in turn. Among them, region D is 19.218 m^2, accounting for 43%; region B is 17.523 m^2, accounting for 40%; region A is 4.089 m^2, accounting for 9%; and region T is 3.692 m^2, accounting for 8%. From the above data, it can be seen that the drop area is the main content of rockery construction, and the projected area of the precipice area is

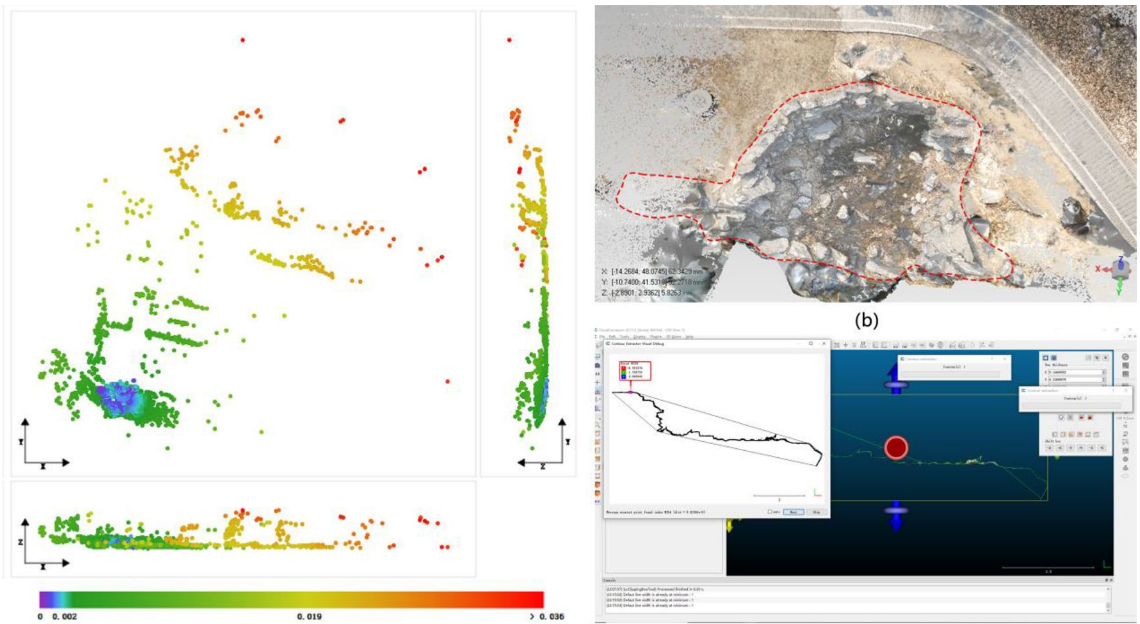


Fig. 4 **a** Resolution of the connection point of Wanfang Anhe Rockery. **b** Triangular mesh model of Wanfang Anhe Rockery. **c** Point cloud slicing extraction of Wanfang Anhe Rockery

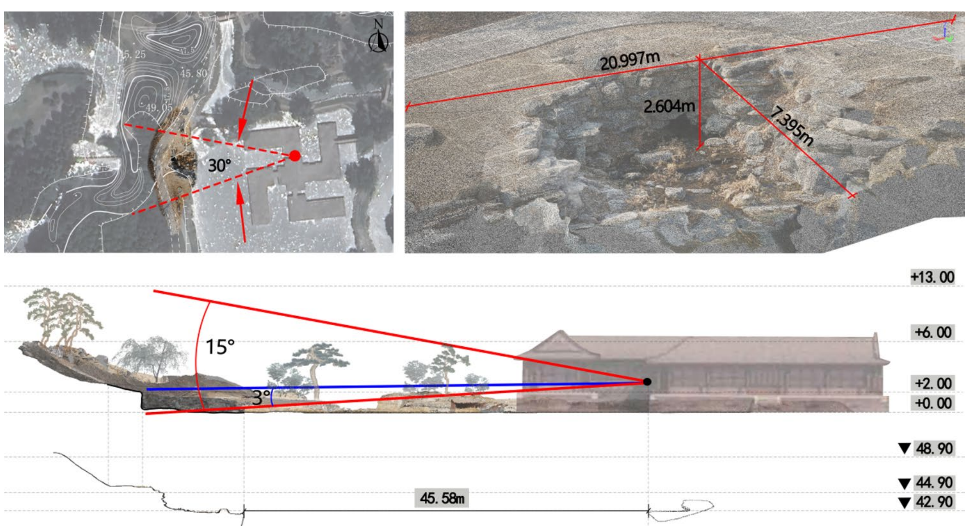


Fig. 5 Viewing angle and viewing distance of Wanfang Anhe Rockery

close to that of the drop area, also an important content of rockery construction here.

Those with surface areas in the rockery from large to small are region B, region D, region A, and region T in turn. Among them, region B is 424.697 m^2, accounting for 88%; region D is 36.615 m^2, accounting for 8%; region A is 14.673 m^2, accounting for 3%; and region T is 5.305 m^2, accounting for 1%. From the above data, it can be seen that the precipice area is the viewing core and key content of the rockery, accounting for an absolute proportion. The precipice area not only has the basic form of celestial mountains, but also provides a good simulated natural background environment for water features.

