Civil Engineering and Architecture 14(3): 1757-1772, 2026 http://www.hrpub.org
DOI: 10.13189/cea.2026.140325

Nusantara Traditional Houses in Borobudur Reliefs: 3D Architectural Reconstruction and Typological Analysis

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Received November 23, 2025; Revised March 4, 2026; Accepted April 14, 2026

Cite This Paper in the Following Citation Styles

(a): *[1] Chinue Abyatina Audrey, Agung Budi Sardjono , "Nusantara Traditional Houses in Borobudur Reliefs: 3D Architectural Reconstruction and Typological Analysis," Civil Engineering and Architecture, Vol. 14, No. 3, pp. 1757 - 1772, 2026. DOI: 10.13189/cea.2026.140325.*

(b): *Chinue Abyatina Audrey, Agung Budi Sardjono (2026). Nusantara Traditional Houses in Borobudur Reliefs: 3D Architectural Reconstruction and Typological Analysis. Civil Engineering and Architecture, 14(3), 1757 - 1772. DOI: 10.13189/cea.2026.140325.*

Abstract This study found new knowledge that the traditional house relief in Borobudur is not only ancient Javanese, as some researchers mentioned, but also broader Javanese in Nusantara (Indonesian archipelago). The research classification of conventional Javanese houses based on roof forms has not addressed the stilted house. Existing theories are built on houses from the Islamic Sultanate/Mataram Islam era (1500–1800 AD). In Borobudur Temple (pre-Mataram Islam/Hindu-Buddhist era), constructed in the 8^{th} – 9^{th} century AD, archaeologists have identified six house typologies based on roof form, presented in two-dimensional architectural drawings. It is essential to reconstruct these into three-dimensional architecture and compare them with five Javanese architectural typologies and house forms outside Java. This study uses literature review, 2-dimensional drawing, and is constructed for 3D architectural modelling. The findings indicate continuity in Limas' roof typologies between Borobudur reliefs and Mataram Islam-era traditional Javanese houses. At the same time, stilt structures can be observed in conventional houses outside Java, such as Minangkabau (Sumatra) and Toraja (Sulawesi). The stilt and roof forms in Borobudur reliefs reflect not only Javanese traditional houses, but also those in Nusantara (the Indonesian archipelago).

Keywords Javanese Traditional House, Relief, Borobudur Temple, 3D Model, Nusantara, Stilt

1. Introduction

This paper provides new insights into the traditional houses depicted in the reliefs of Borobudur Temple. The distribution of these traditional house forms extends beyond the regional context of Java, where the temple is located, to a broader scale across the Indonesian archipelago. Borobudur Temple, a UNESCO World Heritage Site, functions as a monumental cultural memory that preserves architectural information from the 8th and 9th centuries [1]. Archaeology is crucial in reconstructing information from ruins and historical fragments, which serve as memory sources in architecture, heritage, and material archives [2]. In architectural history, memory often emerges through the recognition of loss, wherein ruins and ancient manuscripts remain as fragmented traces of once-flourishing civilizations [3]. In Indonesia, efforts to reconstruct these lost architectural forms through the study of Borobudur's reliefs have engaged archaeologists, historians, and architects for decades [4], [5], [6], [7].

However, a significant discrepancy exists between the iconography depicted in the Borobudur reliefs and established theories of traditional Javanese architecture. While the Borobudur reliefs clearly depict various stilt-house typologies, prevailing classifications of traditional Javanese architecture primarily describe houses constructed directly on the ground, with no stilted structures represented [8], [9]. Existing theories on traditional Javanese house typologies have not adequately addressed the presence of stilt houses as represented in the Borobudur reliefs [4]. Consequently, earlier theories of

Javanese house typologies were primarily oriented toward social hierarchy and cosmological principles associated with sultanate cities. These frameworks emphasized cosmological meanings expressed through roof typologies such as Joglo, Limasan, and Kampung, which functioned as markers of social status. Joglo roofs were typically associated with the nobility (*ningrat*), Limasan roofs with the middle class (*priyayi*), and Kampung roofs with commoners (*wong cilik*). The Panggang-pe roof form, one of the simplest in traditional Javanese architecture, was generally applied to non-residential structures, while the Tajug roof form was commonly reserved for religious buildings [8], [9], [10].

The absence of stilt houses in established classifications of traditional Javanese architecture may be partly explained by the geographical and historical scope of earlier studies, which were largely conducted within the core regions of the Mataram Islamic Sultanate, including the Yogyakarta Sultanate (established in 1755 AD) and the Kota Gede Sultanate (1586–1613 AD). Both centers were located in inland areas, where landed house typologies predominated [8], [9], [10]. Similarly, in the Surakarta Sultanate, established in 1745, residential architecture for the nobility was governed by strict spatial and architectural regulations. Following the Giyanti Agreement in 1755, the Mataram Sultanate was divided into the Surakarta and Yogyakarta Sultanates, resulting in two politically and culturally distinct courts with differing traditions.

Evidence of pre-Surakarta residential forms can still be observed in Batik Laweyan Village, a traditional settlement that predates the establishment of Surakarta. Over time, its buildings underwent significant transformation, as the inhabitants were independent Javanese batik entrepreneurs rather than members of, or dependents on, the royal court [11]. This context suggests that residential architecture outside the direct influence of the sultanates may have developed independently of these rules.

Koentjaraningrat introduced the terms inland Javanese culture (*Nagarigung*) and coastal culture (*Pesisir*) in his book *Kebudayaan Jawa*. He observed that coastal culture has received comparatively less scholarly attention [4]. This categorisation reflects the orientation of earlier studies, which tended to classify traditional Javanese architectural typologies based on inland Java, particularly within the context of Islamic sultanates (see Figure 1).

Coastal houses were developed with ecological factors in mind, particularly the need to mitigate flooding, humidity, and animal disturbance, leading to the emergence of the stilt-house typology [12]. Stilt houses along the coast were frequently noted by sailors during the Dutch colonial period, especially in coastal, swampy, and riverine environments. Colonial architects such as Henri Maclaine Pont, Thomas Karsten, and C. P. Wolff Schoemaker contributed to the formation of a dominant architectural narrative by emphasizing monumental and representative Javanese forms adapted into "Indische" architecture [13]. As a result, stilt houses in Java were largely absent from the official narrative of traditional Javanese architecture, both by local researchers and Dutch scholars.

Colonial-era photographic archives, historical records, archaeological evidence, and travelogues preserved in the KITLV Leiden collections document the presence of coastal stilt houses in Java from the 19th to 20th centuries [14], [15], [16]. This body of evidence supports the hypothesis that stilt architecture functioned as a widespread ecological solution across much of the archipelago, including parts of ancient Java, before inland landed traditions became dominant (see Figure 2).

