Displacement Analysis of Five-Story Stone Pagoda in Geumgolsan Mountain, Jindo, Using Terrestrial Laser Scanning

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Abstract

Background/Objectives: This study focuses on a three-dimensional digital documentation and displacement analysis to evaluate the structural stability of a five-story stone pagoda in Geumgolsan Mountain, Jindo, and using terrestrial laser scanning.

Methods/Statistical analysis: A field scan was conducted using a digital inclinometer with 0.01° precision to establish the absolute horizontal and vertical directions of the stone pagoda. Point clouds were then acquired from a three-dimensional terrestrial laser scan and restored as digital heritage via registering and merging the data, filtering the data, and constructing a polygon model to calculate the structural displacement of the stone pagoda.

Findings: The results revealed that the stone pagoda had moved to the north by 24.6–69.5 mm and to the east by 35.3–179.2 mm. The central displacement of the stone pagoda was between 24.3 and 174.2 mm toward the northeast. Overall, the stone pagoda exhibited a large displacement to the east and a rapid deformation between the third and fourth stories owing to the gaps, cracks, and distortion of the stone members, the loss of the gravel-reinforced foundation, and the weathering of supports.

Improvements/Applications: The results of this study will be utilized to monitor the structural change process of the stone pagoda over time. Monitoring of structural deformation via periodic terrestrial laser scanning is required to conserve the original forms of the five-story stone pagoda in Geumgolsan Mountain.

Keywords: Displacement Analysis, Digital Documentation, Five-story Stone Pagoda in Geumgolsan Mountain, Structural Stability Evaluation, Terrestrial Laser Scanning System

1. Introduction

Architectural heritage can develop structural problems over time through pressures such as the decreasing durability of members, external shocks, and artificial damage. Structural deteriorations of architectural heritage can be observed in the case of stonemasonry heritage such as pagodas. Monitoring the structural response to these pressures is important as it increases the capacity for a long-term stable conservation of this heritage. The technology to obtain static and dynamic measurements using advanced sensors and image-based methods is available. These methods are widely used to obtain monitoring data.

This technology is capable of obtaining measurements using sensors that enable real-time monitoring with high precision. There are some limitations, however, because relatively complex wired and wireless networks are required to collect data and installing the system in sites with poor accessibility is difficult. Despite this, image-based methods can simultaneously analyze a wide range of data and are appropriate for periodic monitoring of the macroscopic deformation of a heritage structure. One of the most widely used image-based monitoring technologies is terrestrial laser scanning.

This approach has mainly been utilized for three-dimensional reverse engineering and digital documentation of cultural heritage. More recently, its application has expanded to the field of conservation to enable the virtual restoration of missing parts of structures and the detailed monitoring and evaluating of the deterioration...
and conservation of cultural heritage\textsuperscript{2,3,9}. In particular, terrestrial laser scanning has been used to optimize the application of displacement analysis to architectural heritage\textsuperscript{10}. This approach is used to minimize the impact of environmental influences on data collection. It also has the capacity to obtain three-dimensional geometric information for entire structural shapes.

This study focuses on the three-dimensional digital documentation and displacement analysis of the structurally unstable five-story stone pagoda in Geumgolsan Mountain, Jindo, and using terrestrial laser scanning. Horizontal, central, and plane displacements were analyzed to evaluate the overall structural stability of the stone pagoda. The results of this study will be evaluated over time to periodically monitor the deterioration and conservation change processes of the stone pagoda.

2. Research Object

The five-story stone pagoda (Korean Treasure No. 529) in Geumgolsan Mountain, Jindo, is representative of cultural heritage from the end of the Goryeo dynasty (10\textsuperscript{th} to 14\textsuperscript{th} century) in Korea (Figure 1a). The pagoda comprises a low foundation region and a high first body stone. The stone pagoda is composed of lithic tuffs that have weaker physical properties than granites, and the pumice from the original rock surface has been lost (Figure 1b).

In addition to this, the stone pagoda has experienced physical and structural deteriorations such as cracking, blistering, scaling, gap formation, discoloration, and biological colonization. Foundation sections have accelerated surface deterioration with 3 to 5 layers of blistering and scaling. Iron and manganese hydroxides are distributed on the surface weathering layers (Figure 1c).