Those with volumes in the rockery from large to small are region B, region D, region A, and region T in turn. Among them, region B is 20.553 m^3, accounting for 71%;

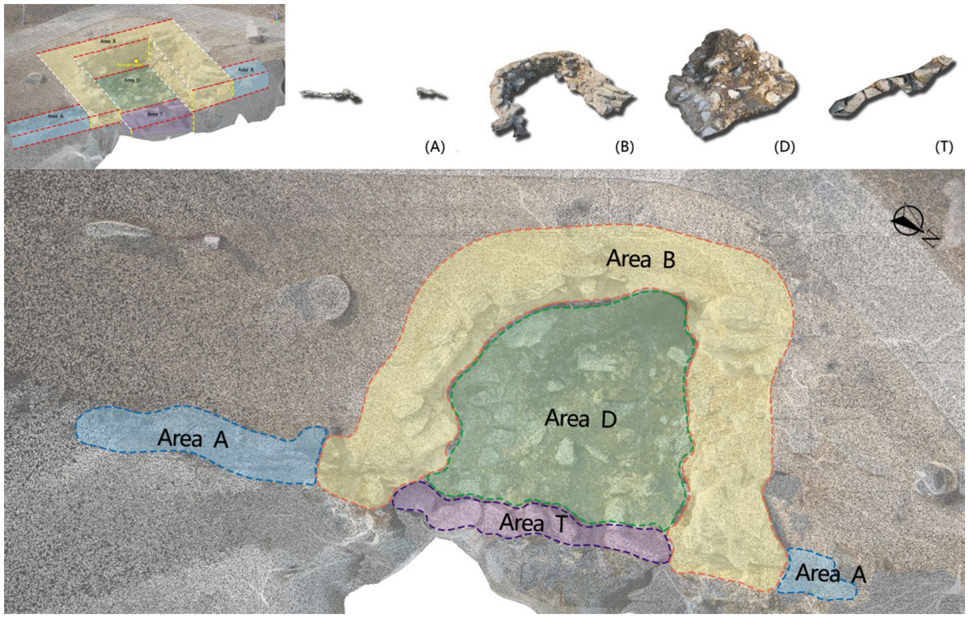
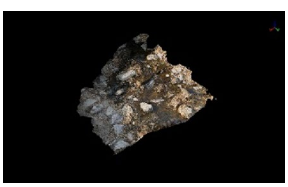


Fig. 6 Region division of Wanfang Anhe Rockery

Table 3 Quantification of Area and Volume of Wanfang Anhe Rockery

	Point cloud model partitioning	Projected area (m^2)	Proportion of projected area %	Surface area (m^2)	Proportion of surface area %	Volume (m^3)	Proportion of volume %
D Drop		19.218	43	36.615	8	4.669	16
B Precipice		17.523	40	424.697	88	20.553	71
T Tread		3.692	8	5.305	1	0.913	3
A Revetment		4.089	9	14.673	3	2.884	10
Total		44.522	100	481.289	100	29.019	100

region D is 4.669 m^3, accounting for 16%; region A is 2.884 m^3, accounting for 10%; and region T is 0.913 m^3, accounting for 3%. From the above data, it can be seen that the precipice region is the region with the highest consumption of rockery rock materials, followed by the drop region.

Hierarchical data results and analysis

By slicing point cloud, a typical vertical section of the rockery can be obtained for analysis and display from both distance (mileage) and elevation. From the slice, it can be seen that the rockery can be divided into two areas in terms of elevation, i.e. drop (D) and precipice (B) according to the location of the water outlet (Point P), wherein region D can be divided into two hierarchies from low to high, namely D-I and D-II; and region B as a precipice has strong overall integrity in the vertical section.

In region D, the height difference of the water outlet (P) is determined by the water level difference on both sides of the embankment, and the total head drop is 0.328 m, including 0.146 m for D-I and 0.182 m for D-II, with a head drop ratio of 1: 1.25. The head drop between region B and region D is 2.276 m, with a head drop ratio of 1: 6.94. From the horizontal distance, the total length of region D is 5.058 m, with an overall slope of about 6.5%. Among them, the length of D-I is 2.420 m, with a slope of about 6.0%; and the length of D-II is 2.637 m, with a slope of about 6.9%. In terms of projected area, the total projected area of region D is 15.445 m^2. Among them, the area of D-I is 9.519m^2, accounting for 58% of the total projected area of the drop region; and the area of D-II is 6.926m^2, accounting for 42% (as shown in Fig. 7).

In order to better extract and display the three hierarchies existing in region B, the elevation expansion map of the precipice region on the side of region B is extracted and formed. According to the contour line of the rockery and the outline of actual rocks in this region, the three hierarchies of bottom, middle and top are obtained, namely B-I, B-II and B-III. The area and average height of three hierarchies can be obtained by measuring the elevation expansion map of region B.

