Stability Interpretation for the Tomb of King Muryeong and the Royal Tombs in Baekje Kingdom of Ancient Korea Using 3D Deviation Analysis and Microscale Behavior Measurement

Il Kyu Choi , Hye Ri Yang , and Chan Hee Lee$^{(\boxtimes)}$

Department of Cultural Heritage Conservation Sciences, Kongju National University,
Gongju 32588, Republic of Korea
`chanlee@kongju.ac.kr`

Abstract. The Tomb of King Muryeong and the Royal Tombs in Gongju, Republic of Korea has been registered as UNESCO World Heritage sites in 2015 regarding the values as one of the representative cultural heritages of the Woongjin period (475 to 538 AD) in Baekje Kingdom. After the excavation of tombs, several damages occurred due to rapid environmental change. This study uses a 3D precise scanning to visualize microscopic changes in wall composition materials that are difficult to distinguish using sensors and record 3D shape information on vulnerable parts within the tombs. In addition, the obtained data were used to calculate the displacement during the study period through comparative analysis with the previous data of the tomb complex. Based on the RMS deviation analysis, no visible deviation was found in the tolerance ranges ± 2 mm and ± 1 mm. The results indicate that no additional cracks or detachment occurred in all vulnerable parts. However, the displacement analysis confirmed the sagging behavior for the lintel in the Tomb No. 5, which also appeared in the position transducer installed at the Tomb No. 5, indicating that minute movement occurred. It is estimated that the steel supports currently supporting the lintel are not providing adequate support due to corrosion, therefore reinforcement should be considered. The results of this study are expected to be applied as important basic data in preparing and processing conservation measures for the Tomb of King Muryeong and Royal Tombs in Gongju in the future.

Keywords: Tomb complex in Baekje Kingdom · 3D scanning · Displacement · Deviation analysis · Conservation measure

1 Introduction

The Tomb of King Muryeong and the Royal Tombs in Gongju are registered as UNESCO World Heritage Sites and are preserved as cultural heritages representing the Woongjin period (475 to 538 AD) of Baekje Kingdom in ancient Korea. The targets of this study were the tombs of royal families during the Baekje Kingdom, and more than 20 tombs were known to have existed, but a total of 7 tombs are maintained in the current Royal

Tombs in Gongju (Fig. 1) [1]. In this study, monitoring was performed on the Tomb No. 5, Tomb No. 6 and the Tomb of King Muryeong (Fig. 2).

Tomb No. 5 was built using gneiss, which are not uniform in shape. And plaster is applied in each wall, but only traces of it remain. Tomb No. 6 is made of bricks and murals are painted on the walls. The murals in the Tomb No. 6 are the only example in Korea painted on bricks. However, most of the murals have been lost, and only the base layer remains. The Tomb of King Muryeong is the only tomb in the Three Kingdoms Period that records the identity of the deceased and the construction date of the tomb. Since then, the Tomb of King Muryeong has become a standard for the study of tomb culture and chronological research during the Baekje Period, and it is evaluated as a cultural heritage that can examine the historical and cultural influence of neighboring countries at the time. However, after the royal tombs was opened to the public, various damages such as leaks, cracks and behavior of walls have been occurred due to rapid environmental changes inside the tombs [2, 3].

Therefore, scientific analysis was required, and comprehensive research on stability of tombs were studied [4–7]. However, measurement and monitoring of the inside of the tomb have been mainly carried out through precision measurement sensors, and research using three-dimensional scanning has been relatively less performed [8]. In this study, the vulnerable parts within the royal tombs were selected, and three-dimensional precision scanning was performed to visualize the micro displacement occurring inside the tomb compared to the preceding data and to check the progress of the damages.

2 Subject and Methodology

Prior to 3D scanning, the vulnerable parts inside the Royal Tombs were selected [8]. In the Tomb No. 5, plastered stone walls with a high possibility of lime loss and lintel stones, which sagging occurred were selected in the four directions of the wall. There are murals inside the Tomb No. 6, and the durability has weakened due to weathering [3]. In this study, the cracks in the mural of the four directions were selected. In the Tomb of King Muryeong, the arch part of the burial entrance where observed downward movement of the bricks was selected as a scanning point.