For example, the first body stone in particular is highly deteriorated with gaps between members, cracks developed along the bedding, and nearly 100% microorganism colonization (Figure 1d). The inside of the first body stone is structurally unstable owing to the absence of a gravel-reinforced foundation. Moreover, severe weathering of lithic tuffs, used between the stone members for support, has induced structural deformation of the stone pagoda (Figure 1e).

3. Methodology

3.1 Equipment and Software

Terrestrial laser scanning technology comprises a three-dimensional scanner and post-processing software. The operation of the scanner (Leica, HDS3000) is based on the time-of-flight of a laser pulse. The laser light pulse is projected on a surface and the reflected beam is collected on the scanner's sensor. The time-of-flight of the laser between its emission and reception provides three-dimensional geometrical information of the object's surface. The scanner used for this study has a maximum scan speed of 4,000 points per second and accuracy of 6 mm (position) and 4 mm (distance).

The post-processing of the scanned data was conducted using three software packages: Cyclone (3-D point cloud processing software), Geomagic Studio (3-D reverse engineering software), and AutoCAD (Computer-Aided Drawing software). Cyclone was used to control the three-dimensional scanner and registering and merging the acquired point clouds. Geomagic Studio was used to complete digital heritage by converting the merged point clouds to a polygon model. Finally, the structural displacement of the stone pagoda was determined using AutoCAD.

3.2 Field Scan

A field scan of the stone pagoda was conducted by dividing it into lower and upper sections. The lower section of the stone pagoda was scanned from eight stations using a tripod. The upper section was scanned from four stations using a movable scaffold and the roof of a surrounding building (Figure 2a). After installing the three-dimensional scanner at the scan station, the scanner's level and plumb were adjusted using a hand-operated spirit level (Figure 2b).
The adjustment process of the scanner has the potential to cause coordinate deformation with respect to the gravity vector, and deformed coordinates can be reflected in data post-processing. Although an unbalanced post-processing result is a significant factor, it is not as significant a problem for digital heritage as it is for actual structures. The absolute horizontal and vertical geometry still should be considered as important for precise displacement analysis. The absolute horizontal and vertical directions of the stone pagoda were determined during the field scan using a digital inclinometer with 0.01° precision (Figure 2c).

3.3 Data Post-Processing

Point cloud data acquired from the three-dimensional scanner in the field were utilized in various measurement and analysis methods after completing the digital restoration of the data through a series of post-processing methods. Shape registering was conducted by selecting at least three common corresponding points from each point cloud. Following this, all registered point clouds were merged to complete one object model (Figure 3a). The model was then adjusted to the absolute horizontal and vertical axis based on the digital inclinometer scanned with the stone pagoda (Figure 3b).

The merged model is the only point data aggregation of the same shape compared with the original form of the stone pagoda without forming the faces. Accordingly, polygon mesh modeling was developed by converting three adjacent vertices into triangular faces (Figure 3c). The polygon model of the five-story stone pagoda in Geumgolsan Mountain was completed after filling the holes of non-scanned parts, as shown in Figure 4. This study then conducted displacement analysis to evaluate structural stability of the stone pagoda using the constructed polygon model.

4. Displacement Analysis

4.1 Horizontal Displacement

The horizontal displacement of the stone pagoda was determined through the west elevation indicating the south-north direction and the north elevation indicating the east-west direction. For this, an absolute vertical line was constructed based on the center of gravity of the foundation section. Tilt angles and displacements were then calculated by analyzing the displacement differences between the center of gravity of each body stone and the absolute vertical line.

The horizontal displacements in the south-north direction using the west elevation revealed that all members moved to the north. The first body stone had a tilt angle of 0.99° and was horizontally displaced by 26.6 mm. The second body stone had a tilt angle of 0.64° and a displacement of 32.3 mm. The third body stone, 0.72° and 47.7 mm; 0.43° and 33.6 mm for the fourth; 0.77° and 69.5 mm for the fifth; and 0.29° and 29.5 mm for the final upper stone. In general, the tilt angles and displacements increased with the height of the stone pagoda (Figure 5a, Table 1).
The results for tilt angles and horizontal displacements in the east–west directions using the north elevation revealed that all members moved to the east. The tilt angle and displacement was 1.45° and 35.3 mm on the first body stone, 1.59° and 79.5 mm on the second body stone, 1.42° and 93.3 mm on the third body stone, 1.78° and 137.1 mm on the fourth body stone, 1.78° and 160.0 mm on the fifth body stone, and 1.76° and 179.2 mm on the final upper stone. The overall displacements were significantly higher than the ones in south–north directions. Rapid displacement was observed in particular between the third and fourth stories. Overall, the stone pagoda moved to the north by 24.6 to 69.5 mm and to the east by 35.3 to 179.2 mm (Figure 5b, Table 1).