The total elevation area of region B is about 29.846 m^2. The hierarchical areas from large to small are B-I, B-III, and B-II. Among them, B-I covers an area of 12.736 m^2, accounting for 43%; B-II covers an area of 7.728 m^2, accounting for 26%; and B-III covers an area of 9.382 m^2, accounting for 31%. The area results show that the bottom of the rockery in this region has a relatively important influence on the shape of the rockery. The total elevation height of region B is about 2.604 m. The hierarchical heights from large to small are B-III, B-I, and B-II. Among them, B-I is 0.890 m high, B-II is 0.515 m high and B-III is 1.199 m high (as shown in Fig. 8).

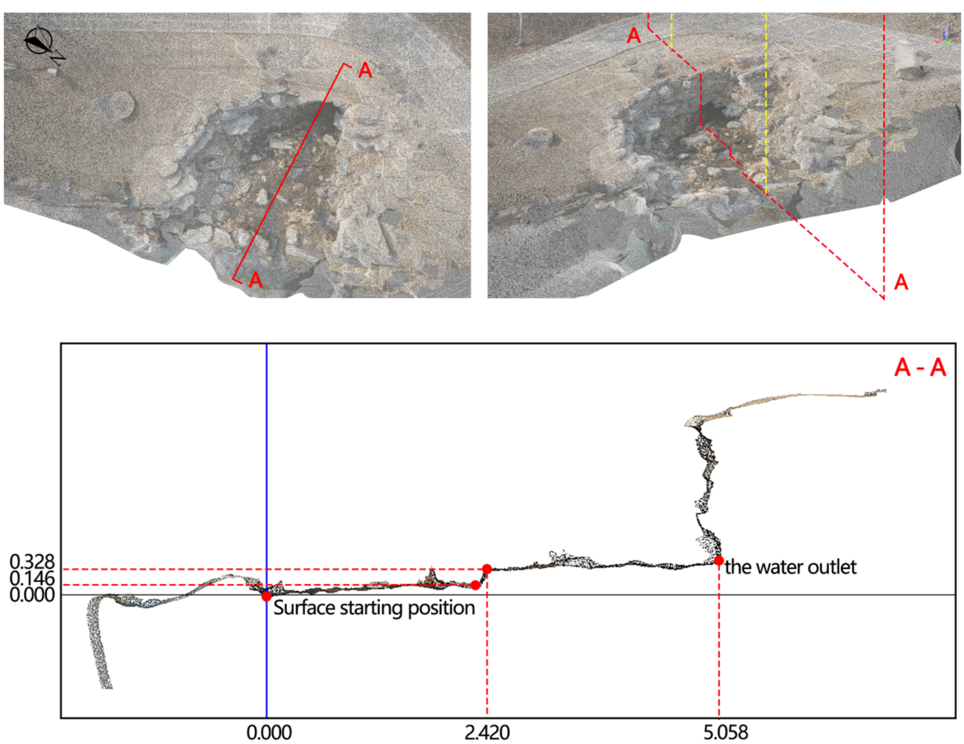


Fig. 7 Hierarchical relationship of Region D of Wanfang Anhe Rockery

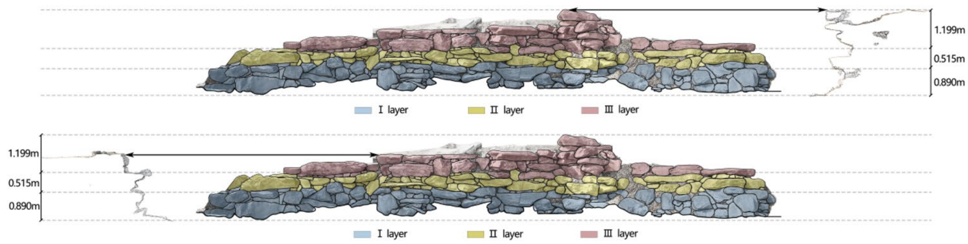


Fig. 8 Hierarchical division of Region B of Wanfang Anhe Rockery

Table 4 Quantification of number of rocks at Wanfang Anhe Rockery

Region	Hierarchy	Quantity	Proportion of number of rocks in each region to total rocks
D	I	11	3%
	II	21	6%
	Total	32	9%
B	I	127	38%
	II	81	24%
	III	67	20%
	Total	275	82%
T	–	13	4%
A	–	16	5%
Total	–	336	100%

Individual data results and analysis

The rockery is composed of stacked individual rocks, which are the basic unit of the rockery. Therefore, the material, shape and volume of individual rocks have a great influence on the overall style and expected effect of the rockery, so it is necessary to make statistics and analysis on individual rocks, especially those that are viewed. There are 336 rocks in the rockery except those at the bottom of the pond in the water, and the quantity relationship of rocks in each region is region B > region D > region A > region T. Among them, there are 275 rocks in region B, accounting for 82% of the total rocks in the rockery. At all hierarchies, there are 127, 81, and 67 rocks in B-I, B-II, and B-III, respectively; while in region D, there are 32 rocks in total, accounting for 9%, because the number of rocks at the bottom of the pond is not counted. At all hierarchies, there are 11 and 21 rocks in D-I and D-II, respectively; there are 13 stepping stones in region T, accounting for 4%; and there are 16 rocks in region A, accounting for 5%. As the key and core region for rockery construction, the number of stones used in region B occupies a high proportion (as shown in Table 4).

