Photogrammetry and 3D reconstruction in Archaeological Excavation on Elephant Terrace, Siem Reap, Cambodia

Minseok Koo [1]

[1] Hanyang University Museum, 222, Wangsimni-ro, Seoul, Republic of Korea - kkooms@naver.com

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Abstract

This study presents the photogrammetric documentation and archaeological investigation of a 14-meter section of the Elephant Terrace in Angkor Thom, Siem Reap, Cambodia. While earlier restoration efforts by the École française d'Extrême-Orient (EFEO) focused on surface-level repairs, this project involved the full dismantling and excavation of the northern terrace segment to examine its internal structure and construction sequence. A total of 705 terrestrial and aerial images were processed using Agisoft Metashape Professional v2.0.2 to generate a high-resolution 3D model. Accuracy was evaluated using Ground Control Points (GCPs) and Check Points (CPs), yielding an RMSE of 3.21 cm and an average reprojection error of 0.438 pixels—both within acceptable thresholds for archaeological documentation. The resulting model enabled a detailed reconstruction of five major construction phases, revealing the use of compacted earth, laterite walls, and sandstone facings. Notably, the photogrammetric data were acquired during excavation, eliminating the need for a dedicated imaging campaign. This demonstrates the method's practicality for integrated field documentation. The study confirms photogrammetry's value in archaeological research, offering accurate visualization, efficient data capture, and improved interpretive potential for heritage structures.

1. Introduction

The Elephant Terrace in Siem Reap, Cambodia, is renowned for its sandstone façade richly adorned with elephant reliefs and its imposing scale. Stretching approximately 350 meters from north to south, it serves as the grand entrance to the road leading to the royal palace. Despite its striking appearance, however, the internal structure of the Elephant Terrace remains largely unknown.

Although previous studies and restoration efforts were conducted by EFEO (École Française d'Extrême-Orient), they primarily focused on surface restoration rather than a detailed investigation of the terrace's internal composition (École française d'Extrême-Orient, 1908-1973). As part of the current project, a 14-meter section on the northern side of the terrace was excavated—the same location where EFEO previously carried out restoration work. During this survey, the Elephant Terrace was completely dismantled from east to west for archaeological excavation, a process that had never been undertaken before (Ahn et al., 2025). This investigation provided crucial insights into the terrace's construction techniques, revealing the earth structures concealed within.

A key aspect of this study is the application of photogrammetry-based 3D reconstruction to visualize the internal structure of the Elephant Terrace in a way that is accessible and easily understandable. Traditional archaeological investigations often rely on excavation records and stratigraphic drawings, which can be difficult for non-specialists to interpret. By integrating photogrammetry and digital modeling, this research not only documents the complex internal composition of the terrace but also reconstructs its construction phases in a detailed, visual manner, making it more comprehensible for scholars and the public alike.

This study identifies five major construction phases: (1) terrain modification and site leveling, (2) foundation construction with laterite and compacted earth, (3) mound formation within the terrace, (4) reinforcement of the perimeter using laterite walls and terracing, and (5) finalization with sandstone and decorative bas-reliefs on the eastern façade. This step-by-step reconstruction highlights the systematic approach employed in building the Elephant Terrace, and through 3D visualization, it bridges the gap between raw archaeological data and an intuitive understanding of the site's historical development.