4.2 Central Displacement

The central displacement of architectural heritage is determined using a plane rather than an elevation. In the case of a stone pagoda, the reliability of the result for the central displacement increases by using a body stone resembling a square. The body stone cannot be observed in the plane view, however, as it is smaller than the roof stone. Accordingly, section planes of the body stone and the foundation section needed to be created through the use of reverse engineer-

4.3 Plane Displacement

The five-story stone pagoda in Geumgolsan Mountain was observed to be structurally unstable owing to the overall distortion of its members. Plane deformation of the stone pagoda was analyzed by determining the plane angle and displacement for each story calculated with reference to the foundation section. For this, the absolute horizontal lines were drawn on the south faces of the section planes.

The displacement analysis determined that all members had rotated to the northeast, with a plane angle of 0.73° and displacement of 11.68 mm on the first body stone, 2.33° and 29.90 mm on the second body stone, 2.71° and 93.3 mm on the third body stone, 1.78° and 137.1 mm on the fourth body stone, 1.78° and 160.0 mm on the fifth body stone, and 1.76° and 179.2 mm on the final upper stone. The overall displacements were significantly higher than the ones in south–north directions. Rapid displacement was observed in particular between the third and fourth stories. Overall, the stone pagoda moved to the north by 24.6 to 69.5 mm and to the east by 35.3 to 179.2 mm (Figure 5b, Table 1).

Figure 5. Horizontal displacement analysis of the stone pagoda. (a) Tilt angles and displacements of the south–north directions using the west elevation and (b) The east–west directions using the north elevation.
Table 1.  Horizontal tilt angles and displacements of the stone pagoda

| Location  | South-north displacement | East-west displacement |
|-----------|--------------------------|------------------------|
|           | Direction | Tilt angle | Displacement | Direction | Tilt angle | Displacement |
| 1st story | North     | 0.99º      | 24.6 mm       | East      | 1.45º      | 35.3 mm      |
| 2nd story | North     | 0.64º      | 32.3 mm       | East      | 1.59º      | 79.5 mm      |
| 3rd story | North     | 0.72º      | 47.7 mm       | East      | 1.42º      | 93.3 mm      |
| 4th story | North     | 0.43º      | 33.6 mm       | East      | 1.78º      | 137.1 mm     |
| 5th story | North     | 0.77º      | 69.5 mm       | East      | 1.78º      | 160.0 mm     |
| Upper final | North | 0.29º      | 29.5 mm       | East      | 1.76º      | 179.2 mm     |

Figure 6. Central and plane displacements of the stone pagoda. (a) Central displacement of each story based on the center of gravity of the section planes. (b) Plane angles and displacements on each story based on the foundation part.

Table 2. Azimuths and displacements of the center of gravity of each story

| Location   | Displacement     | Vector |
|------------|------------------|--------|
|            | South-north direction | East-west direction | Azimuth | Displacement |
| 1st story  | 0.2 mm           | 24.3 mm          | 89.5º   | 24.3 mm      |
| 2nd story  | 2.8 mm           | 62.5 mm          | 87.4º   | 62.5 mm      |
| 3rd story  | 14.2 mm          | 82.9 mm          | 80.3º   | 84.1 mm      |
| 4th story  | 1.5 mm           | 120.6 mm         | 89.3º   | 120.6 mm     |
| 5th story  | 30.5 mm          | 151.7 mm         | 78.6º   | 154.7 mm     |
| Upper final| 0.1 mm           | 174.2 mm         | 89.9º   | 174.2 mm     |

and 29.6 mm on the third body stone, 3.16º and 31.7 mm on the fourth body stone, and 4.56º and 34.1 mm on the fifth body stone. In general, plane angles and displacements increased with the height of the stone pagoda and the most rapid deformation occurred in the fifth body stone. The overall displacement direction corresponded to the horizontal and central displacements of the stone pagoda (Figure 6b).
5. Discussion and Conclusion

A three-dimensional reverse engineering and digital documentation of a five-story stone pagoda in Geumgolsan Mountain was conducted using terrestrial laser scanning technology. The results of this study were analyzed to determine horizontal, central, and plane displacements due to deterioration pressures on the pagoda and conduct an evaluation of the structural stability of the architectural heritage. The stone pagoda showed a maximum structural deformation of 179.2 mm in the elevation and 174.2 mm in the section plane. This is attributed to the gaps, cracks, and distortions observed in the stone members through the loss of gravel-reinforced foundation, and weathered supports. The stone pagoda showed a large displacement to the east and a rapid deformation was detected between its third and fourth stories.