On this basis, the main ornamental surface of region B, namely the elevation, is taken as the research object, and the horizontal direction of individual rocks is set as the long side, and the vertical direction is set as the short side. The four data about long side, short side, ratio of long and short sides, and area against 275 individual rocks are statistically analyzed (as shown in Table 5).

As for the long side, the long side of the whole individual rocks in region B is between 0.051 m and 2.114 m. From the average, B-III > B-II > B-I, only the average of B-III is 0.537 m, greater than the total average of 0.467 m; from the median, B-III > B-I > B-II, only the median of B-III is 0.371 m, greater than the total median of 0.352 m; and from the standard deviation, B-III > B-II > B-I, and the long side of the three hierarchies varies significantly, with that of the B-III being greater than the total standard deviation, resulting in the largest change.

As for the short side, the short side of the whole individual rocks in region B is between 0.015 m and 0.593 m. From the average, B-I > B-III > B-II, only the average of B-II is 0.157 m, greater than the total average of 0.178 m; from the median, B-I > B-III > B-II, only the median of B-I is 0.153 m, greater than the total median of 0.148 m; and from the standard deviation, B-I > B-III > B-II, and the short side of the three hierarchies varies insignificantly, with that of the B-II being less than the total standard deviation, resulting in the smallest change.

As for the ratio of long and short sides, the ratio of long and short sides of the whole individual rocks in region B is between 1.008 and 13.365. From the average, B-III > B-II > B-I, only the average of B-I is 2.781, greater than the total average of 3.201; from the median, B-III > B-II > B-I, only the median of B-I is 2.310, greater than the total median of 2.611; and from the standard deviation, B-III > B-II > B-I, and the ratio of long and short sides of the three hierarchies varies significantly, with that of the B-III being greater than the total standard deviation, resulting in the largest change.

As for the area, the area of the whole individual rocks in region B is between 0.003m^2 and 0.789m^2. From the average, B-III > B-I > B-II, only the average of B-III is 0.120m^2, greater than the total average of 0.096m^2; from

Table 5 Quantification of individual dimensions and shapes of rocks at region B of Wanfang Anhe Rockery

Name	Sample Size	Minimum	Maximum	Average	Standard Deviation	Median
B-I long side	127	0.051	1.546	0.434	0.278	0.344
B-II long side	81	0.106	1.918	0.460	0.363	0.337
B-III long side	67	0.115	2.114	0.537	0.437	0.371
Long side	275	0.051	2.114	0.467	0.349	0.352
B-I short side	127	0.015	0.593	0.189	0.131	0.153
B-II short side	81	0.021	0.434	0.157	0.101	0.128
B-III short side	67	0.030	0.568	0.183	0.129	0.143
Short side	275	0.015	0.593	0.178	0.123	0.148
B-I area	127	0.004	0.707	0.091	0.109	0.048
B-II area	81	0.003	0.722	0.084	0.113	0.043
B-III area	67	0.006	0.789	0.120	0.148	0.037
Area	275	0.003	0.789	0.096	0.121	0.046
B-I long-short side ratio	127	1.049	12.217	2.781	1.735	2.310
B-II long-short side ratio	81	1.015	13.365	3.557	2.385	2.778
B-III long-short side ratio	67	1.008	11.456	3.568	2.388	2.820
Ratio of long side to short side	275	1.008	13.365	3.201	2.138	2.611

the median, B-I > B-II > B-III, only the median of B-I is 0.048 m^2, greater than the total median of 0.046m^2; and from the standard deviation, B-III > B-II > B-I, and the area of the three hierarchies varies insignificantly, with that of the B-III being greater than the total standard deviation, resulting in the largest change.

Further analysis of long side, short side, ratio of long and short sides, and area of region B shows that the number of rocks in the range of 0.2–0.4 m is ranked the largest, accounting for 41%, followed by the 0.4–0.6 m range, accounting for 20%. The number of rocks mainly distributed in the range of 0.05–0.1 m in the short side is 60, accounting for 22%. The proportion of the total number of rocks in the range of 0–0.02m^2 is the highest, accounting for 30%. The number of rocks with the ratio of long and short sides distributed in the range of 1–2 accounts for 33% (as shown in Fig. 9).

By associating the statistical data about the long side, short side, ratio of long and short sides and area with the spatial distribution of individual rocks in region B,

