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RESEARCH

Three-dimensional deviation analysis and digital visualization of shape change before and after conservation treatment of historic kiln site

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Abstract

The Gangjin Celadon Kiln, after its excavation in 1982, was relocated and restored in 1987 and subjected to primary conservation treatment in 2007. However, many problems such as soil disintegration and cavitation occurred in the kiln until recently. In this study, the shape changes due to the conservation treatment in 2020, which was performed to maintain the original shape of the kiln site, were recorded via three-dimensional (3D) scanning, and numerical analysis was conducted to ensure continuous monitoring and preventive conservation. From the results of this study, the locations and ranges of shape changes before and after the conservation treatment of the kiln site were identified through root-mean-square (RMS) deviation analysis and visualization, and the ranges of reinforcement and soil mulch removal were quantified through the deviations at different points. In particular, the most noticeable shape changes occurring from the conservation treatment on the kiln site with 11.2 m long and 16.7° slope were around 15 mm, and many relative changes of 40 mm or more were also observed. In addition, a reinforcement of approximately 40 mm thickness at the least and a flattening were prominently evident on the floor of the working space; the inside of the combustion chamber was visualized with a reinforcement of at least about 50 mm. Damage caused by natural or artificial factors is expected because two extensive conservation treatments were applied in 2007 and 2020 to the kiln sites. Therefore, short-term monitoring using periodic 3D scanning and time-series data comparisons is necessary for the identification of the point of shape change and the determination of major damaged areas so that a mid- to long-term monitoring plan can be established based on the findings of such observations. In addition, predictive modeling research is mandated to detect areas in the entire kiln site that exhibit a greater probability of deterioration based on the available shape change data.

Keywords Three-dimensional scanning, Root-mean-square analysis, Deviation visualization, Conservation treatment, Gangjin celadon kiln

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Introduction

Records of the conservation treatment of cultural heritage monuments and archaeological sites are generated primarily on the basis of descriptive methods and digital photographs. These methods are simple and universal because of the low technical barriers and have great advantages in making qualitative judgment before and after conservation treatment [1]. However, since the conservation process causes multidirectional shape changes, these methods have a limitation in recording various types of information only with description and photos [2]. Hence, technical methods such as three-dimensional (3D) scanning are needed to digitize and record the shape changes before and after conservation treatment of cultural heritage monuments and archaeological sites.

The most important thing in analyzing changes in the shape of cultural heritage monuments and archaeological sites using 3D scanning is to select a technology appropriate for the size of the scan object and recording purpose [3, 4]. To achieve this, it is necessary to first understand the operating principles, resolution, accuracy, and accessibility of 3D scanning technology. In general, there are cases where digital recording is possible with only one scanning technology, but in most cases, optimal results can be obtained when various scanning technologies are used complementary [5–8]. In particular, the archaeological sites exposed through excavation are larger and less well-preserved than the traditional artifacts, so the scan methods should be different depending on the purpose of digital documentation [9], shape analysis [10], interpretation [11], and monitoring [12].

Terrestrial laser scanning has a long measurement distance and is advantageous for data acquisition and point-based macroscopic analysis of archaeological sites [13–15] and architectural heritages [16–19]. However, the scanning technology has low point density resolution, so there are limitations in the recording and analysis of detail shapes. To compensate for this, handheld precision scanning technology with high density resolution is widely used [20]. While this method has the advantage of detailed geometry recording and shape analysis based on high-density resolution, it has the disadvantage that cumulative errors occur when the scan target is large and data processing is difficult. Therefore, it is necessary to use terrestrial laser scanning and handheld precision scanning together to digitally record excavated sites and analyze shape changes.

Meanwhile, the analysis of shape changes in cultural heritage monuments and archaeological sites largely is focused on comparing surveying data of different chronological periods [21] and detecting short-term weathering [14, 22, 23]. These studies were primarily aimed at time-series monitoring due to natural deterioration and did not address the analysis of shape changes due to artificial interventions such as conservation treatment. In addition, although researches on the kiln sites using digital technology are being conducted on a very wide scale, such as feature detection using aerial LiDAR-derived digital elevation models [24], underwater archaeological investigation using ground penetrating radar [25], simulation study of the manufacturing technology [26], and a conceptual model based on metadata and ontology [27], there is no conservation scientific approach.

Therefore, in this study, celadon kiln in Yongun-ri, Gangjin, which was subjected to relocation restoration and several conservation treatments after excavation, was digitally recorded through 3D scanning, and changes in its shapes were numerically analyzed. In particular, geometric information obtained before and after the conservation treatment in 2020 formed the basic data for the continuous monitoring and preventive conservation actions performed to compensate for the soil disintegration and cavitation phenomenon. To achieve this goal, spatial information of the entire kiln was acquired through terrestrial laser scanning, and precise data on working spaces, including the combustion chamber, were constructed by using a handheld scanner. In particular, all 3D scanning was performed once each before and after the conservation treatment, and the shape changes due to the conservation treatment were quantified and visualized using a numerical analysis model.

Materials

Celadon dates to the Goryeo Dynasty period (918–1392) and displays a beautiful jade-like color combination of gray clay and blue-green glaze. In particular, inlaid celadon is renowned across the world as a representative Korean cultural heritage artifact. Celadons were produced predominantly in Gangjin and Buan, Jeollanam-do. The Goryeo celadons produced in this region are highly valued for their technical excellence and artistry [28]. Gangjin is rich in kaolin and quartzite, which form the raw materials for pottery. The area also holds an abundance of high-quality wood, which makes it convenient for pottery firing. In addition, Gangjin is located adjacent to the sea and is thus a natural contender for sea transportation. Unsurprisingly, 188 kiln sites were discovered in five regions (Fig. 1) in Gangjin alone. These locations are currently placed on the tentative list of UNESCO World Heritage and named the "Gangjin Kiln Sites" in recognition of the large-scale Goryeo Dynasty pottery found in this area.