This broader pattern of stilt-house architecture across coastal Java and other islands of the archipelago invites a re-examination of the Borobudur reliefs. Previous archaeological interpretations by Setyawan [6], [7] and Sasurya [5], have generally identified the houses depicted in the Borobudur reliefs as ancient Javanese dwellings, with limited consideration of comparable stilt-house traditions found in other regions of the archipelago. Rather than interpreting the depicted houses exclusively as representations of ancient Javanese architecture, the reliefs may reflect architectural knowledge drawn from a wider Nusantara context [17].

Recent studies by Kurniawan et al. [18] on the loss of the Austronesian saddle roof suggest that the architectural DNA reflected in the Borobudur reliefs is shared with broader regional traditions across the Indonesian archipelago, particularly in Sumatra and Sulawesi. Several panels of the Karmawibhangga reliefs depict stilted houses whose forms resemble traditional architectures beyond Java. However, previous research has largely remained descriptive and two-dimensional [5], [6], [7], focusing primarily on visual representation rather than three-dimensional architectural form and spatial configuration.

One relief panel shows notable similarities to the Bolon house of North Sumatra, characterized by its stilted structure, raised floor system, and roof form [19], [20]. Another panel resembles the Tongkonan house of South Sulawesi, particularly in its elevated construction and distinctive roof form, which developed as an adaptive response to environmental conditions [21], [22], [23].

However, these similarities have not been analyzed using three-dimensional architectural methods. It also remains unclear whether the Borobudur reliefs represent exclusively ancient Javanese architecture or reflect broader Nusantara architectural traditions. Table 1 summarizes the presence of stilted houses across different regions, highlighting their correspondences with the relief panels.

in this relief is depicted as stone, a material identical to Borobudur Temple itself. Therefore, this study hypothesizes that the building may represent a sacred shrine or a temple building situated within a palace compound, rather than a residential wooden palace. To assist with general visualization of these architectural forms, the Borobudur Conservation Office has provided physical scale models based on these reliefs (see Figure 5). Distinct from Setyawan's functional classification and Sasurya's [5] material-based categorization, this research specifically focuses on the stilt-structure typology to trace the technical and structural evolution of these dwellings.

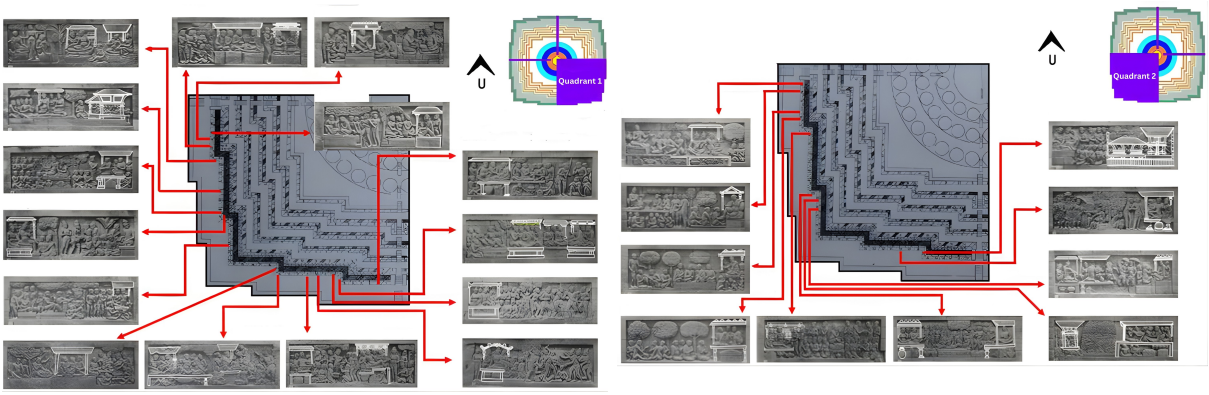
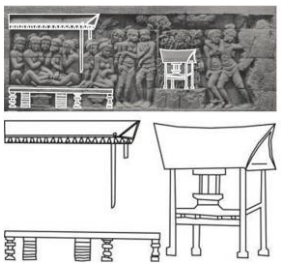
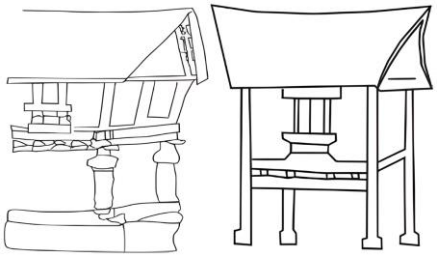


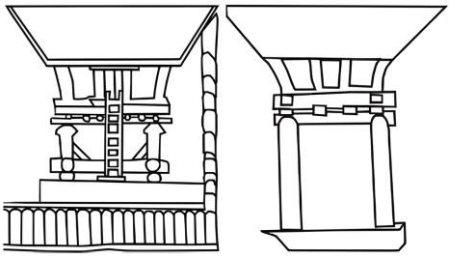
Figure 3. Highlight in white of the Wooden-Structured house depicted in the Karmawibhangga Reliefs of Borobudur Temple. Source: [6]



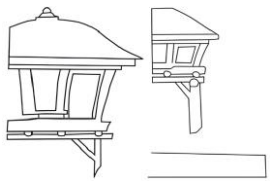
A, Two-dimensional (2D) reconstruction of a stilt house typology from the Borobudur Temple reliefs.



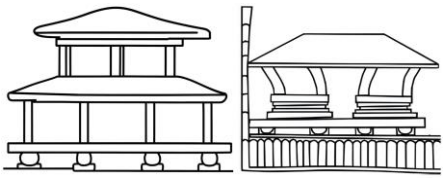
B, Stilt house typology with a gable roof.



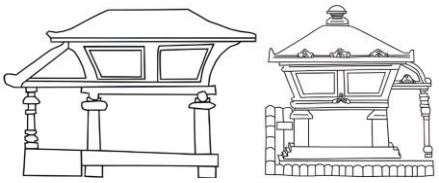
C, Stilt house typology with a gable roof sloping outward.



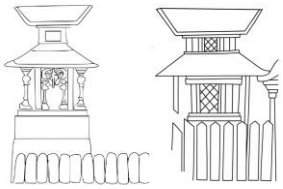
D, Stilt house with curved pyramidal roof.