In this study, 3D precision scanning was performed with reference to previous studies [8], and the displacement inside the tomb was visually analyzed by comparing it with precision measurement data. A precision scanner (Artec3D, Eva, Luxembourg) was used to acquire 3D data for each tomb's monitoring point. In the field, 3D data were acquired using Artec Studio software. The same program was used for post-processing of the received information. The completed polygon mesh was edited using the Geomagic Design X program. In addition, the completed data was analyzed for deviation by calculating the RMS (root mean square) with previous data, and displacement was visualized by comparing the vertical and horizontal distances between members. The analysis compared the changes between the data acquired in 2020 and the data obtained in 2021. And Geomagic Control X software was used for RMS deviation analysis.

Fig.1. Geographic map of the Tomb of King Muryeong and the Royal Tombs in Gongju.

Fig. 2. Photographs showing the Tomb of King Muryeong and the Royal Tombs in Gongju. (A) Tomb No. 5. (B) Tomb No. 6. (C) Tomb of King Muryeong.

3   Results and Interpretation

3.1   RMS Deviation Analysis

Based on the 3D scan data, RMS deviation analysis was performed on the plaster wall of the Tomb No. 5 differences between data were visualized by applying color differences to the results. The standard data was set to images acquired in 2020, and the tolerance range was set to ±2 mm for precise analysis. The deviation was not found in the tolerance range of ±2 mm in the case of the Tomb No. 5.

This is believed to be because the tolerance set in the analysis is wider than the actual deviation, and further investigation was conducted by narrowing the tolerance range to ±1 mm for more precise analysis (Fig. 3). In this result, more than 94% of the average data were within the tolerance range (Table 1). Therefore, during the study period, it was interpreted that no additional damages such as peeling, exfoliation or break out occurred on the plaster wall of the Tomb No. 5, and it is observed to be relatively stable.

In Tomb No. 6, RMS deviation analysis was conducted to identify microscopic changes, such as cracks and breaks out in the base layer of the mural. The analysis
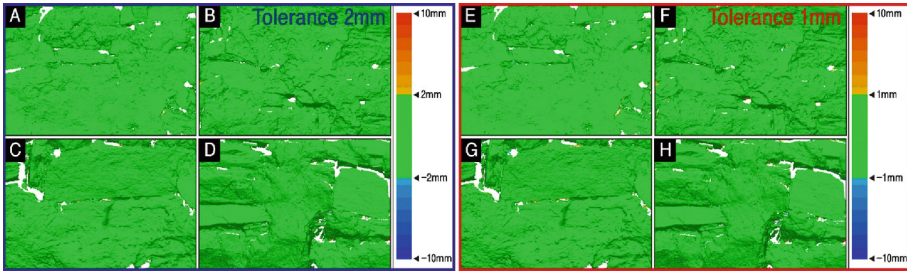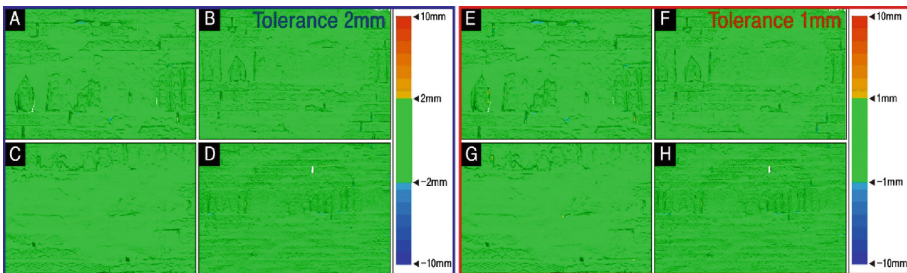
Fig. 3. Photographs showing the digital images of RMS deviation analysis of the vulnerable parts in the Tomb No. 5. (A, E) East wall. (B, F) West wall. (C, G) South wall. (D, H) North wall.

Table 1. Results of RMS deviation analysis for the Tomb No. 5

Tomb No. 5		Within Tolerance		Out of tolerance	
		±2 mm	±1 mm	±2 mm	±1 mm
Plaster wall	East	98.14	96.79	1.86	3.21
	West	96.01	94.03	3.99	5.97
	South	95.37	93.44	4.63	6.56
	North	96.43	94.42	3.57	5.58

conditions were the same as those of the Tomb No. 5, and the tolerance range was set to ±2 mm and ±1 mm to conduct the analysis. And characteristic changes are not identified. But a small amount of deviation is confirmed in the joints between the members. This deviation was caused by the data error acquired between the three-dimensional shape information, not the actual exfoliation or break out of the joint (Fig. 4, Table 2).