Most of the kiln sites have been maintained after their excavation and are well preserved in their original locations. However, Site No. 10 (10th to eleventh century) of the celadon kilns distributed in Yongun-ri was excavated in 1982 and was in danger of being submerged when the Dangjeon Reservoir was built. Therefore, a decision was made to relocate and restore Site No. 10–1, whose condition was appraised as the best of the four kilns excavated at this location.

The kiln is shaped as a semibasement with a vaulted ceiling and is largely composed of a working space, furnace, combustion chamber, and firing room. It is an

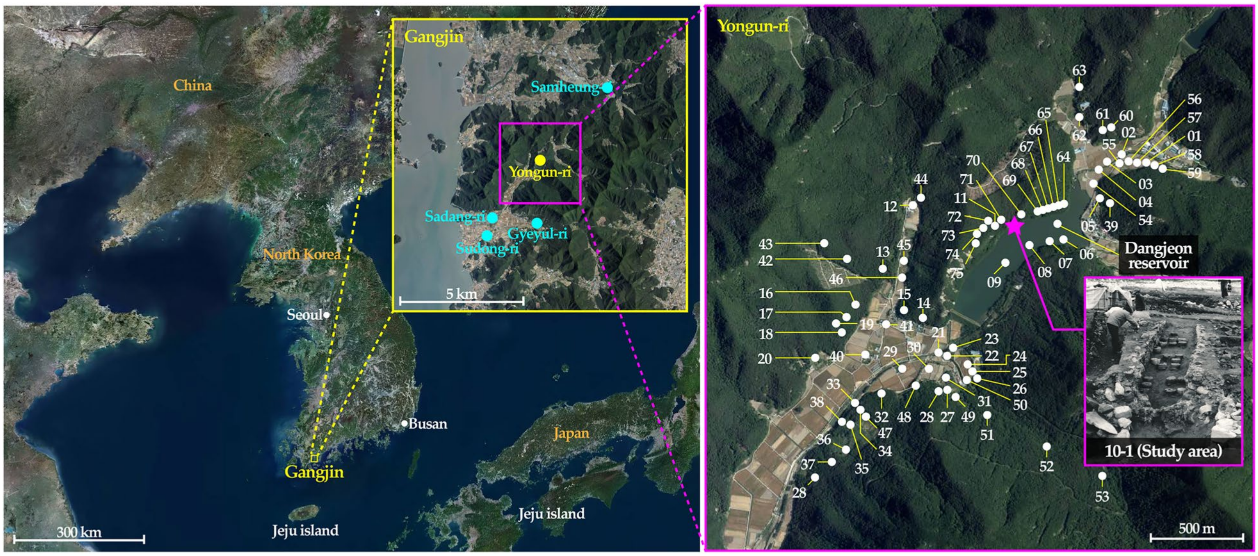

Fig. 1 Location of celadon kiln excavated in Yongun-ri, Gangjin

ascending kiln with a sloped floor. The entrance of the furnace was constructed by stacking cylindrical bowls made of clay that could withstand high temperatures. The right wall of the kiln has an access facility for loading and unloading bowls, and a small fire hole for checking the flame inside the kiln remains on the opposite side (Fig. 2a). Additionally, the walls of the kiln are made of cylindrical bowls and smeared clay, similar to furnace, and the bottom of the kiln is covered with a thick layer of fine burned sand. The unique feature of the kiln is that there is an ancillary room on the left side of the furnace. This room is potentially a facility for collecting ash generated in the combustion chamber or storing embers. These characteristics are important data that enable us to gain an immediate insight into the process of origin, development, and decline of Goryeo celadon and are considered invaluable data out of Gangjin Kilns where early celadons were produced.

The Gangjin Kiln site was hardened and dismantled after excavation in 1982 for relocation. It was restored at its current location (the outdoor exhibition area of the Gwangju National Museum) in 1987 (Fig. 2b, c). The restoration was performed by placing the combustion chamber and the left and right kiln walls according to the slope of the kiln on a reinforced concrete foundation. Then, the outer wall of the kiln and the damaged part were reinforced with synthetic resin. Since then, because of deterioration over 20 years, aesthetic problems arose, as parts of the kiln walls cracked and fell off. Subsequently, in 2007, an effort was made to preserve

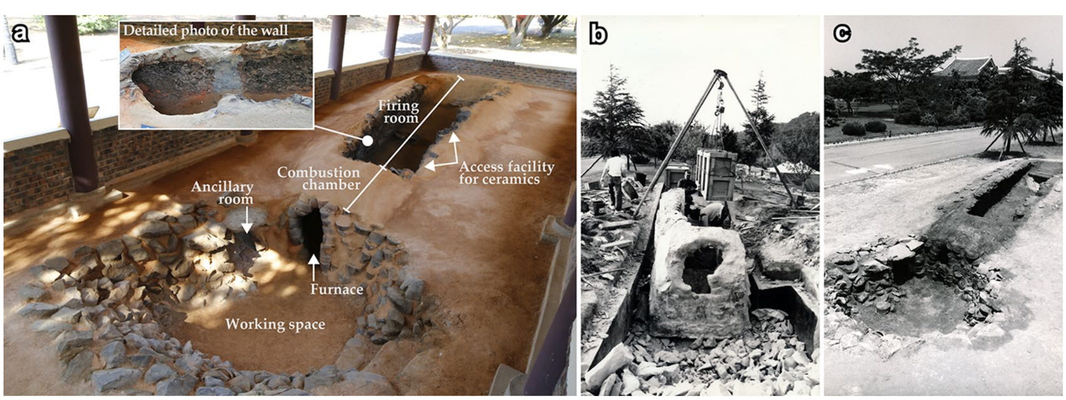

Fig. 2 Status of Gangjin Celadon Kiln. **a** Field existence of the kiln in 2020. **b**, **c** The kiln restored at the outdoor exhibition hall of the Gwangju National Museum in 1987

