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ORIGINAL ARTICLE

Behavioral characteristics and structural stability of the walls in the ancient Korean Royal Tombs from the sixth century Baekje Kingdom

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Abstract

The Royal Tombs at Songsanri have played considerable roles in the study of Baekje history since the Royal Tomb of King Muryeong was excavated, in untouched condition, in 1971. However, the stability of the Royal Tombs at Songsanri has been threatened by constant exposure to the external environment and infiltration by rainwater. In this study, behavioral monitoring of the walls was conducted using tilt sensors to obtain very precise data about the deformation of the structurally vulnerable walls, evaluate their behavioral characteristics and the influence of environmental changes on these behaviors, and diagnose the structural stability of the ancient tombs. In tomb no. 5, with the exception of relatively rapid behavioral changes attributed to the stabilization process of the tilt sensors, the walls remained stable. However, abnormal changes were observed at several positions in the walls of tomb no. 6 and the Royal Tomb of King Muryeong. These changes were attributed to environmental changes. Furthermore, the abnormal changes in the walls were found to coincide with increases in the soil water content due to rainfall and artificial environmental changes caused by the investigations in the tombs. These findings are expected to be useful in creating policies and designing countermeasures to preserve these historically and culturally valuable tombs.

Keywords Royal Tombs at Songsanri · Automatic measuring system · Behavioral monitoring · Environmental change · Displacement

Introduction

The Royal Tombs at Songsanri are located in Gongju, Republic of Korea, and are dated from 475 to 538 AD, during the Ungjin Period in the Baekje Kingdom. Among the tombs in Songsanri is the Royal Tomb of King Muryeong, which was discovered in untouched condition, excavated (Fig. 1), and studied to determine when it was constructed and confirm the identity of the dead that were entombed there. Of the several tombs uncovered from this historic period, this is the one for which the dead have been identified. Thus, the Royal Tomb of King Muryeong has become an essential landmark in the chronological order of the Baekje period and, accordingly, has been assessed as a precious component of the cultural heritage of the Korean Peninsula.

The Royal Tomb of King Muryeong and tomb no. 6 in Songsanri are brick-chambered tombs. The structures of the tombs imitate the style of the tombs from the Chinese Southern Liang Dynasty, providing evidence of close cultural exchanges with China. Additionally, tomb no. 6 contains murals of the Four Deities (the blue dragon of the east, the red phoenix of the south, the white tiger of the west, and the black tortoise of the north), which is the first discovered instance of wall painting on brick-chambered tombs in Korea. This tomb exhibits unique characteristics of the Baekje Dynasty, including construction techniques that were derived from the Southern Liang Dynasty of China.

Therefore, the Royal Tombs at Songsanri have been considered extremely important in archeological studies of East Asia. Furthermore, their historical and academic value has been widely recognized, notably by its designation as a world heritage site by the UNESCO. However, the tombs have suffered from instability due to exposure to the external

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Fig. 1 Photographs showing the excavation of the Royal Tomb of King Muryeong and the uncovered relics: **a** ceremony before the excavation in 1971 (Cultural Heritage Administration 1974). **b** Relics including the stone guardian and stone memorial tables for King Muryeong and his queen at the time of the excavation (Cultural Heritage Administration 1974). **c** Image of the stone memorial tablet for King Muryeong

environment, rainfall, and poor drainage since they were excavated. Leakage, microorganisms, and wall movement have been found. To mitigate the damage, the tombs were permanently closed in 1997; however, the problems with structural stability have intensified regardless.

Most conservation strategies rely on measuring and monitoring structural stability. In recent years, improvements to sensor technologies have facilitated the structural monitoring of many heritage buildings. Furthermore, behavioral monitoring is performed in heritage buildings to identify their structural characteristics and vulnerabilities (Binda et al. 2000; Lorenzoni et al. 2016; Saisi et al. 2016; Verstrynge et al. 2018; Addabbo et al. 2019). Such efforts ensure stable preservation and management of these buildings and help prevent future structural problems. Recently, an automated measurement system has been established to conduct real-time monitoring (Gentile et al. 2016; Basto et al. 2017; Hester et al. 2017; Saisi et al. 2017; Mesquita et al. 2018).

This behavioral monitoring can be used to identify early indicators of structural weakening in certain areas. Furthermore, behavioral monitoring data can be used to fuel research into conservation activities for heritage buildings (Burland et al. 1998; Jo and Lee 2014; Ubertini et al. 2016). However, previous studies have mostly focused on architectural heritage sites and monuments, exhibiting different structural and behavioral characteristics compared to tombs. Therefore, the present study represents the first investigation of the damage states of the Royal Tombs at Songsanri. Herein, we describe the behavioral monitoring conducted using an automated measuring system and the use of the obtained data to evaluate the structural stability of the tombs.

Sites of interest

The Royal Tombs at Songsanri include 20 tombs but only seven of them, including the Royal Tomb of King Muryeong, remain preserved as they are located about 120 m above sea level on the southern slope of Songsan. Tomb nos. 1–4 are arranged in a row approximately 20–30 m apart in the northeast section of a small valley. Tomb nos. 5 and 6 and the Royal Tomb of King Muryeong, the focus of the present study, are arranged in a triangle on the west side of the same valley (Fig. 2). The area locating the Royal Tombs at Songsanri belongs to Gongju basin comprising sedimentary rocks and has a large fault along the boundary between sedimentary rock and migmatitic gneiss on the geological map. In some places, basal conglomerate comprising breccia, agglomerate, and tuff is distributed.

Tomb no. 5 is a stone-chamber tomb built by gneiss with irregular shapes; however, material study of the gneiss has not been performed yet. Currently, the damage largely comprises structural cracks and shear fractures with several stones being dislocated by vertical deformation (Fig. 3a). In particular, the swelling phenomenon of the rock in the upper parts of the northern and south-western walls provides evidence of structural instability (Fig. 3b). The western and northern sides of the walls exhibit more physical damage than the rest do, such as cracking and separation of stones. Some stones of the northern wall even moved independently or fell due to the weakening of the structural support between adjacent stones.