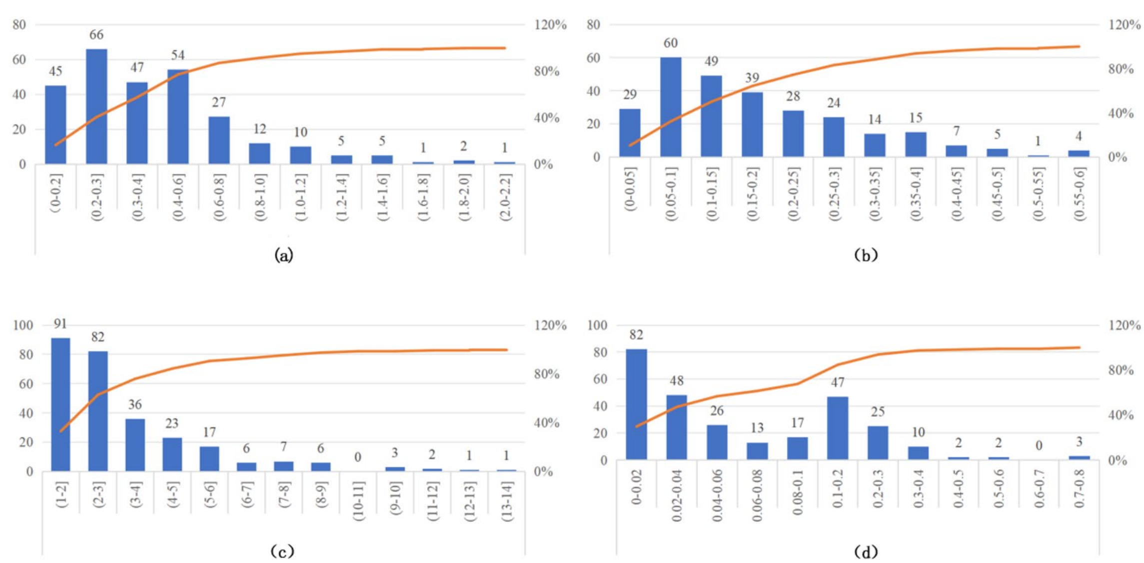


Fig. 9 Frequency statistics of long side length (**a**), short side length (**b**), long-short side ratio (**c**), and area (**d**) of individual rocks in region B

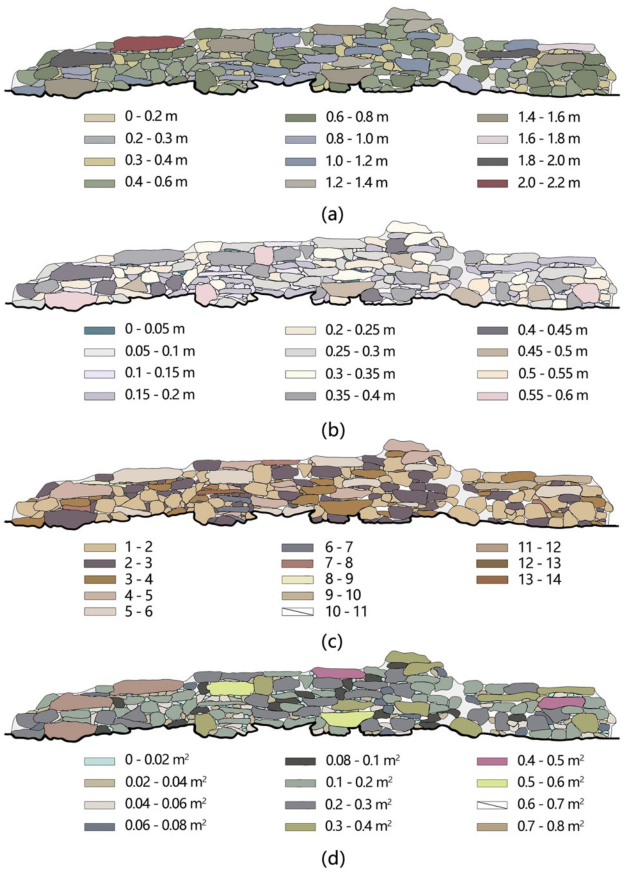


Fig. 10 Correlation between rock and spatial position of Wanfang Anhe Rockery (**a**) long side, **b** short side, **c** long-short side ratio, **d** area

Fig. 10 is obtained, which can correspond the statistical data to the spatial relationship. Among them, B-III-6 has the longest long side (2.114 m) and the largest area (0.789 m^2), B-I-33 has the longest short side (0.593 m), and B-II-19 has the largest ratio of long and short sides (13.365).

Numbering of rocks at Wanfang Anhe Rockery and digital information management

The rockery database is divided into four basic levels, i.e. overall, regional, hierarchical and individual. At the overall level, the focus is on recording the environmental data around the rockery, such as the earthen mountain, lake surface, and Wanfang Anhe rockery viewing point. At the regional level, these rockeries are classified, and basic data such as projected area, surface area, and volume are counted. At the hierarchical level, each region is layered, while marking the hierarchical scope and relationship and collecting basic data about height, elevation area, and typical slices of each hierarchy. At the individual level, these individual rocks are numbered, and the spatial and attribute information about the position and scale of the current individual rocks are counted, so as to establish an individual rock retrieval database. To achieve digital recording and information management of the rockery, the ArcGIS Pro software is used to add attributes from different angles and levels, and the corresponding rock attribute tables are associated (as shown in Fig. 11). Finally, the 3D data model extracted by category is loaded into the corresponding data layer. Digital historical archives and rockery quantification objectively demonstrate the value and significance of such rockeries,