Figure 1. Elephant Terrace and Research area

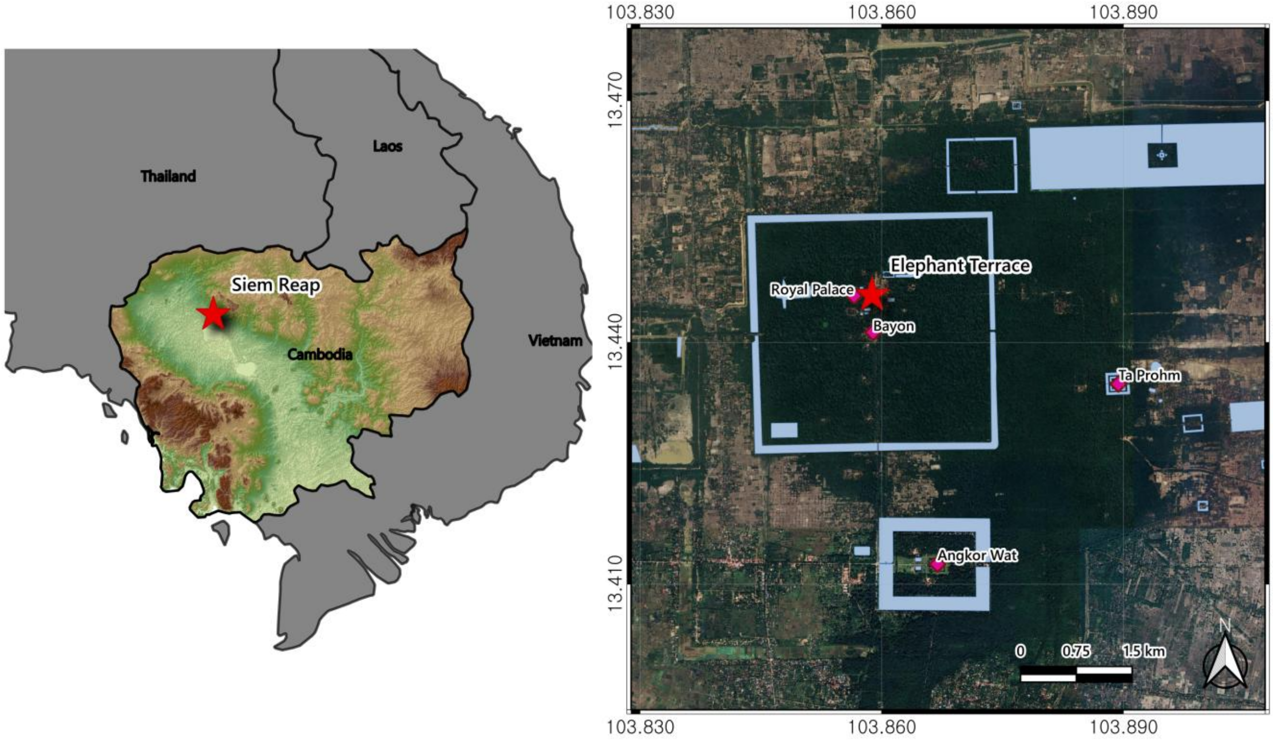

Figure 2. The site of Elephant Terrace and near archaeological site on the Cambodia

2. Review of Previous Studies on the Elephant Terrace

2.1 General Research on the Elephant Terrace

From as early as 1911, documentation exists regarding the restoration and maintenance of the Elephant Terrace. Most of the efforts were aimed at preventing further deterioration, including general repairs to the structure, clearing of vegetation, and treatment with sodium hypochlorite.

Comprehensive dismantling for restoration and the accompanying archaeological excavations was mostly carried out on the perrons. According to the excavation report (Pottier, 1997), an excavation and restoration project was carried out from 1996 to 1997 at the northern perron of the Elephant Terrace under the direction of Christophe Pottier. The work was prompted by concerns over structural instability and the need to understand the underlying construction. During this intervention, the entire upper sandstone section was dismantled, allowing access to the internal fill and laterite structures. The findings confirmed the presence of multiple construction phases, including compacted earth layers, reused stone blocks, and systematically arranged laterite walls. These features provided important insights into the terrace's engineering and historical modifications. The restoration process was completed by reassembling the sandstone blocks based on their original positions and using photographic documentation for accuracy.

While full-scale excavations have been carried out on the perrons of the Elephant Terrace, comprehensive archaeological investigations beyond these areas have been rare. This lack of exploration in the non-perron sections underscores the importance of the present study, which focuses on revealing the internal composition of a previously unexplored area of the terrace.