Fig. 4. Photographs showing the digital images of RMS deviation analysis of the murals in the Tomb No. 6. (A, E) East wall. (B, F) West wall. (C, G) South wall. (D, H) North wall.

Table 2. Results of RMS deviation analysis for the Tomb No. 6

Tomb No. 6		Within Tolerance		Out of tolerance	
		±2 mm	±1 mm	±2 mm	±1 mm
Mural	East	97.52	95.46	2.48	45.45
	West	99.03	97.91	0.97	2.09
	South	99.47	98.57	0.53	1.43
	North	99.52	94.43	0.48	5.57

3.2 Displacement Analysis

To analysis the deviation of the plaster wall, displacement on the entrance lintel stone was performed in the Tomb No. 5. The 3D data obtained in the study were used for the displacement analysis, and the distance between the members was measured by selecting 10 points in the vertical and horizontal directions on the lintel stone and the surrounding wall, respectively. Then the data was compared with the previous data in 2020 to identify the behavior of the lintel (Fig. 5).
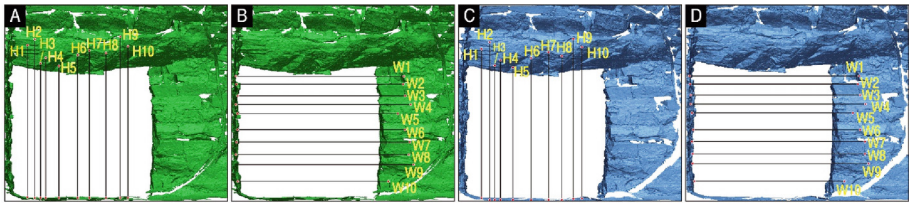
Fig. 5. Measurement points for vertical and horizontal distances in lintel stone of the Tomb No. 5. (A, B) 3D data acquired in 2020. (C, D) 3D data acquired in 2021.

As a result of the displacement analysis of the lintel stone of the Tomb No. 5, it was found that between the lintel and the bottom of the entrance, the sinking occurred from 0.24 mm to 0.54 mm with average 0.40 mm in vertical direction. In addition, it was confirmed that the horizontal distance between the walls constituting the lintel part increased from 0.03 mm to 0.21 mm and average 0.12 mm (Table 3). It is considered that sinking occurs in the lintel stone of the Tomb No. 5, and that the wall that make up the entrance subjected to vertical loads are slightly pushed to the outside of the tomb. Through this, it was found that the lintel stone is currently in the process of sagging behavior.

For the displacement analysis of the entrance arch in the Tomb of King Muryeong, the vertical and horizontal distances were calculated. This study compares the 3D data acquired in 2020 with the research data established in 2021 to review the behavior of the arch (Fig. 6). As a result, the entrance arch had a displacement between –0.11 to 0.09, and the average is −0.03 mm at 10 points appeared. But, both increase and decrease were observed depending on the point where the measurement was performed (Table 4).

Table 3. Results of displacement in lintel stone within the Tomb No. 5. Point numbers are the same as those of Fig. 5

Displacement (mm)										
H1	H2	H3	H4	H5	H6	H7	H8	H9	H10	Mean
−0.33	−0.41	−0.32	−0.49	−0.34	−0.54	−0.45	−0.24	−0.41	−0.45	−0.40
W1	W2	W3	W4	W5	W6	W7	W8	W9	W10	Mean
0.12	0.08	0.21	0.13	0.15	0.03	0.12	0.17	0.09	0.11	0.12

The vertical distance was analyzed to examine the behavior of the arch ceiling downward moving member. This also shows the increase and decrease of the distance between the members according to the point in the same way as the arch part. It can be estimated that actual behavior occurred in the entrance arch during this study period. However, considering that the accuracy of the 3D scanner used for precision scanning is 0.1mm, both analysis points show errors within the accuracy, which can be interpreted as not showing actual behavior.

Fig. 6. Measurement points for vertical and horizontal distances in entrance arch within the Tomb of King Muryeong. (A, B) 3D data acquired in 2020. (C, D) 3D data acquired in 2021.