Moreover, the large stone forming the entrance of the burial chamber exhibited considerable subsidence due to the concentrated load at the central part as well as cracks due to the concentration of tensile and frictional forces on the sides of the stone (Fig. 3c). Additionally, a large-scale structural crack can be observed at the base of the stone. To mitigate the structural instability, straight vertical steel supports were installed. However, they have since been corroded due to the moisture in the environment and those installed between the ground and structure are being deformed by the constant load.

Tomb no. 6 has a tunnel-type ceiling that includes a structure in the shape of an arc and a rectangular plane. This arch design is the most stable as it efficiently distributes the weight in the center to each end of the arch (Tóth et al. 2009;

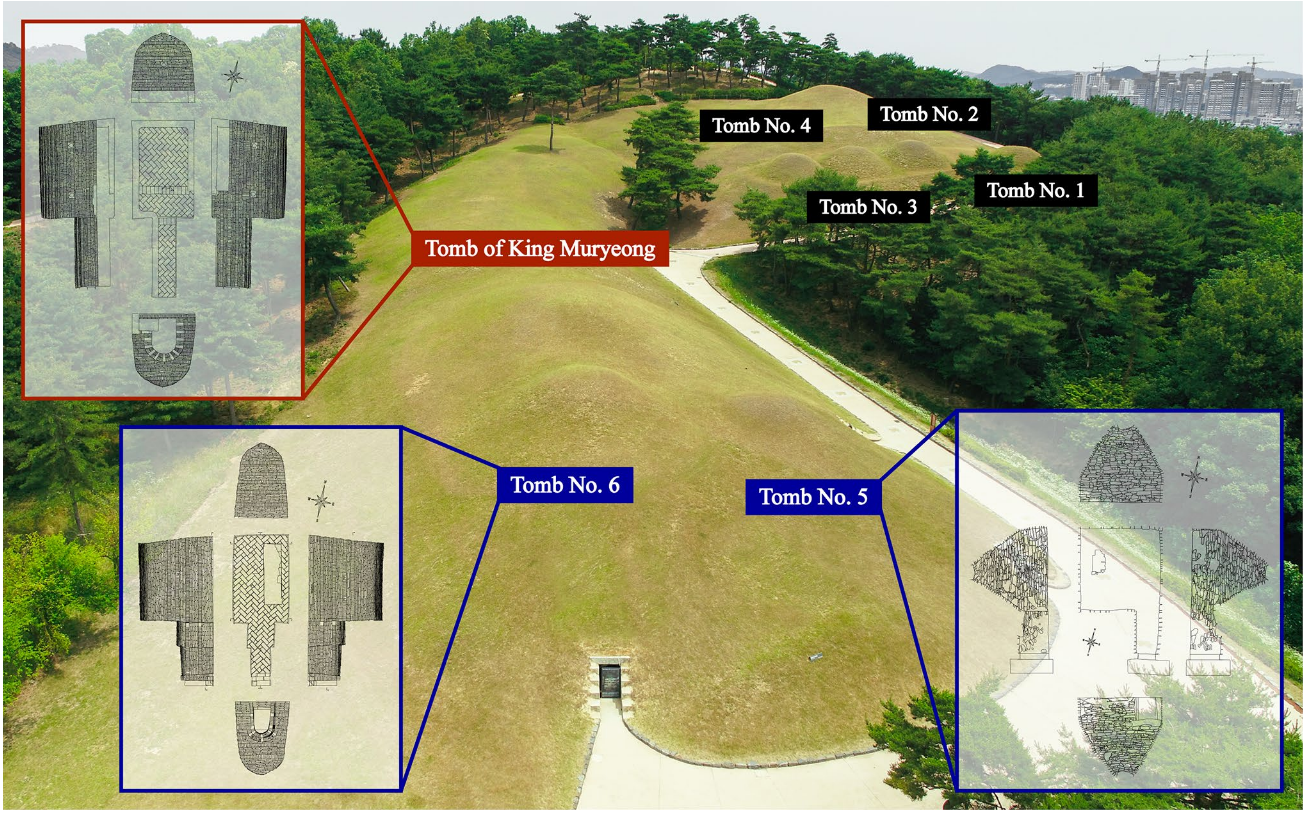


Fig. 2 Field images of the Royal Tombs at Songsanri in Gongju

Kim et al. 2012; Moreira et al. 2016). However, physical damage to the bricks and structural deformation appear to have occurred over the long period since its construction. The physical damage is concentrated in the ceilings of the burial chamber and the dromos (Fig. 3d). Furthermore, many horizontally placed bricks of the internal walls have numerous structural cracks and fractures and some of the vertically placed bricks that are stacked between front and back walls are irregularly arranged (Fig. 3e).

Unlike tomb no. 5 and the Royal Tomb of King Muryeong, there are paintings on the brick walls of this tomb (Fig. 3f). Unfortunately, all that remains of these wall paintings are unclear traces of white-colored paint on the background layer and this white-pigmented layer is undergoing a powdering process as the binder degrades. Thus, it is necessary to maintain proper environmental conditions to preserve these paintings. However, the high humidity within the tomb results in frequent condensation on the walls, which can accelerate the powdering of the bricks and base layers of the murals and exacerbate the damage. Additionally, it has been found that the moisture condensation can induce micro-movements, support the growth of micro-organisms, and corrode the nails, thereby discoloring the bricks.

The architecture of the Royal Tomb of King Muryeong has a central dromos style like tomb no. 6 and a tunnel-like ceiling with an arch structure. Compared with the others, the physical and structural damage in this tomb is more conspicuous than that in tomb no. 6, including cracking, fracturing, separation, and twisting. The horizontally placed bricks on all four walls exhibit significant physical damage in the form of cracks, fractures, and missing parts (Fig. 3g). Separation has occurred among many of the bricks, and some of the vertically placed bricks are slightly unstable and have begun to diagonally tilt owing to structural deformation.

Notably, it is believed that the bricks in the center of the ceiling of the dromos have shifted downward; three of these bricks have moved by up to 7 cm (Fig. 3h). In this tomb, bricks have been used to fill the empty spaces that were caused by separation and missing parts; however, most of them are no longer in contact with the adjacent bricks and, thus, do not provide proper support due to the severe extent of the deformation (Fig. 3i). Additionally, large-scale structural cracks can be seen in the floor bricks, resulting in separation between some of the bricks.