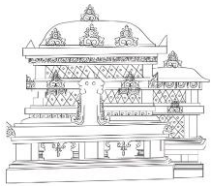
E, Stilt house with pyramidal roof resembling a limasan roof.



F, Stilt house with a pyramidal roof and an additional canopy.

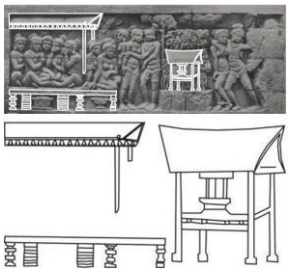


G, Stilt house with double pyramidal roof



H, Landed Building with stone material.

Figure 4. Six types of roof forms from stilt buildings can be identified from the Borobudur Temple reliefs. Source: [6]

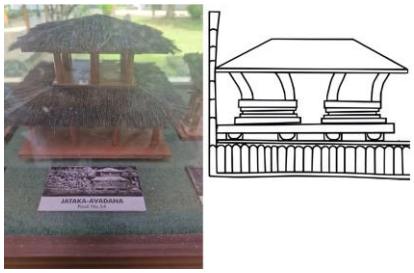


A, Two-dimensional (2D) reconstruction of a stilt house typology from the Borobudur Temple reliefs.

B, Stilt house typology with a gable roof.

C, Stilt house typology with a gable roof sloping outward.

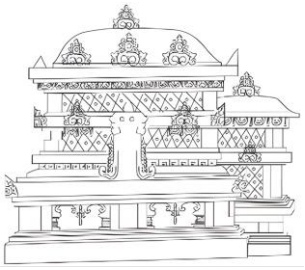
D, Stilt house with curved pyramidal roof.



E, Stilt house with pyramidal roof resembling limasan roof.

F, Stilt house with pyramidal roof and additional canopy

G, Stilt house with double pyramidal roof



H, Landed Building with stone material.

Figure 5. Architectural mockup houses from Borobudur Temple reliefs as a basis for 3D architectural creation. Source: Researcher survey at Borobudur Conservation Hall, 2025

Furthermore, a significant architectural shift is evident when comparing these ancient reliefs to the later studies by G. Cahyono [8] and N. C. Idham [9]. The stilt houses common in the 8th century are notably absent in the palaces of Yogyakarta and Kota Gede, where landed structures became the norm. Despite this structural transformation, a typological continuity persists in roof forms, particularly the *Limas* roof. It is also important to note that the *Joglo* roof, which became a hallmark of Javanese nobility in later centuries, is entirely absent from the Borobudur reliefs. This absence underscores a critical evolutionary boundary between the ancient Javanese period and the later Islamic Sultanate era. To understand this transition, it is necessary to examine the formalized characteristics of Javanese architecture that emerged during the later Mataram period.

2.3. Traditional Javanese Architecture

Building upon the identification of early architectural forms, the landscape of the Mataram Islamic era marked a significant shift towards landed structures. This period formalized the canonical Javanese dwellings widely recognized today, where classification is fundamentally based on roof typologies: Joglo, Limasan, Kampung, Panggang-pe, and Tajug [9] (see Figure 6).

Beyond structural form, these houses are deeply rooted in cosmological spatial aspects, reflecting a dualism between the physical and spiritual realms [29], [30]. Furthermore, Javanese architecture serves as a direct reflection of the cultural values, spirituality, and belief systems of the people [31]. As noted by Koentjaraningrat [4], these values are most evident in the palace culture (*Keraton*) of inland Java, which served as the basis for architectural studies by Cahyono [8] and Idham [9] within the Mataram Islamic Sultanate region.

The history of Javanese architecture is broadly categorized into the Mataram era and the Ancient Java era (4th-15th century CE). The latter, often termed *Jawa Kuna*, is primarily studied through Old Javanese (Kawi, Sanskrit) inscriptions and stone remnants. Eko Punto Hendro [10] suggested that despite the transition to the Islamic period, earlier Hindu-Buddhist elements were not lost but were transformed and preserved in Yogyakarta, which remains the centre of Javanese cultural heritage [32], where ancient spiritual meanings continue to influence architectural forms [17].

While the characteristics of the Mataram Islamic era are well-documented, a comparative analysis linking them back to the Ancient Javanese period remains limited. Existing literature often treats 8th-century relief depictions and later landed houses as separate entities, frequently overlooking the typological continuity in roof forms, such as the *Limasan* and *Kampung*, despite the disappearance of the stilt-structure. Furthermore, upon closer observation, the forms depicted in the Borobudur reliefs exhibit significant structural similarities with traditional stilt houses found in Sumatra and Sulawesi. This suggests a broader Austronesian architectural lineage that connects ancient Java to the wider Nusantara region, a link that remains largely unexplored. To synthesize these findings and highlight the specific gaps in previous studies, Table 2 categorizes the research focus across different historical periods.

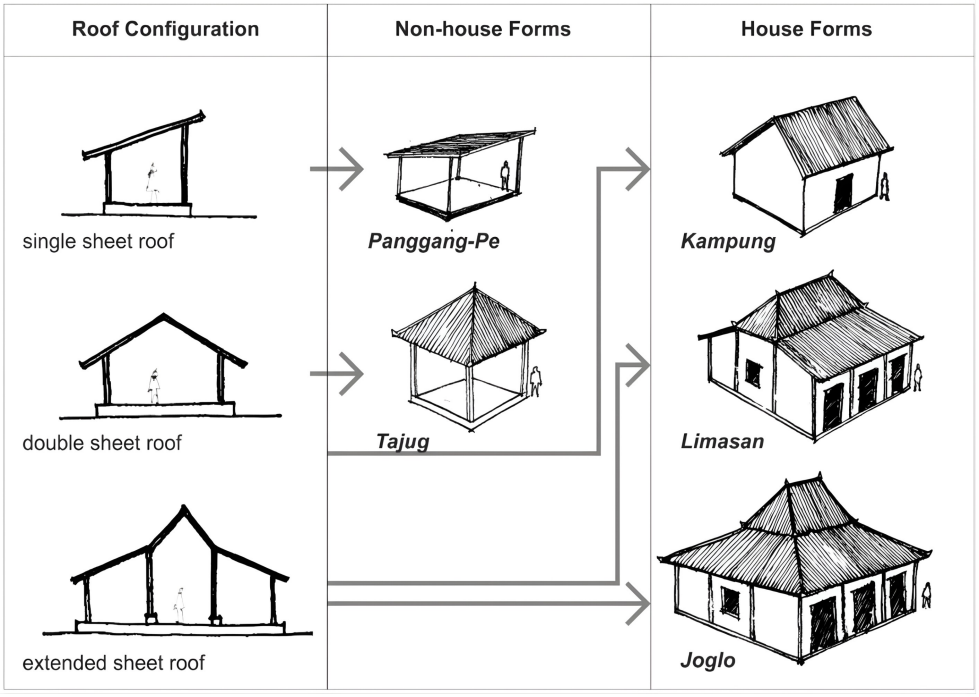


Figure 6. Primary traditional forms of Javanese buildings, which were the focus of older theories explored from the Mataram Islamic Sultanate era. Source: [9]