the original shape through primary conservation treatment. However, soil disintegration and durability degradation occurred continuously over the last 13 years since 2007, and thus, the conservation science team of the Gwangju National Museum was tasked with a secondary conservation treatment in 2020 (Fig. 3a).

The secondary conservation treatment was largely performed for recovering the damaged parts, structural reinforcement, and partial restoration in principle. First, powdered soil was removed from the entire kiln, and the outer wall of the kiln was fixed with bolts and wires. In addition, a material was prepared by mixing red clay, Dobak (Pachymeniopsis elliptica YAMADA) glue, and kneading straw, and the inner and outer walls of the kiln were restored using this material. Some detached pieces were joined using synthetic resin. Thereafter, using mixed materials such as red clay + quicklime and decomposed granite soil + synthetic resin, the inner floor of the kiln, flue, and working space and its periphery were reinforced. Finally, foreign substances were removed by dry and wet cleaning, and the heterogeneity of the restoration was reduced to the maximum extent possible via coloring (Fig. 3b, c).

Methods

Three-dimensional scanning and digital recording

It is crucial to precisely digitize and maintain a detailed record of the present condition of the surface of the kiln, including its spatial information, to monitor the conservation treatment and structural deformation of the kiln site. Digital recording of the kiln site was performed using diverse advanced technologies such as 3D scanning and ground control point survey. Although digital recording is generally possible with a single scanning technology, combining two or more scanning methods is necessary to produce precise and complementary interpretations. It is crucial to macroscopically scan the overall shape of the kiln site, and record it in detail, focusing on the furnace and combustion chamber, which are key conservation targets. Therefore terrestrial laser scanning and handheld medium-precision scanning methods were conducted once each before and after conservation treatment, depending on the scan range. Because this study

Fig. 3 Conservation treatment processes of the kiln site in 2020. **a** Conservation conditions before treatments. **b** Photographs showing detailed conservation treatments for recovering the damaged parts, structural reinforcement, and partial restoration. **c** The kiln site after conservation treatments

did not produce a single 3D model, we did not combine terrestrial laser scanning and medium-precision scanning data; however, we focused on analyzing the RMS deviation for shape changes before and after conservation treatment.

First, a 3D scan was performed before and after the conservation treatment of the interior and exterior of the kiln, including the protecting shelter of the kiln site. A terrestrial laser scan (BLK360, Leica Geosystems, USA), with an 3D point accuracy of 4 mm at a distance of less than 10 m, was performed for a total of 56 points considering the height and overlap ratio so that the point density was uniformly distributed throughout the kiln site. The point density was set to 5 × 5 mm/10 m considering the scan range and resolution. Then, 3D post-processing (Cyclone 9.2, Leica Geosystems, USA) of individually scanned point cloud data was completed through registering, filtering, merging, and texture mapping as reported in many previous studies [6, 29, 30].

The spatial information model of the completed kiln site basically has a relative coordinate system (Fig. 4a). Therefore, to link the coordinates with the real-world coordinates, a georeferencing process that can convert the relative coordinate system into an absolute coordinate system is required. Currently, in South Korea, the planar positions of national and city reference points are determined based on the global navigation satellite system (GNSS). For surveying the ground control points of the kiln site, five random points that had no obstacles around them and uninterrupted GPS signals were selected. Then, the ground control points were surveyed using GNSS equipment (V100, Hi-Target, China) to locate the spatial information data on real-world coordinates. From the information of each control point, it is seen that the kiln site is located in a terrain with a slight slope rather than on a horizontal terrain in the longitudinal direction; it has an altitude of 51.2–52.7 m. This ground control point information was used to correct the absolute position of the 3D model built based on terrestrial laser scanning data (Fig. 4b).

Meanwhile, in this study, precision recording was performed using a handheld scanner (Eva, Artec 3D, Luxembourg), considering the size and accessibility of the kiln site. Precision scan, with a 3D resolution of up to 0.2 mm and an 3D point accuracy of up to 0.1 mm, was conducted for the working space and combustion chamber, which are the regions where most shape changes are predicted to occur during kiln site conservation treatment. The 3D scan was performed at a rate of about 16 frames per second in an environment without direct sunlight because it was necessary to distinguish the structured light scanned on the kiln. The scan data acquired in the field basically underwent almost the same process using dedicated software (Artec Studio 13, Artec 3D, Luxembourg) as the terrestrical laser scanning data, but they are different in that the former data were obtained in the form of a polygon mesh rather than as point cloud data. Geomagic Design X (3D Systems, USA) software used to edit the 3D scan data and extract the final captured images.