In case of the tomb no. 6 and the Royal Tomb of King Muryeong, lime, sand, and gypsum were used as materials of masonry joint (Han 2011), and, based on the bricks, various scientific analyses were conducted for closing the entrance. As a result, it was estimated that most bricks of the two tombs were made by firing the selected clays without

Fig. 3 Present status of the Royal Tombs at Songsanri (**a**–**c** tomb no. 5, **d**–**f** tomb no. 6, **g**–**i** Royal Tomb of King Muryeong): **a** structural cracks and fractures in the rock. **b** Swelling phenomenon on the west wall. **c** Subsidence of the large horizontal member due to loading. **d** Cracking, separation, and distortion concentrated on the ceiling. **e** Vertical bricks arranged unevenly. **f** Wall painting on the south wall (Vermilion Bird). **g** Cracks and fractures concentrated on the horizontal bricks. **h** Lack of dromos ceiling where it appears that the bricks moved downward. **i** Brick that is thought to have been inserted secondarily after being lost

macrocrystalline minerals (quartz and feldspar, etc.) at high temperature from 1000 to 1200 ℃. The rate of absorption and porosity of the bricks showed a wide distribution range from 1.02 to 16.30% and from 2.28 to 29.53%, respectively. Additionally, the ultrasonic velocity of the bricks was from 3000 to 5000 m/s (Jang and Lee 2013).

The bricks of the tomb no. 6 and the Royal Tomb of King Muryeong have different patterns, but it is assumed that the bricks were made using the same materials and manufacturing techniques because they have similar minerals, chemical compositions, and firing temperatures. However, the material characteristics of these bricks may be different from actual building materials (Jang and Lee 2013).

Materials and methods

In this study, an internal investigation was conducted based on preceding studies and records detailing the repair work in ancient tombs. The objective was to characterize precisely the condition and damage in tomb nos. 5 and 6 and the Royal Tomb of King Muryeong. Thus, tilt sensors were installed on the walls that appeared to be structurally unstable to monitor their micro-movements.

Currently, the tombs are closed permanently to the public and access is restricted even for research purposes. Therefore, an automatic measuring system comprising

Table 1 Tilt sensors installed in the Royal Tombs at Songsanri

Specification	T1	T2	T3	T4	T5	T6	T7
Position	Tomb no. 5		Tomb no. 6			Royal Tomb of King Muryeong	
	East wall	North wall	West wall	North wall	Ceiling	West wall	South wall

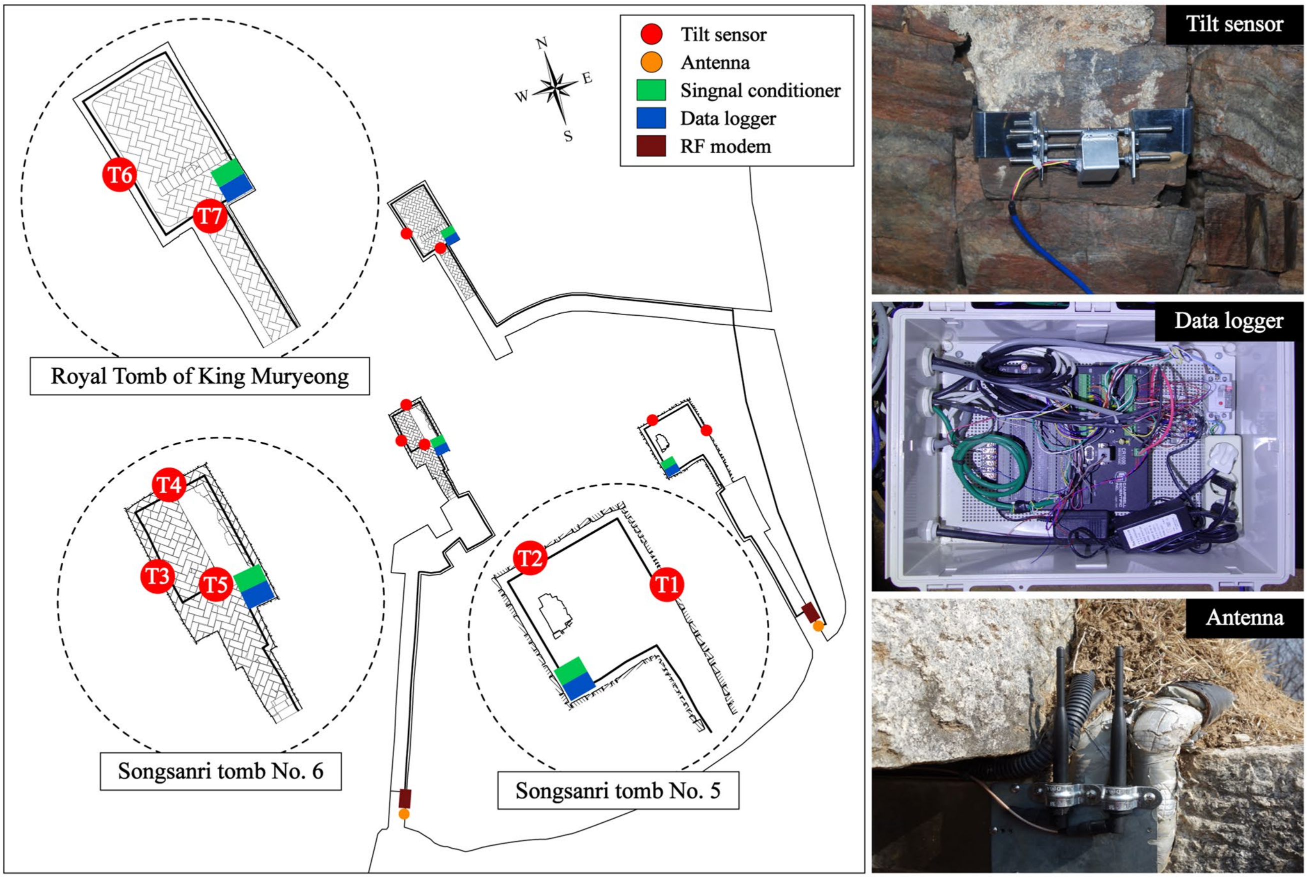


Fig. 4 Schematic diagram showing automatic measuring system installed Royal Tombs at Songsanri

sensors, data loggers, modems, and computers was utilized to monitor the tombs for 23 months from December 8, 2013 to November 8, 2015. To minimize the strain on the walls, seven small, lightweight, single-axis tilt sensors (Model 84053 Ceramic Sensors, Jewell Instrument Company) were installed, as specified in Table 1 and Fig. 4. Waterproof covers were made to protect the sensors from water damage. The displacement of the walls was measured in terms of tilt in toward the interior of the tomb (negative values) or out toward the exterior (positive values). The displacement of the ceiling of tomb no. 6 was measured along the east-to-west direction with positive values representing westward displacement and negative values representing eastward displacement.