2.2 Surveys Related to the Current Excavation Area

In June 1954, a tree collapsed on the upper part of the Elephant Terrace, prompting the beginning of an investigation into that section. The section was found to have sandstone blocks protruding outward, posing a risk of further collapse. Upon removing these blocks, a laterite wall was discovered behind them. The removed sandstone blocks were subsequently reused in the restoration (École française d'Extrême-Orient, 1954). The investigation conducted in 1954 focused only on the eastern part of the Elephant Terrace. While it allowed for the confirmation of the sandstone wall with elephant reliefs and the laterite structure to its west, it did not provide a comprehensive understanding of the overall structure of the terrace.

This indicates that investigations beyond the perron areas primarily focused on the restoration of the eastern sandstone structures. Notably, the laterite wall located behind the sandstone façade was documented during the 1954 investigation—an architectural feature that was similarly confirmed during the present excavation.

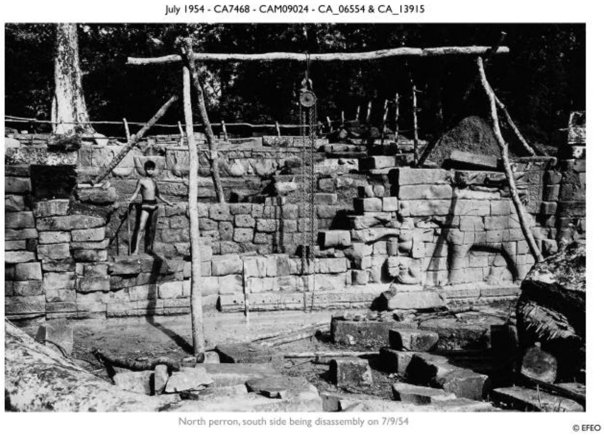

Figure 3. Laterite structure identified in 1954 (provided by EFEO)

3. Photogrammetric Modelling of the Elephant Terrace

3.1 Data Acquisition

The photogrammetric survey of the Elephant Terrace was conducted using a combination of terrestrial and aerial photography. A total of 705 images were captured using two different imaging systems:

1) **Terrestrial Survey**: Canon EOS 90D camera with focal lengths ranging from 18mm to 46mm.

2) **Aerial Survey**: DJI MAVIC 2 drone with an FC2204

camera sensor at an altitude of 8.8 meters above ground level. The captured images were processed to generate high-resolution 3D models, ensuring accurate documentation and analysis of the terrace's current condition.

One advantage of this study is that photogrammetric reconstruction was achieved without requiring a dedicated imaging campaign. The image dataset was compiled from photographs taken during the excavation process, supplemented with additional images where needed. As these photos were acquired at different times and under varying conditions, the dataset lacks uniform lighting, weather, and time-of-day consistency. Nonetheless, they proved sufficient for generating a reliable 3D model.

3.2 Image Processing and 3D Model Generation

The collected images were processed using Agisoft Metashape Professional v2.0.2, following a standard photogrammetric workflow. All spatial outputs were georeferenced to the WGS 84 / UTM Zone 48N coordinate system. A total of 428,852 tie points were identified across the dataset, with a reprojection error of 1.21 pixels. A dense point cloud consisting of 50,825,586 points was generated, followed by mesh generation with 1,713,511 vertices and 3,388,369 faces. Finally, a 4096 x 4096 texture map was applied to enhance visualization.

3.3 Accuracy Assessment & Error Analysis

The accuracy of the 3D model was assessed using Ground Control Points (GCPs) and Check Points (CPs). The Ground Control Points (GCPs) were established using a total station (SOKKIA IM-ZS 5570), referenced from a baseline control point located at the central perron of the Elephant Terrace. These points were distributed across all sides of the excavation area to ensure spatial consistency and minimize distortion during model alignment. The RMSE values for the GCPs were 0.78 cm in the X-axis, 2.82 cm in the Y-axis, and 1.32 cm in the Z-axis, with a total RMSE of 3.21 cm. For the CPs, the average reprojection error was 0.438 pixels. Camera calibration included the adjustment of radial and tangential distortion parameters, resulting in highly precise image alignment. The overall workflow ensured a detailed and geometrically consistent 3D reconstruction suitable for archaeological documentation and heritage conservation.