Analysis of shape change before and after conservation treatment

In statistics, a deviation is the difference between an observed value and the mean. It is expressed as a positive or negative number, indicating that the observed value is greater or smaller, respectively, than the mean. The magnitude indicates how far the observation is from the mean. A deviation can be referred to as an error or a residual and is the observed value minus the mean or median. The variance is obtained by squaring the difference between the observed value and mean, adding the squares for all observations, and dividing this sum by

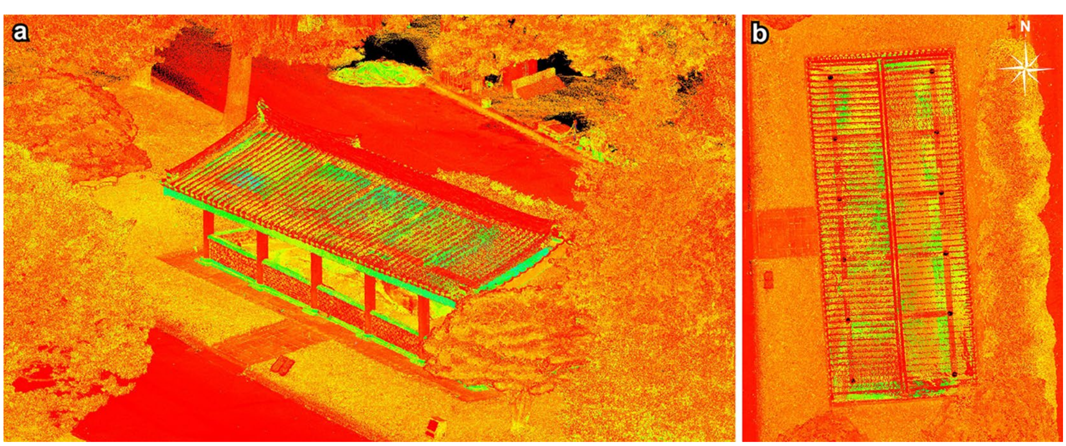

Fig. 4 Completed terrestrial laser scanning results. **a** The spatial information model of the entire kiln site. **b** Orthoimage based on the GNSS

the total number of observations. The standard deviation is the square root of the variance, and it transforms the variance with an enlarged value back to its original magnitude.

The RMS value is a representative value that is indicative of the characteristic or tendency of a certain group, such as the mean, median, or mode. The RMS value is obtained by taking the square root of the mean value of squared deviations. RMS is commonly used when dealing with the difference between an estimated or a predicted value and a value observed in the real world. It is generally suitable for expressing precision. Each difference value is also called a residual, and the RMS deviation aggregates the residuals into one scale. The lower the RMS value, the more accurate is the prediction. A perfect prediction model has an RMS value of zero. This value is easy to interpret because it expresses the difference between the model predicted value and the actual value as a single number, and it is widely used for image analysis because each numerical value can be visualized [31–33].

In this study, RMS analyses were performed using 3D point cloud and mesh data before and after the conservation treatment of the kiln site. The big data of deviations were visualized. Mainly two types of software were used for shape analysis before and after conservation treatment of the kiln site. The terrestrial laser scanning results based on point cloud data were analyzed using CloudCompare, which is an open-source software, and the mesh data constructed by precision scanning using the handheld scanner were compared using Geomagic Control X (3D Systems, USA). Both software types have great strengths in visualizing complex numerical data by analyzing the deviations caused by the deformation of the point cloud or mesh models.

For RMS analysis, the kiln site before the treatment was set as a reference model, and the kiln site after the treatment was set as an analysis model. Thereafter, the two models were registered with the iterative closest point algorithm based on the points that did not experience any shape change because of the conservation treatment (Fig. 5). The deviations between the two shapes were analyzed using the matched 3D model, and based on the results, the statistical values such as the minimum, maximum, mean, RMS, standard deviation, (+) mean, and (−) mean were calculated.

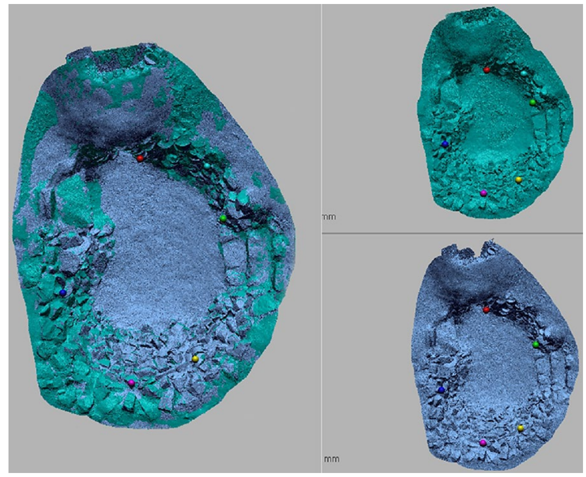

Fig. 5 3D models before and after the conservation treatment registered for the RMS deviation analysis

Results

The overall shape was actually surveyed based on the terrestrial laser canning model of the kiln site. The bottom of the kiln and the combustion chamber were actually measured to be about 6.7 and 1.1 m long, respectively. In addition, the working space extended about 3.4 m in the longitudinal direction. The ancillary room on the left side of the furnace was about 0.5 m deep. The entrance of the combustion chamber, furnace, was 0.7 m wide. By analyzing the left and right longitudinal sections, the slope of the bottom of the kiln was determined to be about 16.7° (Fig. 6). The precision scanning results were of excellent quality in terms of both the polygon mesh and RGB texture mapping results. Further, as the data had millions of high-resolution polygons, the surface texture, manufacturing technique, and cross-sectional structure of the kiln working space, including the entrance of the combustion chamber, were clearly revealed (Fig. 7).