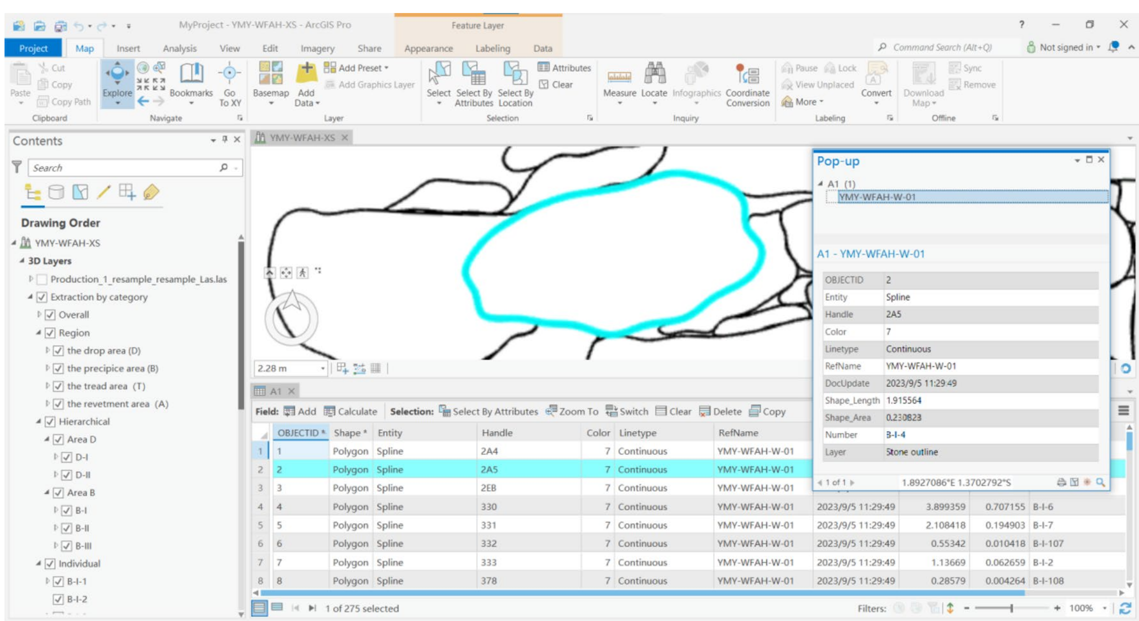


Fig. 11 Digital information management of Wanfang Anhe Rockery

and the loading of historical information and 3D models satisfies the information needs of future landscape management and operation. The rockery information model gradually increases with the deepening of research and analysis, and the database is constantly updated and improved, constituting a dynamic management and maintenance process.

Discussion

Discussion on the quantitative results of Wanfang Anhe Rockery

On the basis of the above statistics and quantitative results, the rockery here is discussed from the following four aspects.

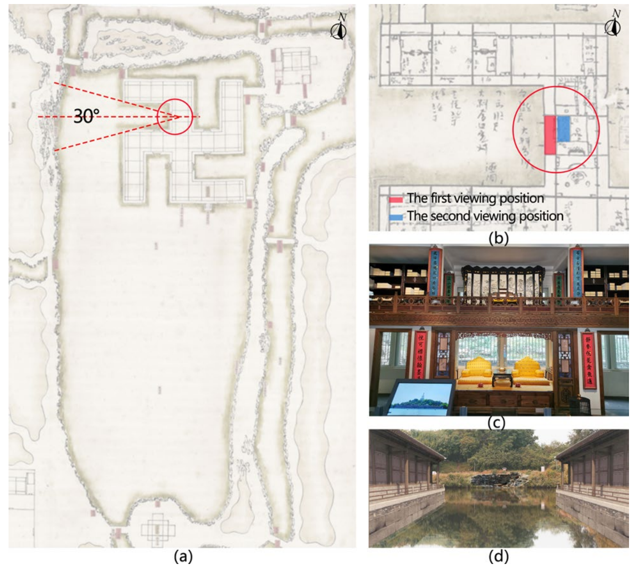


Fig. 12 **a** Viewing line of sight, **b** viewing position, **c** Style reference for immortal tower within the architecture of Wanfang Anhe Rockery (Beihai Immortal Tower), **d** Ornamental effect