Table 2. Synthesis of Architectural Research Focus and Identified Gaps

Comparative Synthesis of Javanese and Nusantara Architectural Research				
Researcher	**Type**	**Research Focus**	**Method**	**Research Gap**
Ancient Java (Hindu-Buddhist) Period				
H. Setyawan [6], [7]	Report & Article	Classification of wooden structures based on roof typologies and functions (dwellings, granaries, pavilions, and shrines).	Archaeological description and 2D reconstruction	Limited to 2D descriptive drawings; lacks 3D structural analysis and links to Nusantara Architecture.
S. Chandra [5]	Thesis	Classification of buildings based on materials depicted in the *Kharmawibhangga* reliefs.	2D visual representation using the space-time-flat method.	Prematurely concludes that temple reliefs are the absolute representation of Ancient Javanese architecture.
Koentjaraningrat [4]	Book	Identification of Borobudur temple as the oldest document providing evidence of Ancient Javanese architecture.	Ethnographic and cultural-historical description.	Lacks specific structural analysis or detailed visual reconstruction of the houses depicted in the reliefs.
Notes / Synthesis	While recognizing the reliefs as historical records, these sources overlook the stilt-structure typology. This gap is significant because, while roof typologies (Limasan and Kampung) persisted into the Sultanate Mataram era, the stilt-base disappeared. This study utilizes this 'missing' stilt-form from the Borobudur reliefs to re-establish the link between Ancient Javanese architecture and the broader Nusantara traditions, specifically the Bolon house (Sumatra) and Tongkonan house (Sulawesi) structures. This positioning reinforces Ancient Javanese architecture as an inseparable part of the Nusantara architectural lineage.			
The Mataram Islamic sultanate (Jogjakarta – Solo) Period				
G. Cahyono [8]	Dissertation	The symbolic dimensions of house shapes, focusing on duality, cosmos, and the center within Javanese traditions in Kota Gede (Jogjakarta)	Qualitative descriptive and symbolic-interpretative analysis	Focuses exclusively on the symbolic and cosmological meanings of Javanese architecture within a specific regional context (Kota Gede), rather than addressing its historical evolution or chronological development.
N. C. Idham [9]	Journal Article	Environmental synchronization and vernacular sustainability of Joglo and Limasan houses across 10 regions in Central Java and Yogyakarta.	Qualitative field study involving 90 building samples, analyzing architectural features (size, orientation, materials) and thermal comfort.	Focuses on the environmental performance of modern landed houses; it does not address the historical-structural transition from ancient stilt-structures to current landed forms.
E. P. G. Hendro [10]	Book	The preservation and transformation of Hindu-Buddhist cultural elements within the Yogyakarta Palace during the Mataram period.	Historical-cultural analysis and qualitative observation.	Focuses on cultural and symbolic continuity; however, it does not provide a technical or 3D structural analysis of the physical architectural evolution from stilt to landed structures.
Notes / Synthesis	These sources primarily analyze Javanese architecture based on its current landed-house typologies (Joglo, Kampung, Limasan) and cosmological meanings within the Yogyakarta-Surakarta region. They largely overlook the chronological transition from Ancient Javanese stilt-structures to the modern landed forms, leaving a gap in understanding the technical evolution of the structure itself.			
Nusantara Perspective				
Kurniawan et al. [18]	Journal Article	The disappearance of Austronesian saddle roofs in Java and their morphological link to Sumatra and Sulawesi based on temple relief evidence.	Architectural-historical strategy using visual analysis of 8th-16th century reliefs and 20th-century archival documentation.	Focuses on the visual-morphological loss of roof forms; does not provide a 3D structural analysis or technical reconstruction of the building's framework.
E. N. Histanto & J. Prijotomo [17]	Journal Article	Design principles of Nusantara Architecture (stilt and timber systems) in Bolon house as a response to seismic and climatic conditions.	Explorative-qualitative approach comparing *Nusantara* design principles with European-Classical architectural mindsets using matrices.	Excessive reliance on European-Classical standards as a benchmark. This study argues that Nusantara architecture should be analyzed within its own indigenous context and technical logic, rather than being validated through Western architectural frameworks.

Table 2 continued

Notes / Synthesis	These studies confirm that Javanese architecture shares a common morphological and structural heritage with the wider Nusantara region, specifically through the use of Austronesian saddle roofs and timber stilt systems.			
State of the Art (SOTA)				
This Study	Journal Article	The structural transformation of Ancient Javanese timber-stilt houses and their technical lineage to Nusantara architecture.	3D Structural Reconstruction and comparative typological analysis with Nusantara architecture.	Fills the research gap by providing technical-structural evidence of the vanished Javanese stilt-house typology through 3D modeling, validated by Nusantara architectural principles.

The literature synthesis highlights a compelling paradox in Javanese architectural history. While there is a clear typological continuity in roof forms from ancient reliefs to the Mataram Islamic era, the fundamental substructure underwent a radical transformation from stilt-based to landed foundations. Previous studies have primarily focused on surviving roof forms and their cosmological meanings, leaving the vanished stilt structure as a critical missing link. By focusing on this specific stilt form, this research establishes a structural bridge between Ancient Java and the broader Nusantara architectural lineage, showing significant technical and historical parallels with the Bolon and Tongkonan. Consequently, the following section will elaborate on the specific characteristics of Nusantara Architecture, focusing on how these surviving traditions serve as vital structural benchmarks for the 3D reconstruction of the Borobudur reliefs.