Importantly, both the GCP-derived RMSE and the CP reprojection error fall within the accepted thresholds for archaeological and cultural heritage applications, where spatial accuracies of up to 5 cm and reprojection errors below 1 pixel are generally considered sufficient (Lerma et al., 2010; Remondino & Campana, 2014; Chiabrando et al., 2017). These values confirm that the reconstructed model meets established quantitative standards and is thus reliable for further interpretive and spatial analysis.

It is also worth noting that the dataset used in this study was not acquired through a photogrammetry-specific data collection campaign but rather obtained during a large-scale archaeological excavation. Since the primary objective of the fieldwork was archaeological documentation rather than optimizing photogrammetric precision, the image acquisition process did not adhere to ideal conditions for minimizing reprojection error or maximizing geometric coverage. In addition, the extensive spatial scope of the excavation site and environmental constraints limited the consistent placement of high-precision control points across the entire area. Nevertheless, despite these practical limitations, the achieved RMSE and reprojection error remained within acceptable ranges for cultural heritage documentation, thereby demonstrating that the resulting 3D model offers a reliable basis for the analysis of construction techniques and spatial organization at the Elephant Terrace.

GCPs	*X error(cm)*	*Y error(cm)*	*Z error(cm)*	*Total(cm)*
S2	0.535	-2.725	1.274	3.055
S3	0.231	-1.481	-0.246	1.519
W1	1.358	2.931	2.542	4.111
W2	0.800	-2.355	-2.609	3.604
W3	0.023	-2.796	-0.465	2.834
N1	-0.014	4.231	-0.159	4.237
N2	-0.082	3.473	-0.655	3.629
N3	-0.097	1.516	0.342	1.837
E3	-0.100	-2.796	-0.023	2.971
Total	0.781	2.821	1.322	3.213

Table 1. GCPs error (X-Easting, Y-Northing, Z-Altitude)

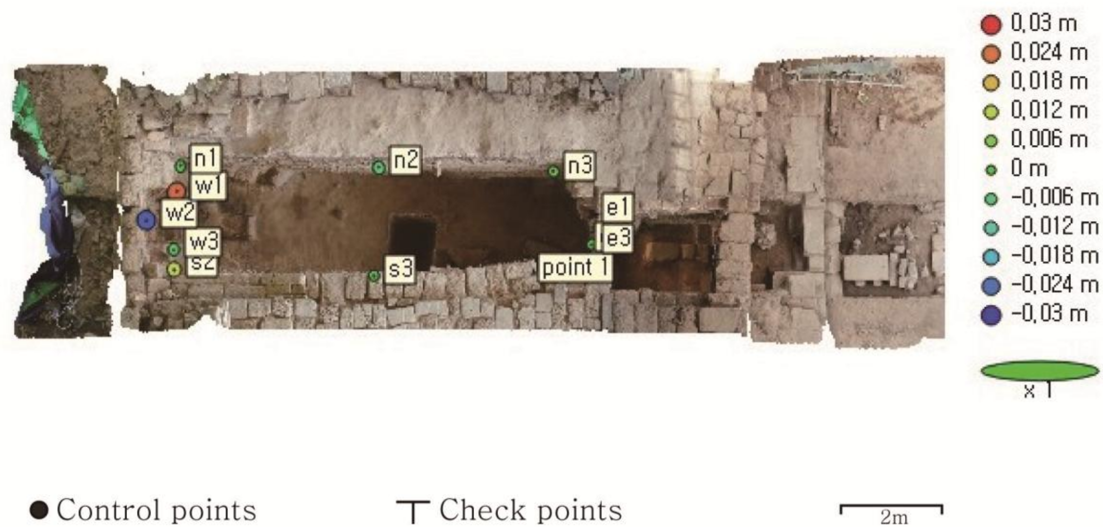

Figure 4. GCPs locations and error estimates (Z error is represented by ellipse color. X, Y errors are represented by ellipse shape)

3.4 Processing Environment and Output Specifications

The photogrammetric processing was carried out using the following hardware and software setup (Table 2). The 3D model has been archived in standard formats (e.g., OBJ, PDF 3D) and will be made available for future conservation planning, virtual dissemination, and educational purposes.