1. As far as the overall scale is concerned, the viewing position and viewing line of sight of emperors of the Qing Dynasty determine the overall scale of the rockery. The results of digital model surveying and mapping contribute to a deeper awareness and understanding of historical information. Based on measurement results with the digital model, the overall straight line length of the rockery is about 20.997 m, the width is about 7.395 m and the height is about 2.604 m. It can be seen from Yangshi Lei Archives that emperors of the Qing Dynasty viewed the rockery at the west-facing "Duipu Immortal Tower" on the north side of Wanfang Anhe Building and the indoor space downstairs, and its internal shape is similar to that of the Daoning Study in Qiong Island, Beihai Park (as shown in Fig. 12). On the horizontal line of sight, the overall straight line length of the rockery is affected by the included angle between the viewing point and the line of sight on both sides of the building, which is 30°, and a viewer here can see the length range of 24.573 m. The overall width of the rockery is affected by the position of the water outlet, the Tinkling Water height is determined by the water level difference on both sides of the embankment, and the overall head drop is only 0.328 m, which requires a certain width to form the level. On the vertical line of sight, the height of the rockery is affected by the line of sight of the earthen mountain as background and the viewing point. The overall height of the rockery should not affect the view of the earthen mountain from the viewing point. The earthen mountain is about 4 m high, its highest point is 73.542 m away from the viewing point, the vertical viewing angle is 5.4°, and the vertical viewing angle from the viewing point to the rockery is 3.5°.
2. From the perspective of the function of the rockery itself, it can be divided into four regions, i.e. drop (D), precipice (B), tread (T) and revetment (A). The basic data obtained from various regions with the digital model can help a more rational understanding of the functional regions of the rockery. The projected area reflects the plan size of each region of the rockery; the surface area, especially the difference between the surface area and the projected area, reflects the size of each region of the rockery as an ornamental surface; and the volume reflects the consumption of rock materials in each region of the rockery. In this case, the precipice region (B) and the drop region (D) account for 40% and 43% of the total projected area, 88% and 8% of the total surface area, as well as 71% and 16% of the total volume, respectively. The data show that the precipice region (B) and the drop region (D) are the main regions for rockery construction here, wherein the precipice region also provides a good simulated natural background environment for water features besides the basic form of celestial mountain, and the drop region (D) is the core content of water feature construction in the rockery. The formation of these two regions determines the basic form of the rockery here.
3. From the hierarchy of the rockery itself, after point cloud slice analysis, region D can be divided into two hierarchies by elevation, in which the head drop of D-I is 0.146 m and the head drop of D-II is 0.182 m, with a head drop ratio of 1: 1.25. The projected area increases with the decrease of water level. Region B is divided into three hierarchies from low to high

by expanding the elevation vector diagram; among them, B-I covers an area of 12.736m^2, accounting for 43%; B-II covers an area of 7.728m^2, accounting for 26%; and B-III covers an area of 9.382m^2, accounting for 31%. The area results show that the bottom of the rockery in region B has a relatively important influence on the shape of the rockery. The effect of simulating natural forms and forming good soundscapes can be achieved by controlling head drop, slope and area.

4. The scale of individual rocks is determined or influenced by such factors as viewing range, overall height of the rockery and rock materials. In terms of Wanfang Anhe rockery, there are 336 rocks here except those at the bottom of the pond in the water, including 275 rocks in region B, accounting for 82% of the total. The size and viewing range of the objects to be viewed are related to human eye's discrimination and identification. In ancient China, there was a recognition that "a hundred feet brings the form, while a thousand feet brings the potential". After analyzing these individual rocks in region B, it is concluded that the viewing range from the best viewing point to the rockery has a direct impact on the short side length of individual rocks. The main viewing point of the rockery is 45.580 m away from the rockery, it is easy to identify objects with a height of at least 0.0663 m with reference to the E visual chart. Taking region B as an example, the proportion of short side length greater than 0.0663 is 82.91%, and the short side mode is 0.075. The impact of the overall height of the rockery on individual rocks is mainly reflected in the longitudinal texture. The short side of the rock has a significant impact on the number of rock layers. Here taking region B as an example, the main height of the rockery is between 1.405 m and 2.604 m, with 5–9 layers of stacked individual rocks. The median of the short side in this region is 0.148 m. If the median of the 5–9 layers is calculated, the height is about 0.740–1.332 m, accounting for about half of the overall height, which provides room for changes in the natural texture of the scattered rocks among the precipices. The rock material of the rockery is bluestone, which is the fine sandstone extracted from Beijing area and falls into sedimentary rock. Due to material characteristics, it is often stacked horizontally in stacked mountains, resulting in a situation where the length of the long side is greater than that of the short side on individual rocks. Taking region B as an example, the ratio of long and short sides is greater than 1, with a ratio of 1 to 4 accounting for 76%, a median of 2.611 and an average of 3.2. So, it can be seen that there is a clear range control over the ratio of long and short sides in the selection of individual rocks. In addition, the mechanical properties of materials also have a certain impact on the ratio of long and short sides of individual rocks.

Discussion of the method and further application of this study

The multi-level quantitative analysis method proposed in this study can solve the problem of quantifying stone rockeries in terms of scale, shape and quantity, and further and future studies will attempt to find a direct correlation between the quantitative data and the patterns of rockery stacking. Based on a variety of information technology and mathematical tools, from different angles and levels of quantitative analysis of rockeries comprehensive and objective for the rockery stacking law of the summary and generalization of the possibility. In addition, the application of the method to rockeries with different features can add new specific quantitative indicators and content in the four levels so that it can more fully take into account other important characteristics of the rockery, which may be used in the quantification of the same type of rockery and good rockery engineering practices, and thus relate to the performance, structure of the rockery.

At the same time, the method can be further applied to the information management of rockery, which assists with the inheritance of rockery techniques and preventive protection. The continuous development of digital technology enables the protection and management of rockeries to be refined. Among them, Building Information Modeling (BIM) and Geographic Information System (GIS) have advantages in managing 3D models, information storage, data sharing and data visualization. In the meantime, combined with other modern technologies, they can realize the digital expression of specific heritage-related information, thereby being suitable for garden cultural heritage. Taking into account historical information, digital files generated in the data acquisition stage and data storage in the process of reconstructing and analyzing the 3D model, this research established a 3D digital information model database for the entire lifecycle of the rockery, which is conducive to regularly recording and monitoring the rockery, facilitating subsequent analysis of its health status and making correct decisions at the prevention and maintenance levels (Fig. 13).