For analyzing the deviations of the kiln site between before and after the treatment, a terrestrial laser scanning model was used to represent the overall shape, and a precise-scanning model was used to indicate the minute changes in the shapes of the working spaces, including the combustion chamber. First, the changes in the shape of the entire kiln were studied by comparing the shapes after treatment with the terrestrial laser scanning point cloud data (Fig. 8). The results showed that the conservation treatment focused on the floor inside the working space, bottom of the kiln, and upper left wall of the firing room. In addition, there were notable changes on the left side wall of the combustion chamber. In the deviation visualization image, the most noticeable change after conservation treatment was determined to be around 15 mm, and many changes of 40 mm or more were also identified. Red mapping refers principally to areas in which damages have been repaired, light green to yellow areas denote sites that have been structurally strengthened, and blue indicates areas from which contaminants have been removed or where fine conservation treatment has been performed.

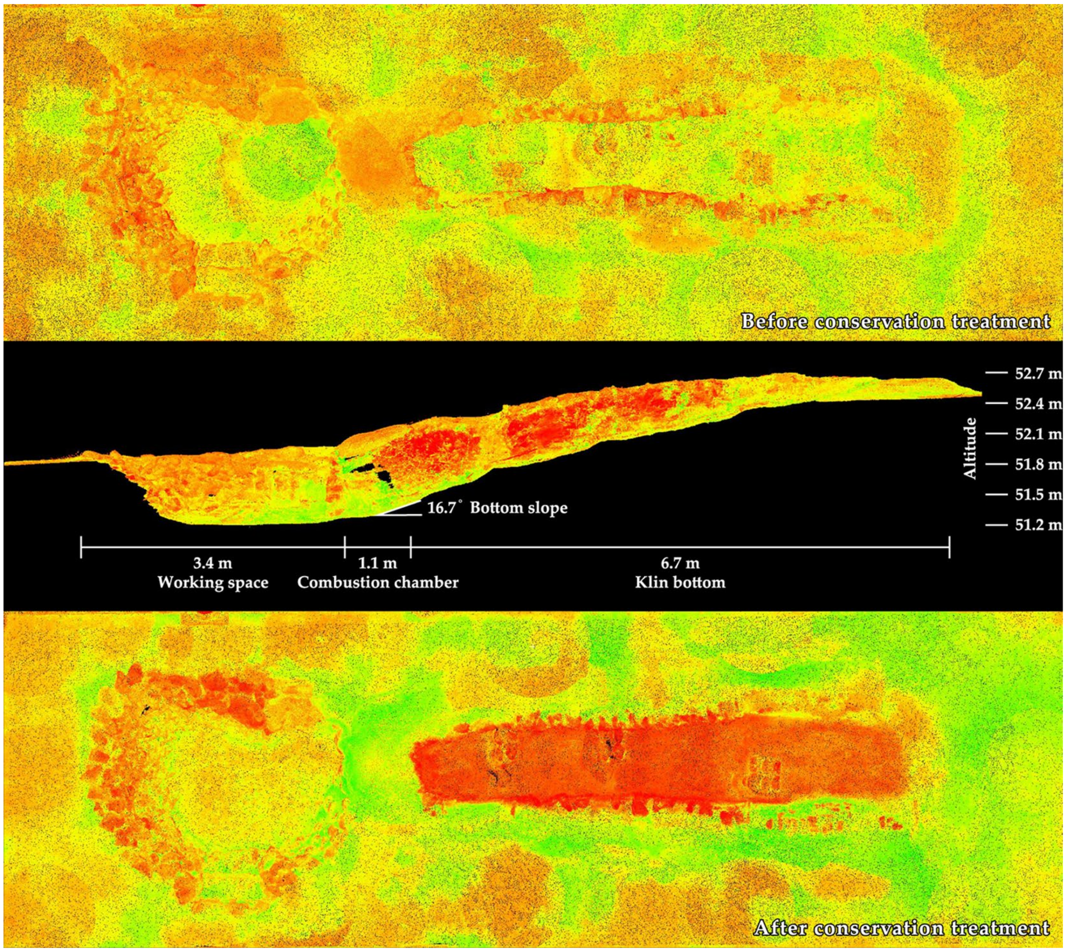

Fig. 6 The overall shape surveyed based on the terrestrial laser scanning model of the kiln site

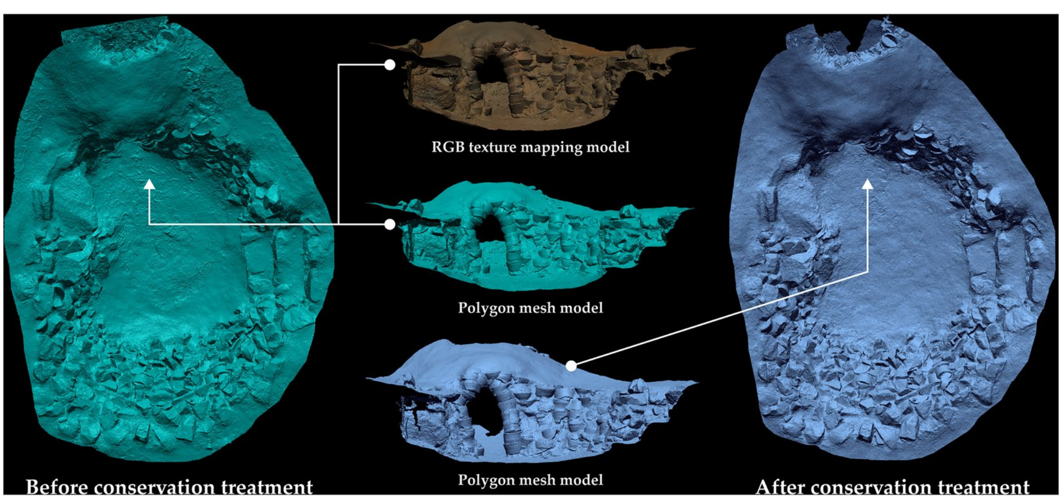

Fig. 7 Polygon mesh and RGB texture mapping models before and after conservation treatment of the kiln site