2.4. Borobudur Temple House Reliefs: Traditional Houses in the Nusantara?

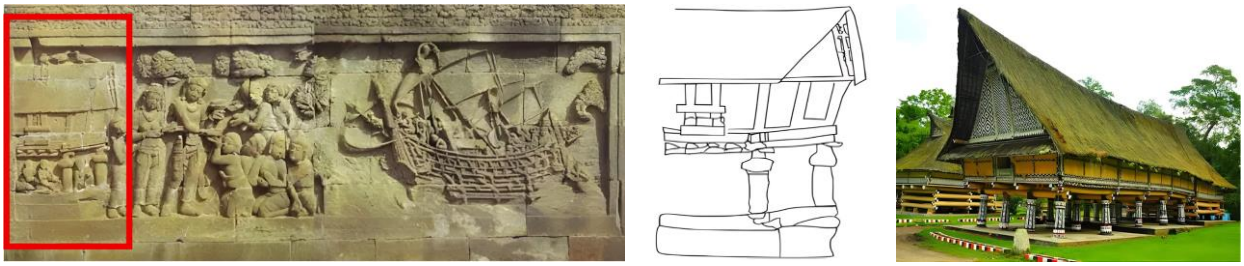
Kurniawan et al. [18] confirm that the Austronesian saddle roof was a well-established architectural feature in Central Java during the construction of Borobudur. This roof form is characterized by an extended ridge line. In contrast, during the Islamic Mataram era of Javanese architecture, the ridge (locally known as *molo*) became shorter to signify a higher social status [11]. The saddle roofs depicted in the reliefs utilized organic materials, specifically *ijuk* (sugar palm fiber), which naturally allowed for a curved profile. It is hypothesized that the characteristic curvature of the limas-style roofs in the reliefs is a direct result of the flexible nature of ijuk. However, as Javanese architecture transitioned into the Islamic Mataram period, the use of clay tiles replaced the traditional *ijuk* roofing. This material shift led to a more rigid structural requirement, resulting in the loss of the characteristic curvature in both limasan and kampung house types.

Histanto [17] defines the primary characteristics of Nusantara architecture as stilt-based structures with a dominant use of timber materials. This aligns with Setyawan's findings, which identify the stilt houses in the Borobudur reliefs as timber-based constructions [6], [7]. Although the stilt structure has vanished from modern Javanese architecture, several relief panels depict houses that closely resemble the Bolon and the Tongkonan. Both traditional house types continue to maintain their stilt foundations and use organic fiber materials (*ijuk*) for their saddle roofs until the present day.

One specific relief in the Karmawibhangga series illustrates a structure resembling the Bolon house, featuring an outward-sloping saddle roof and a sturdy stilt foundation (see Figure 7). This form reflects the traditional Batak house, which has preserved indigenous cultural principles since the prehistoric era. The elevated structure creates a multifunctional space beneath the floor known as the *songkor*. This underfloor area is utilized for various activities, including housing livestock, storing agricultural tools, and serving as an additional workspace [19], [20].

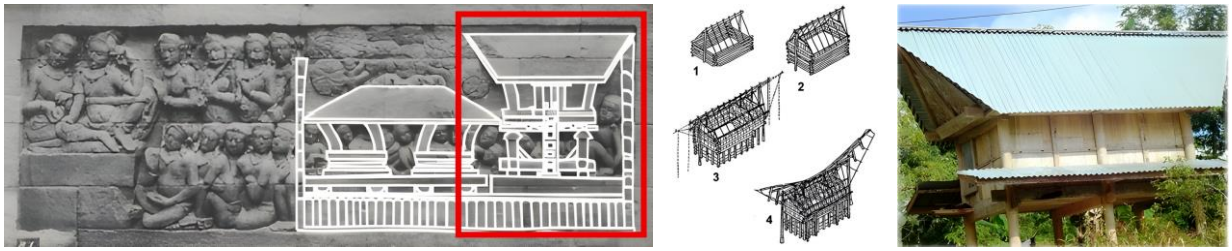
Furthermore, other Karmawibhangga panels represent structures similar to the Tongkonan house of the Toraja people. To honor their ancestral journey (*Aluk Todolo*), the Toraja designed their traditional houses to symbolically resemble boats, with roofs protruding upward like a prow and stern [22], [23]. Within this typology, the space beneath the house (*Sulluk Banua*) is traditionally used for livestock, while the area beneath the rice barn (*Kale Alang*) serves as a social space for receiving guests or conducting small communal meetings. Yulianto suggests that roof forms in this tradition evolved through four stages: from flat, to slightly curved, and eventually to a deep curve [21]. Notably, the third stage of this evolution matches the depictions found in the Borobudur reliefs more closely than the more exaggerated modern forms (see Figure 8).

Based on the theoretical discussion above, a knowledge gap remains regarding the stilt-type traditional houses as depicted in the Borobudur reliefs. The central question is whether these houses are specifically ancient Javanese or if they represent a broader conventional house typology across the Nusantara archipelago. The reliefs may document both a lost Javanese architectural tradition and a shared architectural heritage that connects Java to the wider Indonesian archipelago.



A stilt house with a roof resembling a Bolon house. Source: [33] 3D Reconstruction. Source: [6] 3D Reconstruction. Source: [34]

Figure 7. Reliefs of Traditional Bolon House, North Sumatra



A stilt house with a roof resembling a Bolon house. Source: [6] Evolution of Tongkonan House: [21] The third stage of Tongkonan house evolution: [35]

Figure 8. Reliefs of Traditional Tongkonan House, South Sulawesi

3. Materials and Method

Research specifically on the 3D reconstruction of stilt-type traditional houses from Borobudur reliefs is minimal, representing a critical gap that this study aims to fill. Utilizing literature on the reliefs as primary sources for reconstructing ancient architecture offers a significant opportunity to enhance understanding of the evolution and distribution of architectural typologies. Studies examining whether the architectural typologies depicted in Borobudur reliefs relate to Javanese tradition or the broader Nusantara architecture remain scarce.

3.1 Data Source and Selection

This study addresses the identified knowledge gap regarding the stilt house forms carved on the temple walls. Rather than re-collecting field data from scratch, this research synthesizes existing 2D documentation and photographic records collected by archaeologists [7], [8], as the primary reference for the reconstruction process. The selected panels include various depictions of timber-stilt structures, which serve as the foundation for developing the 3D architectural models.

3.2. 3D Reconstruction Workflow and Scaling Logic

The transformation from 2D relief depictions into 3D architectural models (see Figure 4) follows a rigorous interpretative process. Despite the inherent limitations of 2D visual data, the researcher performed direct on-site surveys at the Borobudur Conservation Office to examine physical architectural mockups. This direct observation provided vital data regarding the side elevations and spatial depth of the structures, which are often flattened in 2D documentation.

To determine the architectural dimensions and scale, the study employs two scientific approaches:

1. Human Proportion Analysis: The researcher hypothesized that the depicted stilt structures maintain a functional clearance height, as evidenced by the human figures shown performing activities beneath the floors. If the underfloor space (kolong) is depicted as a habitable zone, it suggests that the structural columns were of sufficient height to accommodate adult human activity.
2. Comparative Benchmarking: The study establishes scale by comparing the relief depictions with surviving traditional houses in Java, Sumatra, and Sulawesi. This comparative method allows for a more realistic and proportional interpretation of the symbolic relief forms into three-dimensional structures.