Masonry structures, similar to those in the Royal tombs at Songsanri, are affected by environmental changes such as temperature, precipitation, and irradiation (Kumpel et al. 1988; Lee 1993; Suh and Park 1997; Roje-Bonacci et al. 2014; Masciotta et al. 2017; Ubertini et al. 2017; Ye et al. 2018; Kita et al. 2019). Therefore, in this study, environmental data were simultaneously collected with behavioral monitoring to analyze the effects of the external environment on the micro-movements of the structures. Additionally, the temporary environmental changes that occurred when investigators entered the tombs were compared with the micro-movements of the walls to identify the impacts of artificially created environmental changes on the structure.

Table 2 Annual maximum displacement of tomb no. 5

Sensors	Displacement (°)	Direction
5-T1	0.12	Inside
5-T2	0.04	Outside

Results and discussion

Annual changes and behavioral characteristics

Tomb no. 5

As Table 2 and Fig. 5 show, sensors 5-T1 and 5-T2 in tomb no. 5 reported rapid displacements toward the inside of the tomb during the initial stage of monitoring (tilts of 0.07° and 0.04°, respectively). However, the measurements stabilized gradually and the variation had ceased by the end of the study period. Sensor 5-T1, in particular, reported more displacement during the first month than during the subsequent 22 months combined. The tilt observed by sensor 5-T1 was consistently towards the inside of the tomb and the final displacement was approximately 0.12°. In contrast, the direction of the tilt measured by sensor 5-T2 varied, repeatedly alternating throughout the study period; however, the sensor reported a net outward tilt of approximately 0.04°.

The abnormal changes observed during the initial stage of the study period can be attributed to the stabilization process of the sensors and only the changed measured after the rapid initial changes were considered to be due to actual displacements in the structure. Thus, excluding the initial changes, each of 5-T1 and 5-T2 exhibited a minimal tilt in the range of 0.05° and 0.08° that remained constant despite external environmental changes.

To analyze the movements of the walls due to seasonal environmental changes, the abnormal movement data from the initial stabilization stage were excluded and only the data corresponding to actual movements after this initial period were considered. First, the data from sensor 5-T1 revealed that only gradual movements occurred toward the inside during all four seasons of the first year and no distinct behavioral differences were observed between the seasons. During the second year, movements to the inside were observed during the spring, autumn, and winter as in the first year; outward movement was only observed during the summer. Thus, considering that Korea has four distinct seasons and the environmental conditions differ significantly between the summer and winter, it can be concluded that sensor 5-T1 did not detect any seasonal changes.

Sensor 5-T2 generally detected outward movement but also regularly detected repetitive movements in both directions. In both the first and second years, outward movement was observed beginning in the spring, during the summer, and into autumn. Then, in autumn, the movements stabilized and there was a tendency toward inward movement.

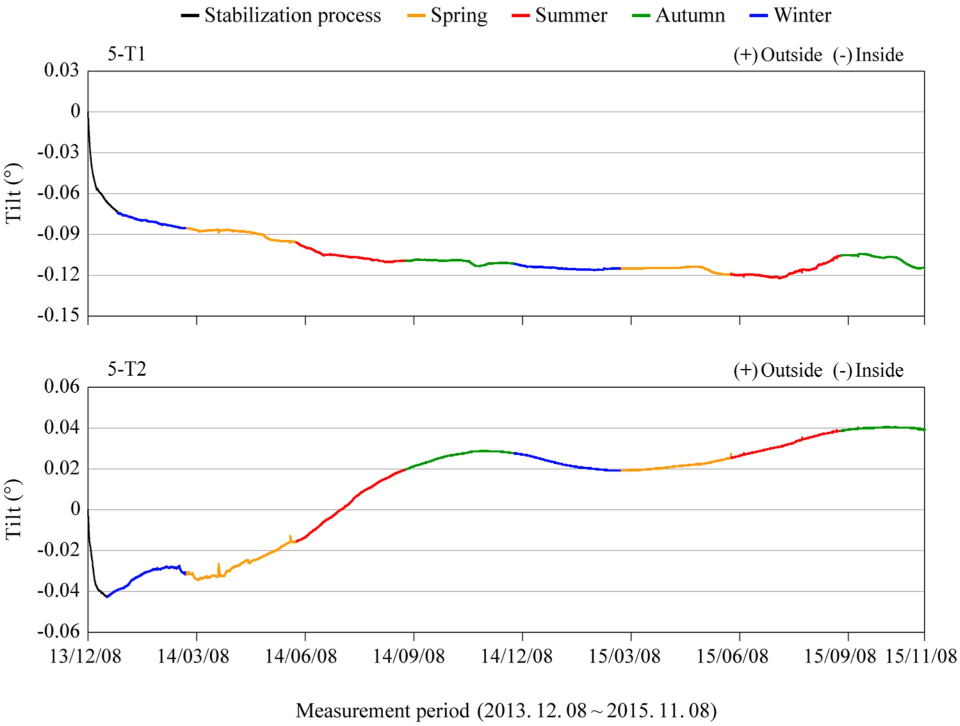


Fig. 5 Annual changes in tomb no. 5

Table 3 Annual maximum displacement of tomb no. 6

Sensors	Displacement (°)	Direction
6-T1	1.21	Inside
6-T2	1.07	Inside
6-T3	0.27	East