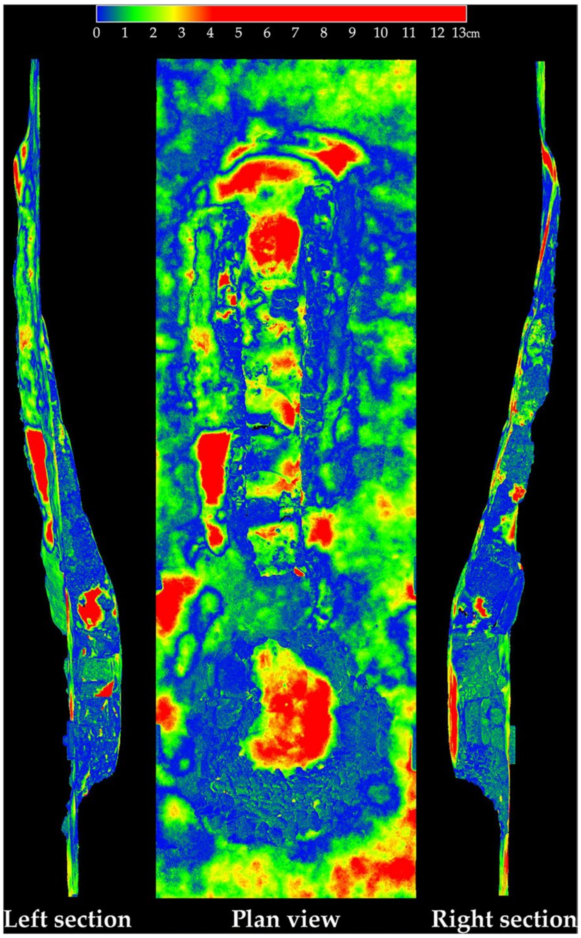

Fig. 8 Visualized images showing the changes in the entire kiln site by comparing the shapes after treatment with the terrestrial laser scanning point cloud data

The changes in the conservation treatment of the working spaces, including the combustion chamber, were analyzed using the precision-scanning polygon model. In particular, not only the visualization image but also points with key shape features were sampled, and the deviation before and after conservation treatment was calculated and presented. First, in the case of the stone works (Fig. 9a) that make up the working space, there was no significant change in shape of 0.2 to 0.9 mm overall, but the positive (+) values were remarkably visualized in the filling material between the stone works. Point 7 showed a relatively large deviation of 18.8 mm. This indicates that reinforcement was performed to prevent deformation of the stone during the conservation treatment. However, it can be seen that the stone was deformed in the negative (−) direction at points 9 (− 12.3 mm) and 10 (− 2.8 mm).

The greatest shape changes in the deviation analysis area were observed in the case of the floor (Fig. 9b) and the interior of the combustion chamber (Fig. 9c). Among these, the floor showed a deviation of 12.2 mm at point 1, which is adjacent to the stone works. In contrast, the deviation increased to a maximum of 52.8 mm (point 5) toward the inside. The floor had been reinforced and flattened to a thickness of at least 40 mm. Positive (+) and negative (−) deviations coexist in complex ways inside the combustion chamber. In particular, the reinforcement thickness increased from the floor (points 1 and 2) to the left wall (points 3–5), with a maximum deviation of 55.7 mm at point 5. There is no significant change in shape at points 6 (− 1.3 mm) and 7 (− 1.4 mm) of the left earthen wall; however, soil was removed from the floor around points 8 (−9.4 mm) and 9 (− 14.4 mm). In particular, it can be seen that the stone located on the floor was deformed by 39.3 mm in the negative (−) direction.

When the numerical analysis results before and after the conservation treatment using handheld precision scan data (1,247,186 poly vertex) in the entire working space and the combustion chamber, were taken together, the RMS was calculated to be 11.2 mm, which is the average shape change due to the conservation treatment. Further, the average deviation value was 7.4 mm in the (+) direction and 3.6 mm in the (−) direction, indicating that the dominant conservation treatment centered on the reinforcement (Table 1). Additionally, the tolerance range (± 1 mm) mapped in green means that almost no conservation intervention occurred, which was calculated to be 32.4% of the total area (Table 2).

Discussion

In principle, archaeological sites are preserved in their original locations after excavation. However, the Gangjin Kiln site (Yongun-ri 10–1) exhibited high preservation value but was situated in a submerged area when it was excavated. Hence, it was relocated and restored to the Gwangju National Museum. Ceramic was produced at this kiln site, and its relocation to the Gwangju National Museum, which specializes in ceramics, was apt to its historical context. Ceramic culture forms the core content of the indoor exhibition hall of the Gwangju National Museum. Visitors could simultaneously view the production and use of celadon through the outdoor display of the kiln site where ceramic was produced. This case is believed to exemplify the musealization of archaeological sites that are difficult to preserve in situ [34].