3.3. Digital Modeling and Validation

All obtained data were processed using SketchUp as the primary 3D modeling medium. SketchUp was selected for its high efficiency in surface-based modeling, which is particularly effective for reconstructing the complex organic curves of saddle roofs and the timber joinery details found in traditional Nusantara architecture. Unlike BIM or Rhino, which prioritize parametric engineering, SketchUp allows for a more flexible visual interpretation of historical artifacts while maintaining precise geometric accuracy.

The modeling process was carried out in stages: forming the basic building mass, determining the structural grid, and finally arranging architectural details based on observational data. Furthermore, this process was supported by existing high-resolution relief documentation and digital datasets. While research [23] does not provide a theoretical typology, its soft-edge enhanced deep learning methods offer beneficial digital datasets for extracting precise roof profiles and pillar proportions. In line with this, the depth analysis facilitated by Registered Relief Depth (RRD) datasets helped identify small architectural details on the panels, serving as a primary source to extract building typologies from the reliefs [24].

4. Results and Discussion

All sources cited in text must appear in the reference list, and all items in the reference list must be cited in text. With the numerical system, references are arranged in the reference list so that they match the order in which they are cited in the text.

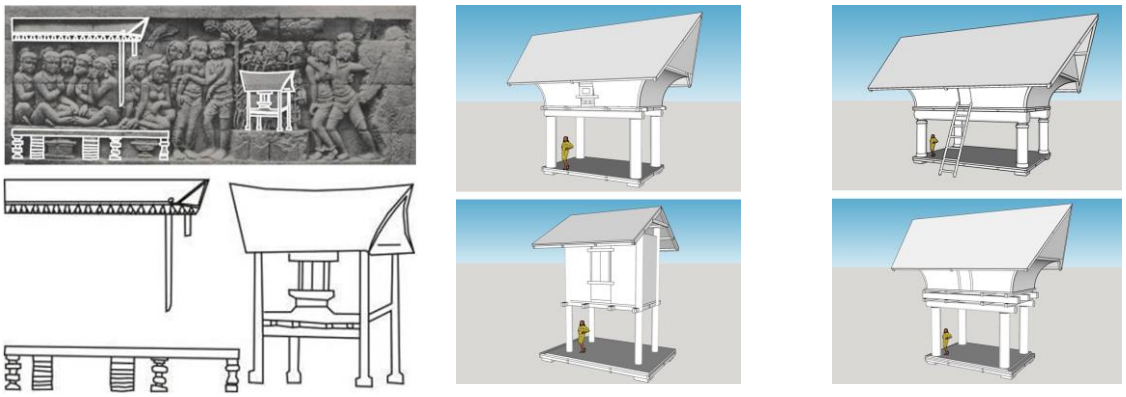
This study examines the literature and visual evidence of houses depicted in the Borobudur reliefs to identify representations of stilted architecture. The findings are presented through 3D models to facilitate structural observation and proportional analysis, providing a realistic representation of the architectural typology from that period.

A primary challenge in analyzing these reliefs is the absence of a standardized technical scale, as the carvings are symbolic and representative rather than technical architectural plans. To address this, several analytical strategies were employed. First, a comparative analysis was conducted using existing traditional Javanese dwellings alongside the Bolon of North Sumatra and the Tongkonan of South Sulawesi. Second, the study applied human proportion analysis; the depiction of human figures engaging in activities beneath the floor structures serves as a vital indicator that the supporting columns were of sufficient height to create a functional and habitable underfloor space.

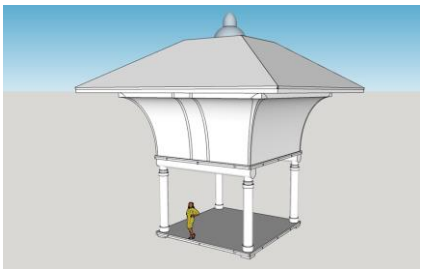
4.1. 3D Architectural Reconstruction

Digital modeling using SketchUp enables a visualization that represents the physical volume of the buildings, facilitating the interpretation of proportions, forms, and stilt systems. Based on the 3D architectural modeling (see Figure 9), the study demonstrates that the houses depicted in the Borobudur reliefs exhibit the following characteristics:

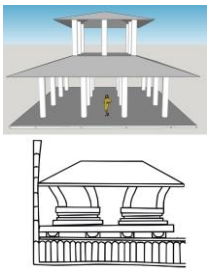
- Stilted Structural Systems: The buildings are elevated, utilizing vertical supporting posts and horizontal beams as the primary structural elements.
- Roof Typologies: The structures feature either single-tiered or stacked saddle roofs, often displaying the characteristic organic curvature.
- Minimalist Exteriors: The depictions focus on the external form and structural skeleton without providing specific interior details.



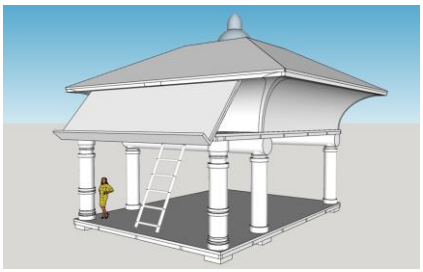
A, Two-dimensional (2D) reconstruction of a stilt house typology from the Borobudur Temple reliefs. **B**, 3D reconstruction of a stilt house typology with a gable roof. **C**, 3D reconstruction of a stilt house typology with a gable roof sloping outward.



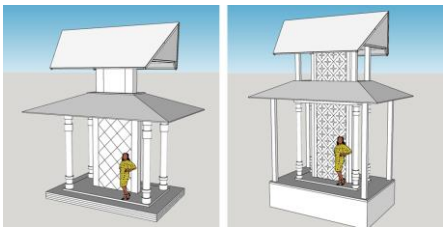
D, 3D reconstruction of a stilt house with curved pyramidal roof.



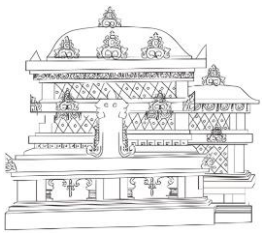
E, 3D reconstruction of a stilt house with pyramidal roof resembling limasan roof.



F, 3D reconstruction of a stilt house with a pyramidal roof and an additional canopy.



G, Stilt house with double pyramidal roof



H, Landed Building with stone material.