Item	*Specification / Description*
Processing Software	Agisoft Metashape Pro 2.0.2
Computer Specs	Intel I7, 40GB RAM, RTX 3080
Processing Time	2 hours 45 minutes
Output Format	OBJ, PLY, 3D PDF, Orthophoto (GeoTIFF)
Final Model Size	Mesh model(+texture) 1.2GB

Table 2. Technical specifications and processing details of the photogrammetric model.

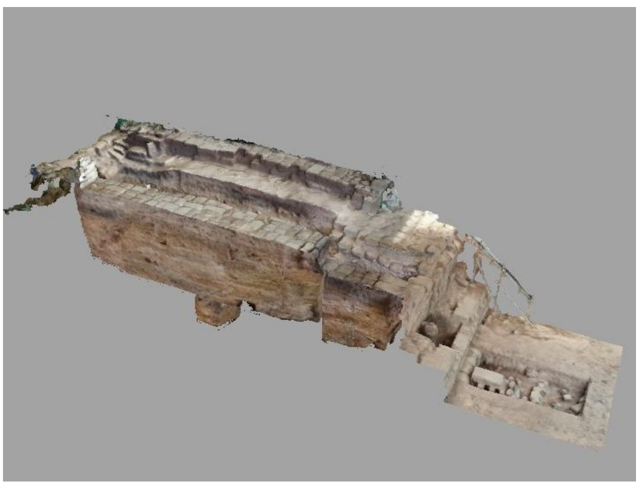

Figure 5. Photogrammetric 3D model of Elephant Terrace

4. 3D reconstruction

Based on the research, a 3D reconstruction of the Elephant Terrace was created in the order of its construction. The reconstruction process was primarily conducted using SketchUp 2025 software, with the photogrammetry-based 3D model serving as the foundation. The focus of this reconstruction was to restore the Elephant Terrace to its pre-collapse state, providing a more comprehensive understanding of its original form and construction sequence.

First, we restored the land creation phase, during which the terrain was modified and levelled (Figure 6). Then, we reconstructed the central mound within the terrace (Figure 7). Next, the fill dirt surrounding the mound was added, followed by the construction of the eastern elevation and the laterite sandstone wall (Figure 8). The final step involved finishing touches to the upper part of the terrace, including soil levelling and the placement of laterite and sandstone layers to complete the structure (Figure 9).

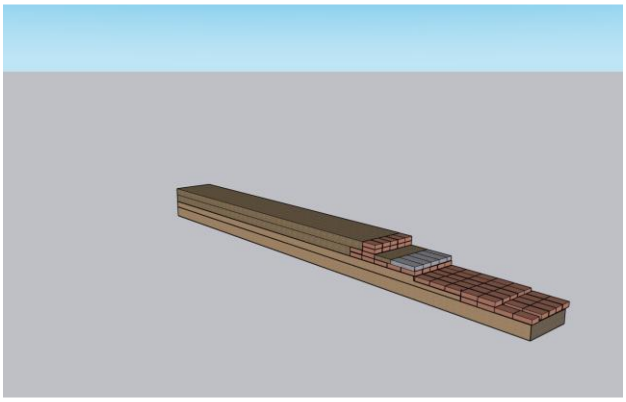

Figure 6. Land creation

This reconstruction process, grounded in photogrammetry and digital modeling, not only allows for a detailed analysis of the Elephant Terrace's construction sequence but also serves as an essential tool for visualizing and preserving its historical integrity before its structural deterioration.

Moreover, the reconstruction was guided by archaeological stratigraphic evidence obtained during the excavation, ensuring that each modeled stage accurately reflects the historical construction sequence. The resulting 3D reconstruction can be used for virtual restoration simulations, interpretive displays for public engagement, and comparative studies with other archaeological sites