Conservation treatments and restorations have been actively applied in South Korea to designated cultural heritage objects since the 2000s when the preservation and transmission of cultural heritage artifacts gained importance. The kiln site also suffered severe damage after its relocation in 1987, so conservation treatment was implemented for the first time in 2007. However,

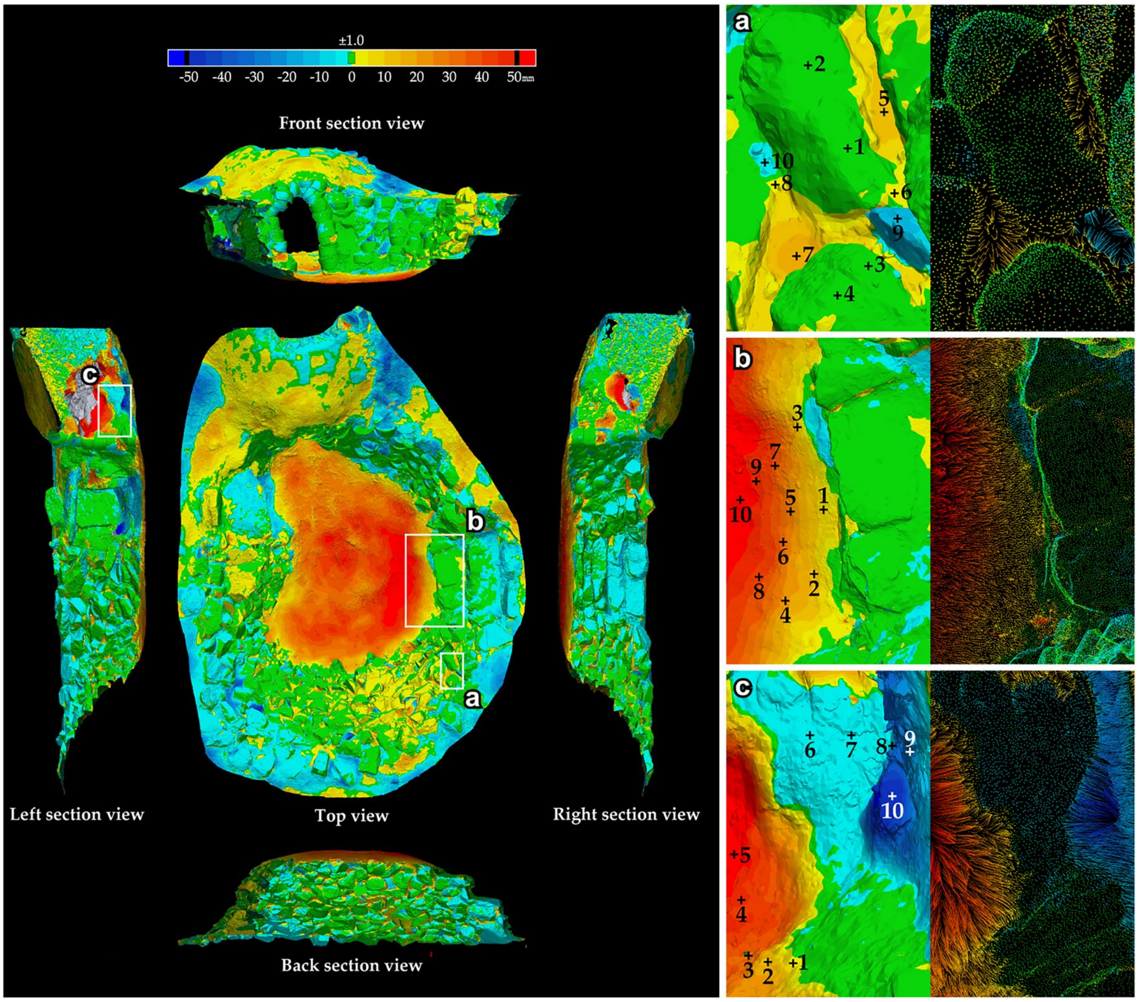

Fig. 9 Visualized images and sampling analysis points showing the changes in the conservation treatment of the working spaces, including the combustion chamber, using the precision-scanning polygon model. **a** Stone works. **b** The floor of the combustion chamber. **c** The interior of the combustion chamber

Table 1 Sampling deviation results before and after the conservation treatment of key shape zones in the entire working space and the combustion chamber

Points	(a) zone	(b) zone	(c) zone
1	0.6 mm	7.1 mm	9.0 mm
2	0.8 mm	13.6 mm	13.0 mm
3	0.2 mm	17.0 mm	32.3 mm
4	0.9 mm	22.4 mm	46.7 mm
5	13.4 mm	27.5 mm	55.7 mm
6	1.7 mm	33.2 mm	− 1.3 mm
7	18.8 mm	36.7 mm	− 1.4 mm
8	2.0 mm	38.8 mm	− 9.4 mm
9	− 10.6 mm	43.2 mm	− 14.4 mm
10	− 2.8 mm	53.8 mm	− 39.3 mm

The analysis points are same as those in Fig. 9

Table 2 Numerical analysis results before and after the conservation treatment of the entire working space, including the combustion chamber

Min.	− 58.4 mm
Max.	58.4 mm
Mean	2.2 mm
RMS	11.2 mm
(+) Mean	7.4 mm
(−) Mean	− 3.6 mm
In tol.	32.4%
Out tol.	67.6%

no digital materials then existed that could reveal the targets and extent of conservation treatments. In addition, soil disintegration and structural deformation occurred after 2007; therefore, a second conservation treatment was executed in 2020. Thus, continuous interventions are required for archaeological sites that have been artificially relocated and restored because a single treatment may be insufficient. Hence, precise records are essential to monitor their conditions and shape changes [35].