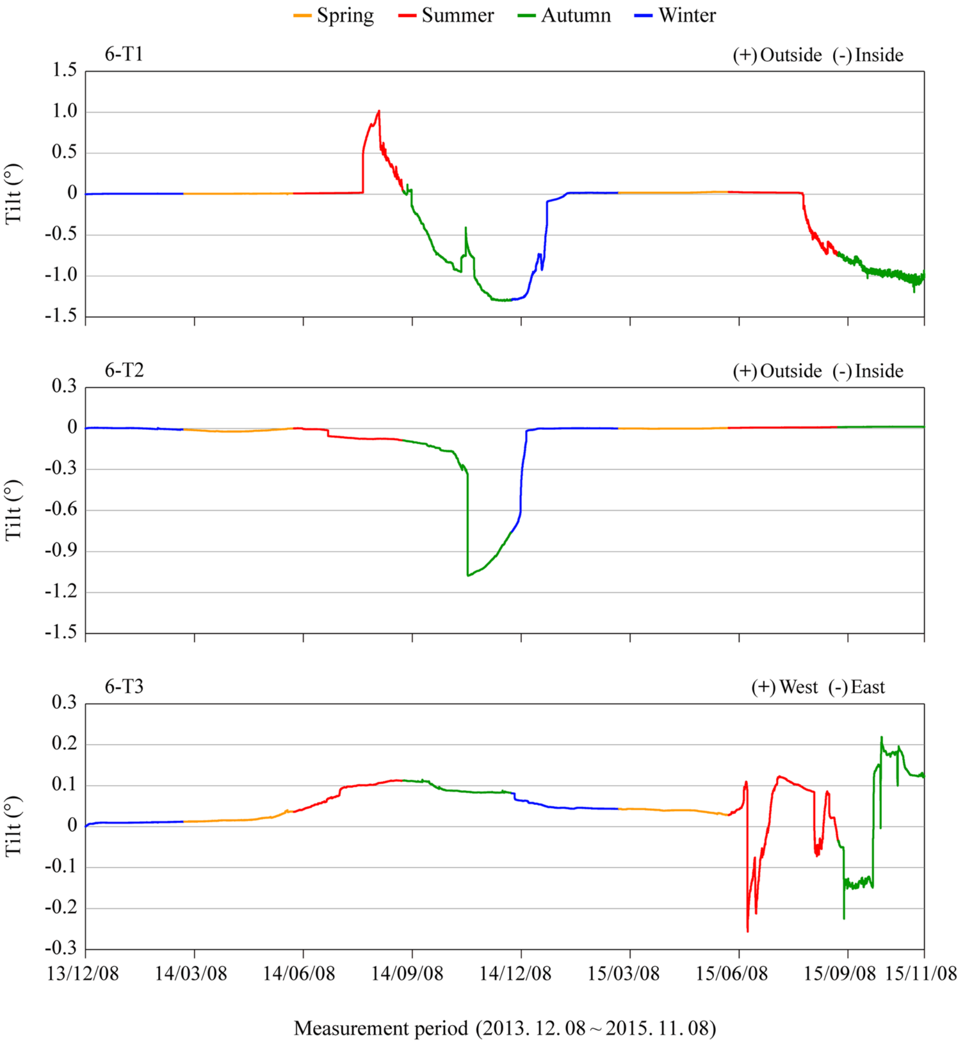
Different movement characteristics were observed in the winters of the first and second years. However, based on these findings, it can be considered that the movement of the wall on which sensor 5-T2 was installed is affected by seasonal environmental changes.

Tomb no. 6

As Table 3 and Fig. 6 show, the walls of tomb no. 6 exhibit numerous abnormal movements. In particular, sensors 6-T1 and 6-T2 detected regular movements within a tilt range of 0.03° but also large movements exceeding 1.07° in periods of contrasting movement characteristics (herein referred to as abnormal periods). Sensor 6-T1 detected two periods of abnormal changes; the first such period involved tilts of over 2.37° and, of the seven sensors used in this study, exhibited the greatest difference in movement behavior compared with the period of normal movement. Similarly, sensor 6-T2 detected only micro-movements during the first six months of the study period but later detected rapid inward movements with significant displacement of 1.07°. However, the wall on which sensor 6-T2 was placed returned to its initial position more quickly than that on which sensor 6-T1 was placed and the net movement was small (within 0.03°) thereafter with no further evidence of abnormal movement.

Sensor 6-T3, which was installed on the ceiling of the tomb, revealed different movement characteristics compared with those of the walls. In the periods during which sensors 6-T1 and 6-T2 detected large movements (i.e., tilts of over 1.07°), the ceiling maintained a relatively stable position, exhibiting displacement of only 0.11°. However, there was an abnormal period, with a maximum displacement of 0.27°,

Fig. 6 Annual changes in tomb no. 6



during the second year, during which sensor 6-T3 detected repetitive movements in the east and west directions. However, by the end of the study period, the net displacement measured by sensor 6-T3 was small due to repetitive movements towards its original position; they may indicate structural damage, because such abnormal movements were only observed during the second year (and not the first).

Of the sensors that were installed in tomb no. 6, the movements detected by sensor 6-T1 corresponding most closely to seasonal changes. In both years of the study period, the measurements were very stable throughout the spring season but were abnormal from summer and until autumn. However, the wall appeared to return to its initial position during the winter of the second year and remained stable thereafter. In the winter of the first year, the wall position was stable from the beginning of monitoring process; thus, it can be deduced that the abnormal movements had already occurred and that the wall had reverted to a stable position before the study period. Based on this pattern of movement, the abnormal movements during the summer can be attributed to heavy rainfall, increasing the water content in the soil that exerts an external force and results in the observed movements of the walls.

The measurements obtained from sensor 6-T2 in the first year were similar to those obtained from sensor 6-T1. Sensor 6-T2 recorded a large displacement, indicating instability; however, the tilt returned to its original state and was stable thereafter. However, in the second-year, such abnormal movements in the summer and autumn did not occur, indicating that the wall was consistently stable during this year. This difference can be attributed to the difference in the amount of rainfall in the first and second years.

Compared with the other sensors, sensor 6-T3 detected a relatively small amount of displacement during the first year; however, there was still evidence that the movement of the ceiling was affected by seasonal changes. The measurements indicating that the ceiling was stable in the winter and spring (with only minor movements in the sprint) but underwent abnormal movements in the summer and autumn; this behavior was observed in both years of the study period but was more prominent during the second year.