Figure 9. 3D reconstruction of six roof types reconstructed from 2D depictions of stilt buildings identified in the reliefs

4.2. Architectural Analysis: Javanese Context

The 2D reconstructions of the relief panels reveal a prevalence of limas-style forms, which are inherently identical to the limasan roof in Javanese architecture. However, these ancient versions are depicted as stilted structures, a feature no longer found in later Javanese eras. Archaeologists and previous researchers agree that these limasan depictions represent Ancient Javanese architecture before its subsequent evolution [5], [6], [7].

The characteristic curvature of the limasan roofs in the reliefs suggests the use of flexible organic materials such as ijuk. This architectural feature vanished during the Islamic Mataram period as clay tiles became the standard roofing material, necessitating a more rigid and straight roof structure. Despite the disappearance of the stilt foundation, a clear typological continuity exists (see Figure 10). For instance, the canopies depicted in the reliefs serve the same functional purpose as the tritisan or overhangs found in later Javanese limasan houses.

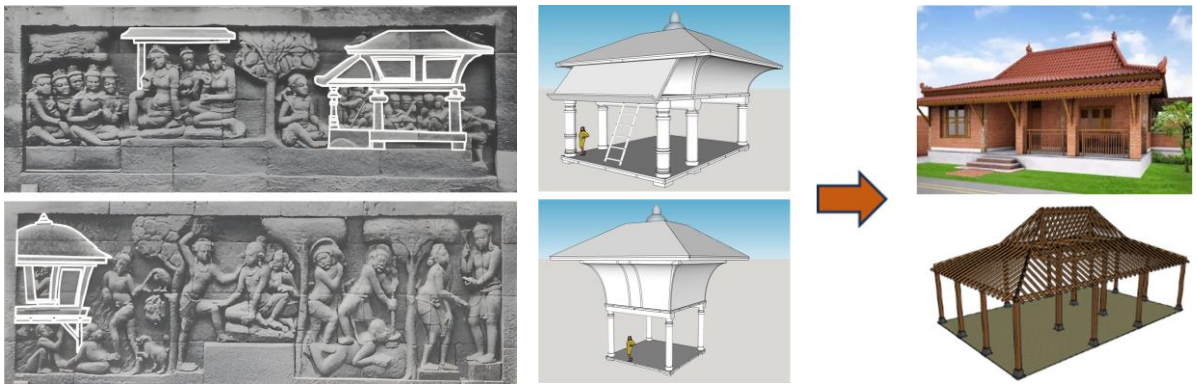
Furthermore, several two-story limasan structures in the reliefs show a striking resemblance to the pendhapa (a traditional Javanese open-sided pavilion)of the Islamic Mataram era. This similarity is evident in the column placement, the form of the tritisan, and the low-profile stilt structure. Structurally, the supporting posts in the reliefs are depicted resting on stone foundations, directly mirroring the use of umpak or stone pedestals in traditional pendapa construction (see Figure 11).

4.3. Architectural Analysis: Bolon House, North Sumatra

The relief panels depict stilt houses with complete wall structures and visible window openings on one side, bearing a strong resemblance to the Bolon house of North Sumatra. Historically, the Bolon house typology has existed since prehistoric times, making its presence in eighth century reliefs highly plausible.

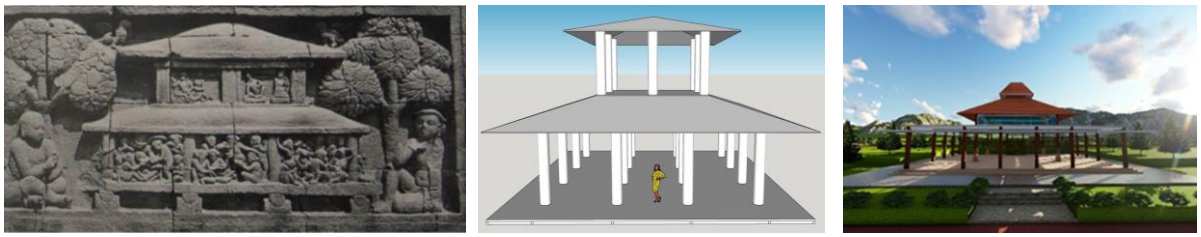
Traditionally, the roof of Bolon house is constructed from ijuk or rumbia leaves, assembled into a high and sharp saddle roof designed to withstand wind pressure and symbolize success. This construction is achieved without nails, instead relying on ijuk or rattan fibers for structural binding. Due to the flexibility of these organic materials, the side profile of the roof maintains a distinct curvature that aligns perfectly with the depictions found in the Borobudur reliefs (see Figure 12).

In the 3D reconstruction, the study highlights that the underfloor space in the reliefs is occupied by various human activities. This observation leads to the hypothesis that the substructure was intentionally built with high clearance. This finding is consistent with contemporary Bolon house structures, where the space beneath the house is functionally utilized for communal tasks or social activities.



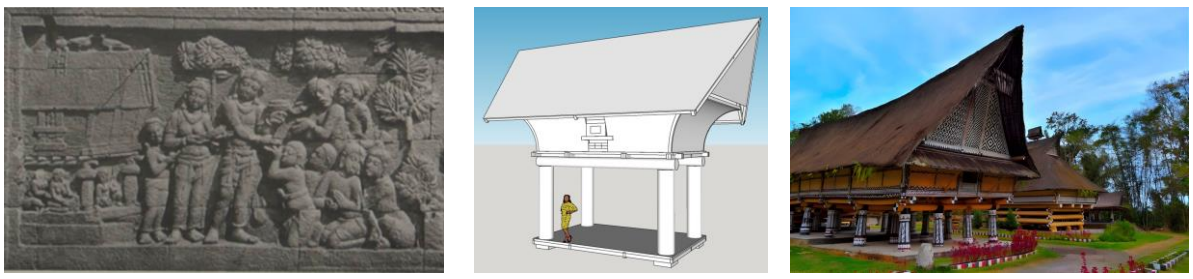
Limasan house in Karmawibhangga relief. Source: [6], [7] | 3D Reconstruction | Limasan House (Sultanate Era). Source: [36]

Figure 10. Comparative 3D analysis of Limasan house between the Karmawibhangga reliefs and the Sultanate era



Stilt structure resembling a *pendhapa.* Source: [5] | 3D Reconstruction | 3D model of a modern *pendhapa* (Author's reconstruction 2025)

Figure 11. Structural resemblance and 3D reconstruction of the Karmawibhangga relief in relation to the pendhapa typology



Stilt Structure Resembling Bolon House. Source: [5] | 3D Reconstruction | Contemporary Bolon house, North Sumatra. Source: [37]