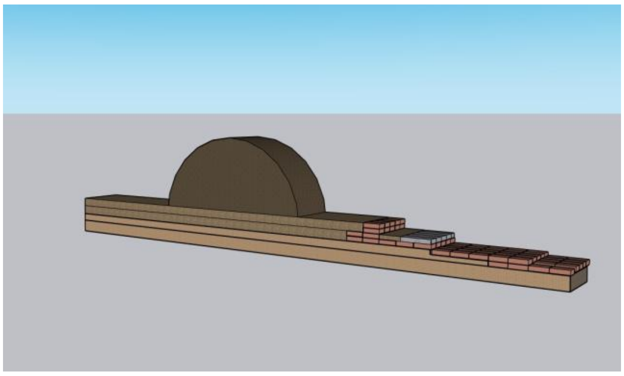

Figure 7. Central mound

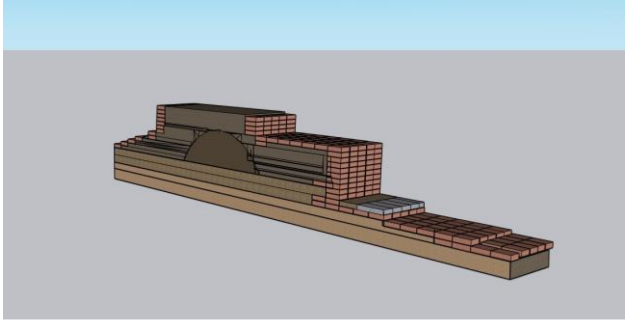

Figure 8. Fill dirt mound and construction laterite wall

5. Conclusions

This study demonstrates the effectiveness of photogrammetry in archaeological excavation, particularly in documenting and reconstructing complex structures such as the Elephant Terrace. By integrating photogrammetric techniques and digital modeling, it is possible to analyze and reconstruct the internal composition of the terrace with high accuracy, providing a more comprehensive and visually intuitive representation of its construction process.

It is true that the photogrammetric survey has a relatively larger margin of error compared to high-precision measurement methods. This error is within the acceptable range for traditional archaeological documentation in typical archaeological drawings scaled down to 1/20 or 1/40. Despite these limitations, photogrammetry is still a useful tool for visualization and analysis, aligning with existing archaeological documentation standards.

This study presents several key advantages. First, photogrammetry was seamlessly integrated into the archaeological excavation at the site, eliminating the need for additional fieldwork for 3D modeling and reconstruction. This significantly reduced the time needed for manual drawing and enhanced the efficiency of documentation.

Second, the photogrammetric data enabled the digital reconstruction of the internal structure of the Elephant Terrace. Since photogrammetry was integrated into both the excavation process and its outcomes, it provided insights into previously unconfirmed structural details and allowed for a systematic interpretation of the terrace's construction techniques.

Third, like all digital information, photogrammetric documentation offers superior storage, accessibility, and usability compared to traditional hand-drawn archaeological drawings. Digital datasets can be efficiently preserved, shared, and utilized for future conservation and research without the limitations of physical documentation.

Finally, the integration of photogrammetry into the excavation workflows does not require additional procedures or prolonged time for archaeological hand drawing.

As a result, this study sheds light on the benefits of using photogrammetry in archaeological excavations. Although challenges remain, particularly in refining accuracy and minimizing error, photogrammetry has demonstrated its potential as a useful tool in archaeological documentation and reconstruction. Therefore, future research is expected to build upon these findings, with the first step being to reduce the level of error and improve the precision of photogrammetric applications in archaeology.