Royal Tomb of King Muryeong

As Table 4 and Fig. 7 show, the two sensors installed in the Royal Tomb of King Muryeong recorded very similar movement characteristics, including clearly distinct alternating stable and abnormal periods. Sensor M-T1 recorded only minor movement (tilt within 0.02°) for about six months but later underwent rapid and large movements toward the

Table 4 Annual maximum displacement of Royal Tomb of King Muryeong

Sensors	Displacement (°)	Direction
M-T1	1.11	Inside
M-T2	0.98	Inside

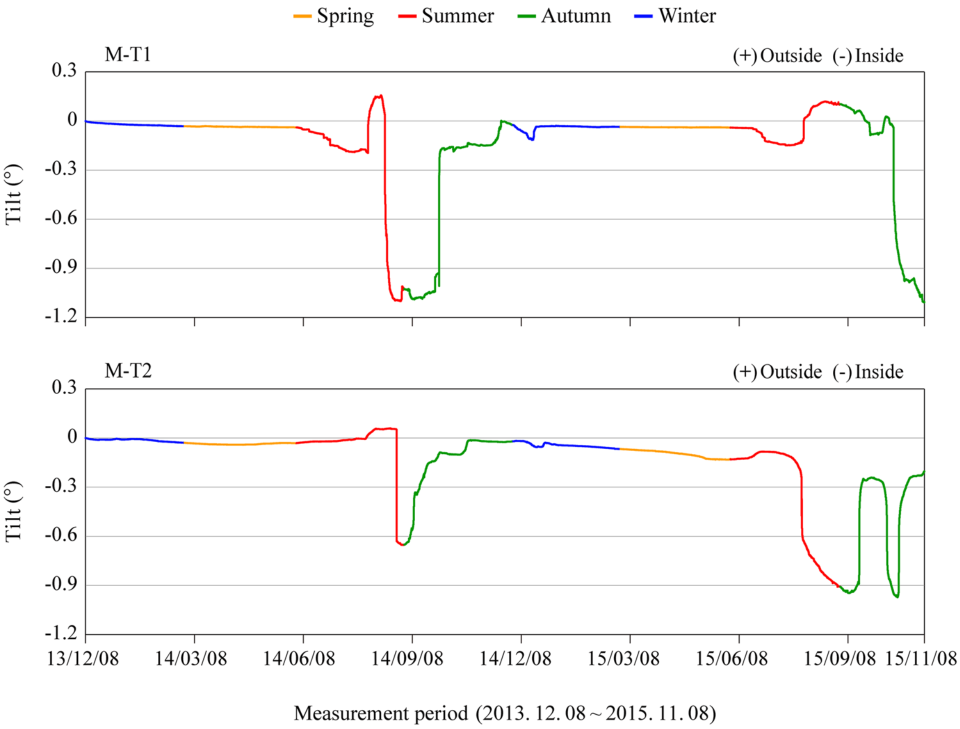


Fig. 7 Annual changes in the Royal Tomb of King Muryeong

interior (up to 1.11°) and exterior (up to 0.16°) of the tomb. Then, this wall returned to its initial state and remained stable for another six months, before another period of abnormal movement (over 1.10°) near the end of the study period.

The measurements from sensor M-T2 revealed a relatively unstable condition in the second year, characterized by abnormal movements with a maximum displacement of 0.18° more than that in the first year. While in the first year period, the wall quickly reverted to its original position following the period of abnormal movements, there were two periods of abnormal movements in a short period of time during the second year, indicating significant instability.

The movement of the walls of the Royal Tomb of King Muryeong closely reflected the seasonal changes. Specifically, the readings from sensors M-T1 and M-T2 exhibited clearly distinguishable variation patterns following the seasons in both years of the study period. The measurements indicated that the walls were stable in the spring when the monitoring began, underwent abnormal movements occurred starting in the summer, indicating instability, then returned to the original state and showed signs of recovery in autumn.

These tendencies observed by sensors M-T1 and M-T2 reflected those of sensor 6-T1 in tomb no. 6. However, unlike the wall on which sensor 6-T1 was installed, which returned to its original state in the winter, the walls with sensors M-T1 and M-T2 exhibited abnormal movement during the winter of the second year with displacements within 0.10° followed by relative stability until the spring. Additionally, there was another period of instability (indicated by a reoccurrence of abnormal movements) from the beginning of the summer until the following autumn. The wall on which sensor M-T2 was installed had reverted to its original position by the end of the study period although that on which sensor M-T1 was installed had not. However, as noted for the ceiling in tomb no. 6 (monitored by sensor 6-T3), these abnormal behaviors may be due to structural damage; therefore, constant monitoring is highly recommended.

Behavioral characteristic corresponding to environmental changes

Rainfall and soil water content

When there is heavy rainfall, the water content in the soil surrounding the tomb increases as water flows into the soil inside the burial mound. This results in changes in the external forces on the tomb, such as the compression pressure, external soil pressure, and internal stress. It was concluded that such changes can induce micro-movements in the walls of tombs. Therefore, the results were examined further to determine if the movement characteristics of each tomb wall correlate with the rainfall and soil water content.

Table 5 Maximum displacements of the stable section of the Royal Tombs at Songsanri and the section that was unstable due to rainfall

Tombs	Sensors	Stable section (°)	Unstable section (°)
Tomb no. 5	5-T1	0.02	0.02
	5-T2	0.03	0.04
Tomb no. 6	6-T1	0.02	2.37
	6-T2	0.03	1.07
	6-T3	0.04	0.48
Royal Tomb of King Muryeong	M-T1	0.02	1.27
	M-T2	0.11	0.98

As Table 5 and Fig. 8 show, tomb no. 5 remained stable even when the soil water content increased rapidly due to the concentrated heavy rainfall during the summer. On the other hand, tomb no. 6 and the Royal Tomb of King Muryeong exhibited abnormal changes and tended to be very unstable during this period. Particularly for the abnormal sections (corresponding to two of the sensors in the Royal Tomb of King Muryeong, M-T1 and M-T2), the changes generally coincided with increases in the soil water content exceeding 20% and the movement continued until the soil water content returned to normal.