Figure 12. Comparative 3D analysis of Karmawibhangga reliefs and Bolon House

4.4 Architectural Analysis: Tongkonan House, South Sulawesi

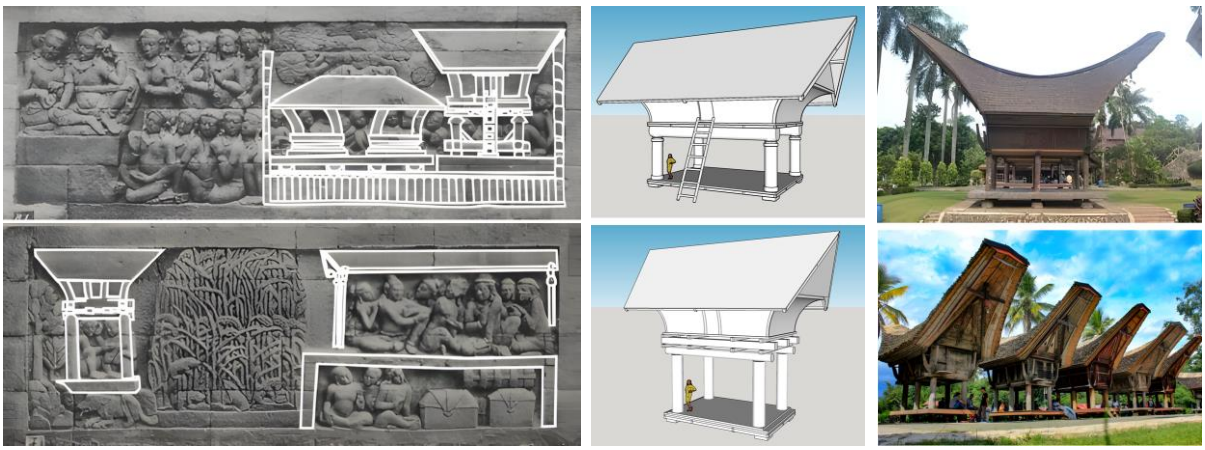
The Tongkonan house represents an ancient construction model originating from the prehistoric era. Its structural logic is considered highly consistent with the timber-stilt buildings depicted in the Karmawibhangga reliefs, particularly regarding the stilt foundations and roof typologies. Architectural theory suggests that the Tongkonan roof evolved through distinct stages, transitioning from simple forms to the modern, exaggerated curvature resembling an inverted boat. The third stage of this evolution matches the depictions found in the Borobudur reliefs more closely than the modern variant.

In Torajan tradition, the Tongkonan is designed as a pair with the *Alang Sura* (rice barn), which shares a similar aesthetic but differs in scale and function. Unlike the multifunctional underfloor space of Bolon house, the area beneath a Tongkonan is specifically reserved for livestock, particularly water buffalo. In contrast, the space beneath the Alang Sura serves as a communal area for social gatherings and meetings (see Figure 13).

Based on a detailed examination of the relief panels, this study identifies 2 distinct but visually similar

structures. While one panel aligns with the residential Tongkonan form, the study hypothesizes that the other represents the Alang Sura or rice barn. This identification is supported by the depiction of human figures gathering beneath the floor, a characteristic social function of the rice barn. Most notably, the presence of vividly carved rice plants immediately adjacent to the building provides a definitive contextual clue. Within the Torajan cosmological framework, the Tongkonan and Alang Sura exist as an inseparable pair, representing the balance between the domestic sphere and food security. Therefore, the appearance of these two similar structures in the reliefs strongly suggests a deliberate representation of this ancient architectural pairing.

The integration of digital 3D models opens significant opportunities for further research, including advanced structural load analysis. The elevation of house floors above ground level is not merely an artistic detail; it reflects a sophisticated adaptation to the tropical climate, soil moisture, seasonal flooding risks, and protection from wildlife. In this sense, the Borobudur reliefs not only serve as evidence of Ancient Javanese civilization but also document the broader architectural heritage of the Nusantara archipelago (see Figure 14). Digital modeling further allows for the testing of design hypotheses, such as variations in post spacing or roof slopes and their direct impact on stilt stability. Ultimately, this approach strengthens the validity of iconographic interpretation and provides a foundation for future experimental and structural simulation studies.



Stilt Structure Resembling Tongkonan House and *Alang Sura.* Source: [5]

3D Reconstruction

Existing Tongkonan house and *Alang Sura* (granary) in Toraja: [24], [38]

Figure 13. Comparative 3D analysis of Borobudur relief structures and Torajan architectural typologies

Figure 14. Distribution of stilt houses from Borobudur reliefs. Red dots: Yogyakarta and Surakarta Sultanates; green dot: Borobudur Temple; orange dots: Bolon and Tongkonan

5. Conclusions

This study concludes that the stilt dwellings depicted in the Borobudur reliefs represent a sophisticated and unified Nusantara architectural system that predates the localized ground-based Javanese typologies identified in later centuries. The 3D reconstruction process confirms that these ancient structures were not merely symbolic icons but functional architectural responses to the tropical environment. This is evidenced by the high clearance of the substructure, which provided essential protection against soil moisture, seasonal flooding, and wildlife. This finding shifts the perspective on ancient Javanese architecture from a purely cosmological interpretation toward a more practical, ecological, and functional understanding.

The research provides a significant contribution to the history of Indonesian architecture by filling a critical knowledge gap. It identifies a missing link in the evolution of Javanese dwellings, where the stilt house tradition, documented as a primary architectural form in the eighth century, eventually vanished in Java due to material transitions and socio-political shifts during the Islamic Mataram era. Furthermore, the striking similarities between the relief depictions and contemporary structures such as the Bolon House and Tongkonan House serve as definitive archaeological evidence of a common ancestry within Nusantara architecture.

While this study provides a novel methodological framework for interpreting symbolic iconography as functional architectural data, it acknowledges certain limitations. This research is primarily based on a literature review and the synthesis of existing archaeological documentation. Given that the reliefs are inherently symbolic and representative, not all architectural elements can be interpreted with absolute technical precision. However, these limitations do not diminish the validity of the findings. Instead, this research paves the way for future studies, particularly in mapping stilt house distributions across the archipelago and performing advanced structural or numerical simulations to test the load-bearing capacities of these ancient timber constructions.

Acknowledgements

The researcher expresses gratitude to Dr. Hari Setiawan MT at the Borobudur Conservation Center for providing literature, photographs of houses in Borobudur and other temples, and for his willingness to participate in interviews and field surveys.

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