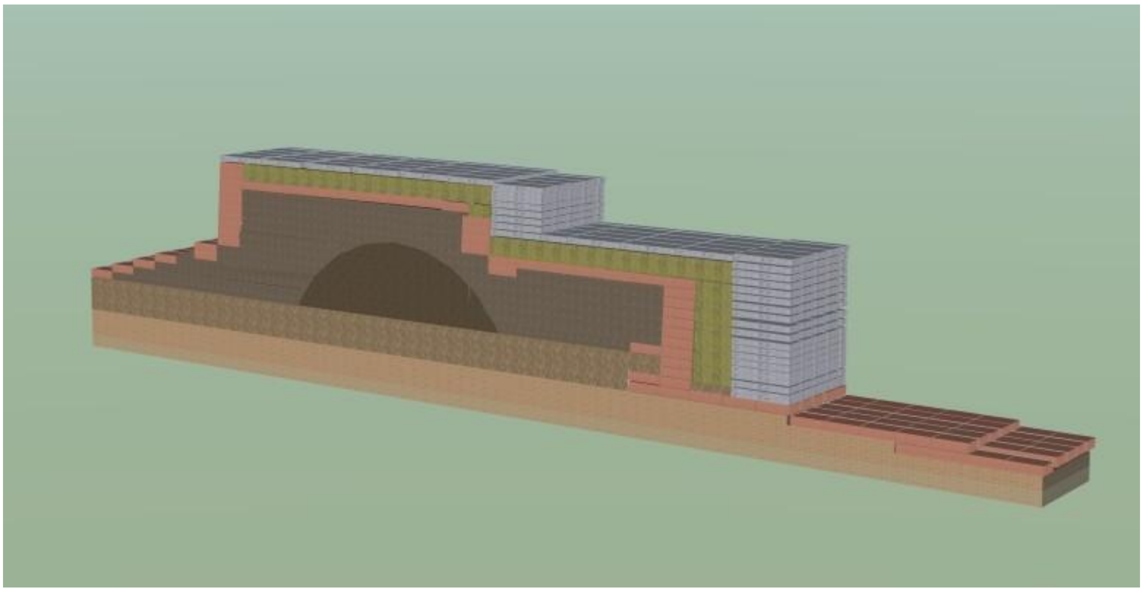

Figure 9. Reconstruction of Elephant Terrace

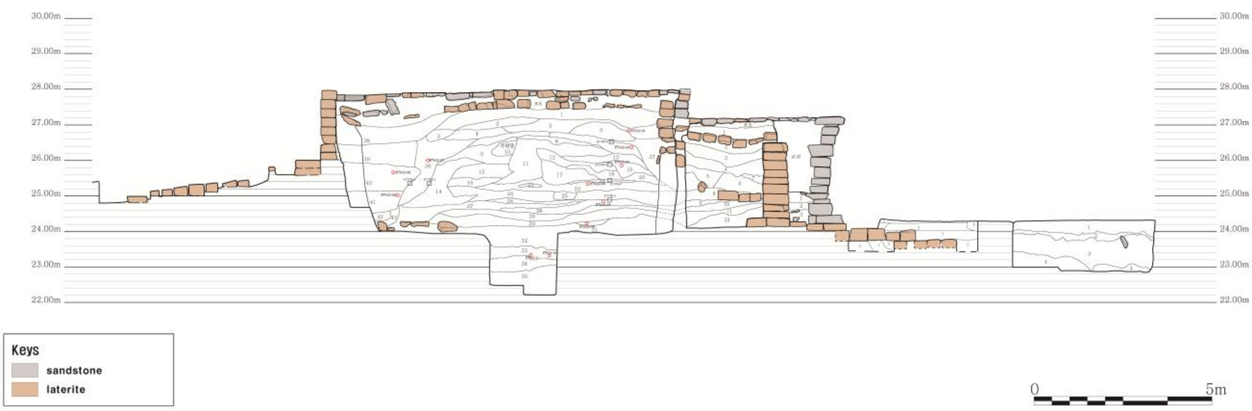

Figure 10. Stratigraphic Drawing illustrating the vertical profile of the excavation trench on the northern section of the Elephant Terrace (Ahn et al., 2025)

In addition to the technical and interpretive benefits, this study emphasizes the practical adaptability of photogrammetric workflows in challenging field environments. Given that the image dataset was primarily acquired during an active archaeological excavation, without the need for a dedicated photogrammetric campaign, the methodology demonstrates strong compatibility with dynamic field conditions.

Furthermore, the integration of photogrammetry with conventional archaeological documentation opens new possibilities for multi-scale, diachronic analyses. The ability to archive and compare successive excavation phases through precise 3D models allows for a more systematic tracking of stratigraphic relationships and structural modifications over time. As digital heritage initiatives expand globally, combining photogrammetry with geospatial datasets and archival records will support interdisciplinary collaboration, improve public dissemination, and contribute to long-term preservation strategies for vulnerable heritage sites such as the Elephant Terrace.

6. Reference

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