Regarding tomb no. 6, abnormal changes indicating instability occurred due to the heavy rainfalls in the summers of both years of the study period (sensors 6-T1 and 6-T2 in the first year and sensors 6-T1 and 6-T3 in the second year). In particular, sensor 6-T1 recorded abnormal changes in both years and extreme changes of over 2.37° in the first year. The abnormal changes (inward and outward movements) at sensor 6-T3 began when the soil water content decreased before the concentrated rainfall in the second year and continuing until the end of the study period. Similarly, the abnormal movements recorded by sensor 6-T2 occurred as the soil water content decreased after rainfall.

Such periods of abnormal behaviors persisted even after the rainy season. Thus, it can be inferred that these changes are because of the remaining internal pressure on the walls, which can affect the micro-movements despite the fact that the soil was completely dehydrated; this implies that the external forces applied to the tomb change even during the dehydration of the soil.

Artificial environmental changes

Relatively fixed temperature and humidity levels have been maintained inside tomb no. 5, tomb no. 6, and the Royal Tomb of King Muryeong. However, it was observed that the interior temperature temporarily increased when the investigators entered into the tombs and the magnitude of the temperature change was correlated with the number of

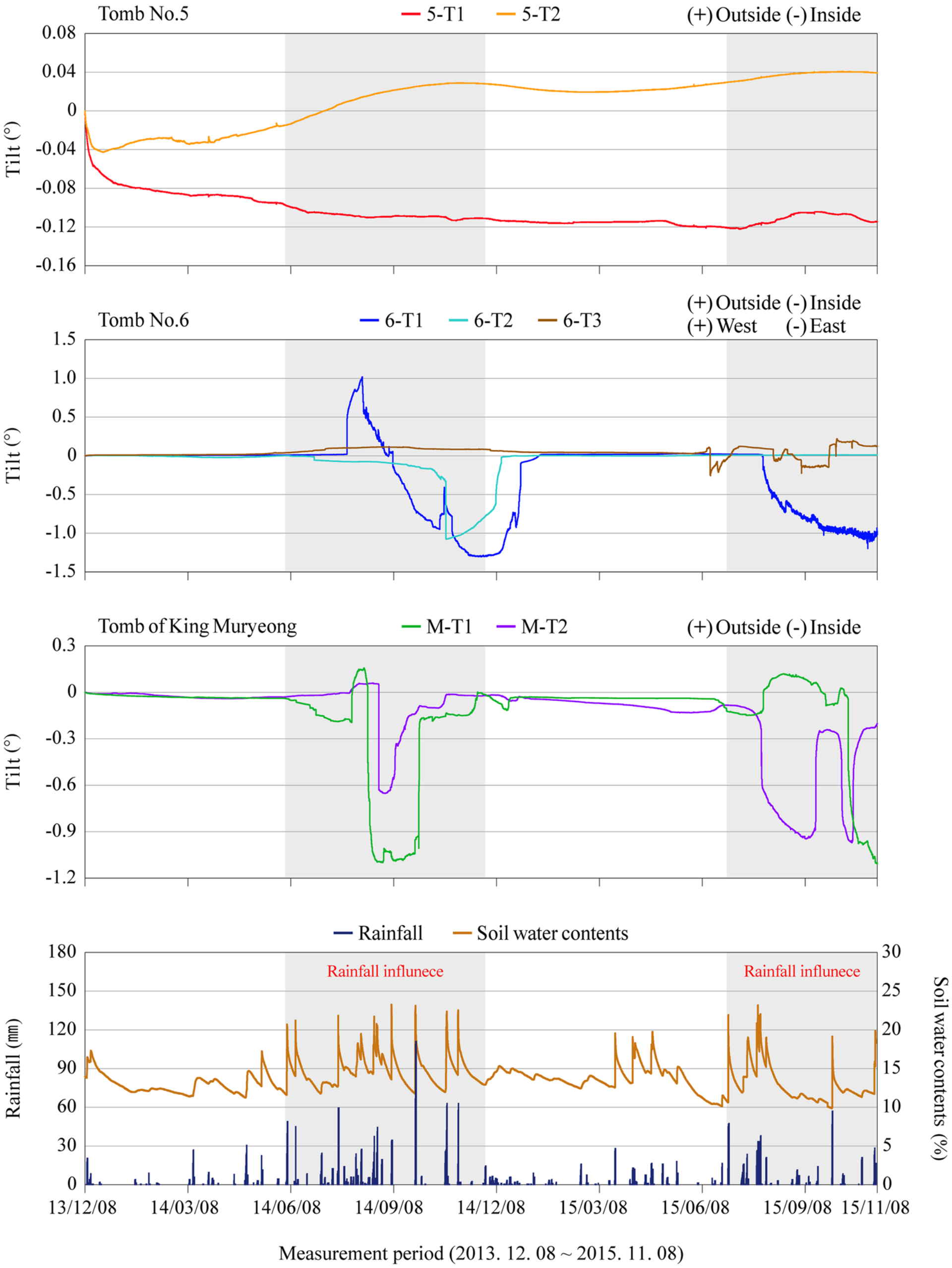


Fig. 8 Behavioral characteristics attributed to rainfall

people that entered and how long they remained. Therefore, to identify the effects of the artificial environmental changes on the micro-movements of walls, a detailed analysis was conducted to characterize the differences in the sensor readings before and after the investigators entered the tomb.

As Fig. 9 shows, abnormal movements were observed on February 6th and May 12th of 2014 in both tomb no. 6 and the Royal Tomb of King Muryeong when investigators entered the tombs. The movements stabilized as the internal temperature decreased after the investigation was complete and most measurements returned to their previous values. However, some sensors detected permanent changes following the artificial activity but the displacement was very minimal. However, some of the movement and internal temperature data were not collected due to errors in the sensors in tomb no. 5; yet, it can be assumed that the movement characteristics were similar to those in tomb no. 6 and the Royal Tomb of King Muryeong.