Table 4. Results of displacement in entrance arch within the Tomb of King Muryeong. Point numbers are the same as those of Fig. 6

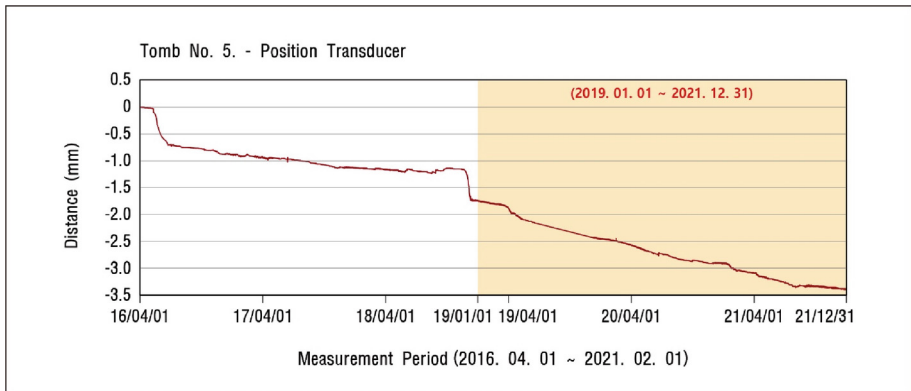| Displacement(mm)										
H1	H2	H3	H4	H5	H6	H7	H8	H9	H10	Mean
0.03	−0.09	-0.07	0.09	−0.05	−0.08	0.05	−0.06	−0.11	−0.03	−0.03
H11	H12	H13								Mean
0.04	−0.08	-0.10								−0.05

4 Discussion and Conclusion

In this study, to analyze the microscopic change of the Royal Tombs in Gongju, 3D precision scanning was performed to analyze deviation and displacement. An average of 95% appears within the allowable range at all analysis points set to tolerance range ±2 mm, and no damage is confirmed. However, it is possible that the set tolerance was larger than the deviation, so additional analysis was performed by narrowing the tolerance range to ±1 mm. As a result, an average of 93% was confirmed within the tolerance, and it is determined that no additional damage occurred. And it is interpreted that the actual behavior was not shown in the results of the displacement analysis on the arch of the Tomb of King Muryeong.

As a results of the displacement analysis, it was found that sagging occurred in the lintel stone of the Tomb No. 5, and it was estimated that the wall of the entrance was outward the tomb. The sag of the lintel stone that occurred during this study period tends to be like the results reported in 2019 (vertical direction; 0.40 mm sag, horizontal direction; about 0.32 mm outward) and 2020 (vertical direction; 0.32 mm sag, horizontal direction; 0.36 mm outward). Considering these results, it can be seen that the lintel stone of the Tomb No. 5 is sagging every year by a certain amount.

The sagging behavior of the lintel stone is also confirmed by the position transducer located at the entrance, during this study period, no rapid deflection displacement was found, but fine behavior appeared continuously (Fig. 7). When the results of displacement analysis through 3D scanning and the results of measuring instruments are analyzed together, it is discussed that sagging occurred in the lintel of the Tomb No. 5 during this study period.

Fig. 7. Diagram showing the displacement on position transducer of lintel in the Tomb No. 5.

The behavior of the wall can be checked through the behavior measurement sensor, but there is a limit to identifying the deformation with the naked eye because the behavior of the wall is minute. Therefore, displacement and deviation analysis were performed by constructing 3D shape data to visualize microscopic changes by selecting representative vulnerable parts for each tomb. The deviation was not visualized in both the tolerance

ranges $\pm$ 2 mm and $\pm$1 mm. In the displacement analysis, it is interpreted that behaviors do not occur inside the Tomb of King Muryeong, and the subsidence behavior of the lintel stone in the Tomb No. 5 was confirmed.

This unusual behavior was also found in the position transducer. Currently, the steel support supporting the lintel is corroded, and its strength is weakened, so it is judged that the bearing capacity should be restored through reinforcement or replacement. And if changes are identified through continuous monitoring of the same point and reviewed together with precise measurement monitoring data, it will be an essential primary data for evaluating the structural stability of the Tomb of King Muryeong and the Royal Tombs in Gongju.

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