Records represent critical components for the monitoring of conservation conditions. Gradually, digitized records obtained using advanced equipment are increasingly utilized rather than conventional handwritten documentation [36–40]. Recently, cultural heritage monuments and archaeological sites have been actively monitored using 3D scanning data. Kim et al. (2019) used an aerial photogrammetry model in a short-term monitoring project conducted to identify the deformation caused to a stone fortress along with severe structural damage because of heavy rain occurring during the rainy season [22]. Campiani et al. [14] and Lercari [41] utilized time-series comparisons of point clouds acquired by terrestrial laser scanning to detect surface changes in ancient earthen architecture [14, 41]. This approach correlates the identification of the wall features with the immediate risk of deterioration based on the detection of patterns of change and the calculation of its significance as a preventative measure. Ma (2023) provided a practical and effective deformation monitoring system based on a stereo digital image correlation (stereo-DIC) technique for 3D deformation evaluation of the stern of an archaeological wooden shipwreck [42]. Thus, continuous photogrammetry and 3D scanning are now being used as core technologies to monitor the condition of cultural heritage monuments and archaeological sites and perform preventive conservation interventions on them [43, 44].

Surface changes and deformation are more noticeable in relocated archaeological sites, such as celadon kilns than in historical buildings undergoing natural transfigurations. In addition, the kiln site underwent extensive conservation treatment twice in 2007 and 2020. Thus, damage caused by natural or artificial factors is expected in the future. Therefore, it is very important to archive the shape changes instigated by conservation interventions along with repair and reinforcement as digital data to restore the original form of the kiln and ensure its sustainability. Even though 3D scanning was not performed in 2007, sufficient basic monitoring data was obtained in 2020 because terrestrial laser scanning and handheld precision scanning were implemented before and after the conservation treatment. Therefore, short-term monitoring using periodic 3D scanning and time-series data comparisons is necessary to identify the point of shape change and major damaged areas and establish a mid- to long-term monitoring plan based on such observations.

Conclusions

The survey of the overall shape based on the 3D scanning model of the kiln site showed that the kiln site was 11.2 m long in the longitudinal direction (6.7 m long at the bottom of the flue, 1.1 m long in the combustion chamber, and 3.4 m long in the working space) and had a slope of 16.7°. In addition, the entrance to the combustion chamber, which is the main target of conservation treatment, was 0.7 m wide, and the furnace had a depth of 0.5 m.

Powdered soil was removed to conserve the damaged kiln site, the inner and outer walls of the kiln were restored, and some detached pieces were joined. The shape changes caused by the conservation treatment undertaken in 2020 were recorded via three-dimensional (3D) scanning, and numerical analysis was performed for continuous monitoring and preventive conservation.

Changes occurring in the shape in the period before and after the conservation treatment of the entire kiln site were examined using point cloud data. The results evidence that the conservation treatment focused on the left side of the flue and upper wall. The most noticeable change in conservation treatment was shown to be around 15 mm. Specifically, a reinforcement of around 40 mm thickness at the least and a flattening were prominently evident on the floor of the working space. The interior of the combustion chamber was also visualized as incorporating a reinforcement of at least 50 mm. Positive (+) values were remarkably visualized in the filling material between the stonework because of reinforcement action taken to prevent the deformation of the stone.

The calculated average RMS value of the working space, including the combustion chamber, was 14.1 mm. This is the average shape change due to the conservation treatment in 2020. In addition, the average deviation value was 10.2 mm in the (+) direction and 4.3 mm in the (−) direction, indicating that the conservation treatment mainly focused on the reinforcement. The RMS deviation analysis provided very useful visual information and numerical data for understanding the locations and extents of shape changes before and after the conservation treatment.

The kiln sites underwent extensive conservation treatment twice in 2007 and 2020. Therefore, it is predicted that they will experience minute shape changes in the future because of natural or artificial factors. Hence, short-term monitoring using periodic 3D scanning and time-series data comparison must be performed to identify the point of shape change and detect major damaged areas so that a mid- to long-term monitoring plan can be established based on such observations. Regular 3D scanning to derive the monitoring cycle and its effects will contribute substantively to expanding the applicability of the time series analysis of similar cultural heritage structures. Predictive modeling research is mandated to advance the present research initiative and to utilize shape change data to identify areas of the kiln site that display an elevated probability of deterioration.

Unlike past efforts that focused on repair and reinforcement after damage to conserve kiln sites and maintain them in their original forms, they should be transformed in the future to effect preventive conservation actions that can envisage and predict damage-related changes. Essentially, such preventive conservation methods are based on continuous digital recording and data-based monitoring. Therefore, additional predictive modeling research based on shape change data will be required to identify areas encompassing entire kiln sites that exhibit a high likelihood of deterioration. Monitoring cycles and effects derived through regular 3D scanning of the kiln site can contribute substantially to expanding the applicability of the time-series analysis of similarly relocated archaeological sites.

Abbreviations

3D	Three-dimensional
RMS	Root-mean-square
GNSS	Global navigation satellite system

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Author contributions
All authors contributed to the planning and design of this article. YHJ and YHK performed the data acquisition and data analysis. HSL performed the conservation treatment. YHJ wrote the manuscript and all authors revised it critically. All authors read and approved the final manuscript.

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Availability of data and materials
The datasets used and/or analyses results obtained in the current study are available from the corresponding author on request.

Declarations

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

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