Conclusion

Based on the characteristics and research difficulties of Chinese classical garden rockeries, integrating the existing theoretical background and supplemented with

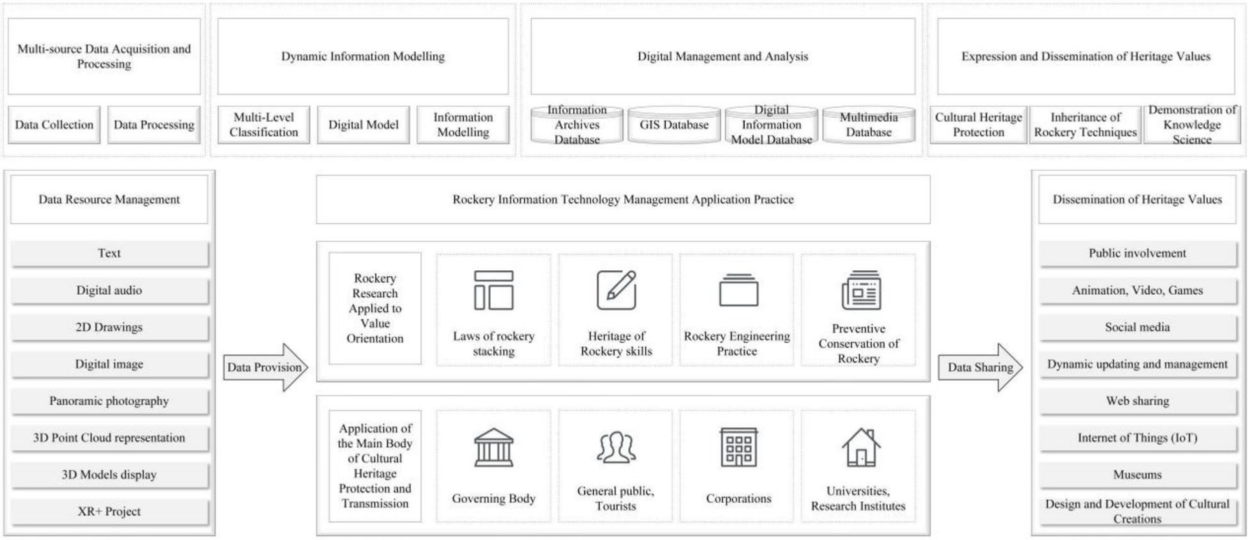


Fig. 13 Information management and application of Chinese classical garden rockery

new digital technologies, this study proposes a multi-level quantitative analysis method to analyze and quantify the surface texture of stone rockeries in Chinese classical gardens from the perspectives of scale, shape and quantity. The method develops four levels—overall, regional, hierarchical and individual—and their corresponding quantitative content, which in turn allow data extraction and analysis of the rockery through different levels. The method was applied to some rockeries in the Chinese classical gardens of Xiangshan Jingyi Garden, the Summer Palace and the Old Summer Palace, and one of the Wanfang Anhe Rockery was selected to be analyzed and validated; these cases represent stone rockeries with different characteristics of Chinese classical gardens.

To sum up, on the basis of digital surveying and mapping as well as the rockery information model, the multi-level quantitative analysis method is feasible and effective for the quantitative analysis of stock rockeries, especially these rockery surfaces that are viewed. Through the division of four different hierarchies, we can extract, analyze and summarize the indexes and data about the scale, function, shape, and quantity of the stone rockery, which can help understand the basic background of stone rockeries and enhance a refined understanding of stone rockery construction, thereby providing data for preventive protection and informatization management of stone rockeries. The 3D rockery model database based on the overall, regional, hierarchical and individual quantitative analysis and numbering method brings a good application prospect for preventive protection and informatization management of the rockery.

The deficiency of this research lies in that this method takes Wanfang Anhe Rockery for targeted analysis and verification, but as restricted by sample selection, there are some limitations in the analysis and discussion of specific data statistics. In the future, we can summarize the data patterns of similar types of rockery cases, increase the diversity of other cases' statistics and analysis, construct corresponding indicator systems as well as improve and optimize this quantitative analysis method.

Acknowledgements
Not applicable.

Author contributions
XL was responsible for data processing and writing of the manuscript, XH drew the images in the manuscript, YX collected the data, and SJ and KQ reviewed and revised the article. All authors approved the final manuscript.

Funding
This research was conducted with Co-financing from the National Natural Science Foundation of China (Award Number: 51908003) and Beijing Yuanmingyuan Ruins Protection Foundation Project [Yuan (Service) Word] [2020] No. 181.

Availability of data and materials
All data generated or analyzed during this study are included in this published article.

Declarations

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

Received: 31 October 2023 Accepted: 14 March 2024
Published online: 27 March 2024

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