The displacement due to abnormal movements did not always correlate with temperature increases and, thus, may have taken place due to various reasons other than temperature changes, such as air pressure change and micro-vibration, which simultaneously occurred. Thus, because artificial environmental changes not only affect the environment of the tombs but also the micro-movements of the walls, it is

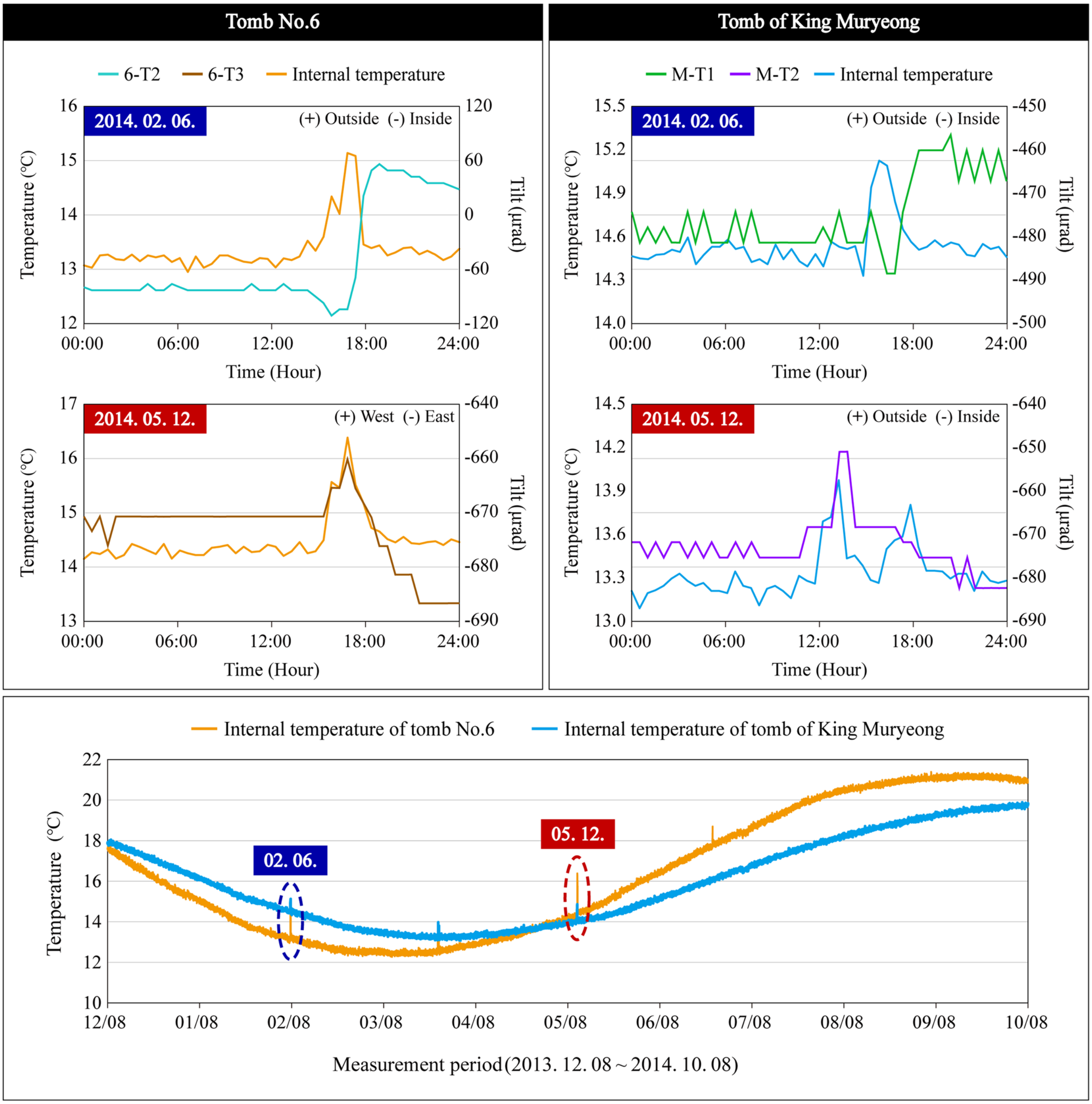


Fig. 9 Changes in tomb no. 6 and the Royal Tomb of King Muryeong corresponding to artificial environmental changes

recommended that access to the tombs be minimized for maintenance and research purposes.

Conclusion

This study was conducted to examine the structural stability of the royal tombs at Songsanri using tilt sensors to precisely monitor the micro-movements because of structural damage and environmental changes, including rainfall and human activity. The results of the behavioral monitoring of the walls of three tombs for 23 months revealed that only small displacements occurred in tomb no. 5 (0.12° for sensor 5-T1 and 0.04° for sensor 5-T2) but larger displacements occurred in tomb no. 6 (1.32°, 1.07°, and 0.27° for sensors 6-T1, 6-T2, and 6-T3, respectively) and the Royal Tomb of King Muryeong (1.11° and 0.98° for sensors M-T1 and M-T2, respectively). Among these, sensors 6-T1, 6-T2, M-T1, and M-T2 detected abnormal movements during periods of concentrated heavy rainfall, characterized by movements over wide ranges of 2.37°, 1.07°, 1.27°, and 0.88°, respectively.

Based on a comprehensive analysis of the measurements, it was concluded that tomb no. 5 was relatively stable despite various environmental changes. However, some of the walls of the Royal Tomb of King Muryeong and tomb no. 6 were found to be unstable during periods of rainfall and seasonal changes, indicating that they are susceptible to changes in external forces and, thus, are structurally vulnerable. Additionally, extensive physical damage to the bricks in tomb no. 6 and the Royal Tomb of King Muryeong have caused problems with structural stability.

To minimize the increase in soil water contents and loads of the mounds due to rainfall, the rain cover could be installed as a temporary expedient. However, the rain cover should be installed in a very wide range, which requires enormous budget and labor. The rain cover is also not a suitable method considering the long-term preservation and views of the World Heritage. Thus, precise and detailed investigations from a structural engineering perspective should be performed to mitigate further damage to the bricks of tomb no. 6 and the Royal Tomb of King Muryeong and recover the structural stability.

Tomb nos. 5 and 6 and the Royal Tomb of King Muryeong are located near a small valley to the west and oriented parallel to the valley. If the soil from the burial mounds slides down the slope due to heavy rainfall every summer and the load on the tomb walls decreases, these walls may move outward. Accordingly, if the behavior of the walls closest to the valley continues for a long time, it may cause stability problems across the entire structure. In particular, the layer of soil over the east wall of tomb no. 5, which is closest to the valley, is thinner than elsewhere over the chamber; thus, this tomb is expected to have the greatest instability. Therefore, continuous monitoring should be conducted and comprehensive maintenance plans should be put in place to ensure long-term preservation in the years to come.

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