The results of this displacement analysis are comparable with those of similar studies at the five-story stone pagoda of Magoksa Temple[10] and the multi-story stone pagoda of Daewonsa Temple[11]. Displacement analysis through three-dimensional reverse-engineering and digital restoration using terrestrial laser scanning was also conducted. The maximum values of the horizontal displacement for the five-story stone pagoda in Geumgolsan Mountain showed far greater tilt angle and displacement than the other two stone pagodas.

The five-story stone pagoda of Geumgolsan Mountain was structurally unstable because it is composed of single members with the exception of the foundation section and the first body stone. Each member observed had a high degree of weathering and weak physical properties. Moreover, it was determined through the results of monitoring using a tilt meter that the stone pagoda had been progressively showing signs of deterioration[12]. The dismantling and restoration of the stone pagoda was completed using the results of various scientific investigations including the results of the displacement analysis, and the structural stability of the stone pagoda was significantly improved. Continued periodic monitoring of the structural deformation using terrestrial laser scanning is required for the continued conservation of the original forms of the five-story stone pagoda in Geumgolsan Mountain.

6. Acknowledgments

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7. References

1. Jo YH, Lee CH, Chun YG. Material characteristics and deterioration evaluation for the 13th century Korean stone pagoda of Magoksa temple. Environmental Earth Sciences. 2012; 66:915–22.
2. Burland JB, Jamilowski M, Viggiani C. Stabilizing the leaning tower of Pisa. Bulletin of Engineering Geology and the Environment. 1998; 57:91–9.
3. Jo YH, Lee CH. Behavioral monitoring and stability evaluation of Korean stone pagoda in Magoksa temple using tilt meter sensor. International Journal of Applied Engineering Research. 2015; 9(22):14659–68.
4. Lorenzoni F, Casarin F, Caltone M, Islami K, Modena C. Uncertainty quantification in structural health monitoring: Applications on cultural heritage buildings. Mechanical Systems and Signal Processing. 2016; 66–67:268–81.
5. Duvedi RK, Rajiv, Lal S. CNC machining of reverse engineered pseudo-symmetric sculptured surface models. Indian Journal of Science and Technology. 2016; 9(36):1–17.
6. Kim YT, Lee CH, Park KS. Establishment of conservation management system and application of cultural contents for stone sculptures in Gyeongbokgung Palace, Korea. Indian Journal of Science and Technology. 2016; 8(25):1–7.
7. Jo YH, Lee CH. Making method of deterioration map and evaluation techniques of surface and three-dimensional deterioration rate for stone cultural heritage. Journal of Conservation Science. 2011; 27(3):251–60.
8. Jo YH, Lee CH. Three-dimensional digital restoration and surface depth modeling for shape analysis of stone cultural heritage: Haenande stone inscription. Journal of Conservation Science. 2012; 28(1):87–94.
9. Lee CH, Jo YH, Kim SD. Three-dimensional image analysis deterioration evaluation and scientific conservation treatment of the Daechiri dinosaur track ways in Haman Country, Korea. Journal of the Geological Society of Korea. 2012; 48(2):179–91.
10. Jo YH, Lee CH. 3D image analysis for digital restoration and structural stability evaluation of stone cultural heritage: five-storied Magoksa temple stone pagoda. Journal of Conservation Science. 2012; 25(2):115–30.
11. Jun BK, Lee CH, Suh M. Stabilility evaluation of multi-storied stone pagoda in the Daewonsa temple using three-dimen- sional image analysis. Journal of Conservation Science. 2008; 22:31–42.
12. Jo YH. Physical deterioration evaluation and structural safety diagnosis of stone cultural heritage using nonde-structive precision technology [PhD thesis]. South Korea, Kongju National University; 2011.