

Article

Transformation from Military Fortresses to Modern Towns: Characteristics of the Morphological Evolution of Coastal Defense Garrisons in Wenzhou During the Ming Dynasty

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Abstract

As a complex heritage site embodying maritime defense civilization, the Ming Dynasty Coastal Defense Garrisons face a profound contradiction between protection and development. Current research has failed to effectively explain the spatial mechanism of the transformation of coastal defense garrisons from military fortresses to modern towns. This study selects three coastal defense garrisons in southern Zhejiang—Jinxiang Garrison, Puzhuang Fort, and Hai'an Fort—and, based on long-term spatial data from 1969 to 2025, uses GIS, spatial syntax, and fractal index methods to construct a morphological analysis framework from four dimensions: architecture, land parcels, streets and alleys, and boundaries, revealing their evolutionary patterns and functional transformation mechanisms. The results show that (1) morphological evolution follows an asynchronous and coordinated rhythm of “buildings filling in first, road network updating lagging behind, and boundaries continuously constraining.” (2) Differences in urbanization pressure, industrial implantation intensity, and cultural heritage management drive the three garrisons to differentiate into three transformation paths: gradual preservation, radical reconstruction, and balanced regularization. The intensity of street and alley renovation is the core indicator for judging whether the historical fabric is preserved. (3) The boundaries of the garrison exhibit a “macroscopically regular but microscopically fragmented” characteristic, with a simple outer boundary and a complex inner boundary. Even after the city walls disintegrated, the moat still served as a morphological inertial line, maintaining the stability of the macroscopic outline. This research can provide quantitative evidence and empirical reference for the differentiated protection of coastal defensive heritage.

Keywords: coastal defense garrison; southern Zhejiang; morphological evolution; spatial syntax; GIS; transition mechanism



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1. Introduction

1.1. Research Background

In the process of rapid urbanization, a large number of historical settlements face the dual pressure of spatial reconstruction and heritage protection [1,2]. As a composite her-

itage of the Ming Dynasty (1368–1644) coastal defense system, which combines military establishment, city form, street order, and subsequent civilian transformation, coastal defense garrison is not only a material carrier of ancient maritime defense civilization but also a spatial recorder of regional social changes [3,4]. However, the core dilemma faced by current protection practices and academic research is not the inadequate protection of individual remains but the failure to effectively explain how coastal defense garrison transformed from an institutional military fortress into a modern town with mixed functions [5,6]. This cognitive fragmentation directly leads to two consequences: on the one hand, the authenticity of the regional military landscape is continuously weakened due to disorderly construction [7]. On the other hand, the fragmentation of historical texture dissolves the continuity and integrity of space, and phenomena such as the weakening of the boundaries of city walls and moats, the widening or cutting of the cross-street framework, and the conversion of military land into residential and industrial land are common occurrences [8–10]. Therefore, the sustainable development of coastal defense garrison can no longer be addressed by static protection or individual restoration. A systematic study of its modern functional transformation and spatial evolution mechanisms is urgently needed.

This practical need echoes the shift in international military heritage research paradigms. In recent years, a consensus has gradually formed in the field of heritage research: the value of military heritage should not be limited to its initial defensive function or architectural style at a specific historical juncture but should be recognized in its long-term evolutionary continuity [11–13]. The concept of protection has thus shifted from simple material restoration to a systematic interpretation of the long-term evolution of heritage sites [14,15]. For coastal defense garrison, its core value lies not only in iconic remains such as walls and gates but also in the long-term coupling relationship between elements such as the topological order of the street framework, the logic of plot organization, the distribution pattern of building density, and the morphological inertia of boundary contours. This expansion of value recognition makes urban morphology—especially a theoretical tool focusing on the hierarchical relationship and historical superposition process of “street-plot-building”—a key path to analyzing the transformation mechanism of coastal defense garrison [16]. However, the evolutionary logic of coastal defense garrison cannot be simply applied to the theoretical models of general settlement morphology studies. There is a fundamental difference in their formation dynamics: general towns are mostly driven by bottom-up forces such as clans, markets, transportation, or agricultural production [17,18]. In contrast, the initial form of coastal defense garrison was rigidly constrained by the Ming Dynasty’s national military system, hierarchical structure, defensive boundaries, and barracks layout, making it a typical product of one-time planning [3,19]. Its subsequent evolution underwent a series of unique transformation processes, including the civilianization of military space, the residentialization of military land, the integration of military facilities into daily life, the dissolution of city defense boundaries, and the replacement of urban functions. In other words, general settlement studies answer the question of “how organic growth occurs,” while coastal defense garrison studies need to explore “how institutional planning forms are rewritten by modern urbanization.” The latter exhibits unique characteristics in its evolutionary driving forces, spatial response methods, and morphological transformation paths, distinguishing it from general settlements, and urgently requires a targeted analytical framework.

1.2. Progress and Limitations in the Study of the Morphological Evolution of Coastal Defense Garrison

Research on coastal defense garrisons has undergone a paradigm shift from military engineering history and architectural archeology to defensive landscapes, historical town landscapes, and dynamic conservation [12,20–23]. Existing findings can be summarized

from four levels: macro-system, individual morphology, quantitative methods, and conservation revitalization. While advancing our understanding, these findings also provide a reference for the entry point of this study.

- (1) Macro-system and institutional research. At the macro scale, researchers are committed to revealing the spatial organizational logic of coastal defense settlements. Scholars such as Zhang & Li (2005) and Tan (2012) were among the first to outline the hierarchical framework and distribution characteristics of the Ming Dynasty's coastal defense system [24,25]. In international research, Lee focused on the spatial hierarchy of the defense system [26], while Guedouh et al. (2025) and Oulmas et al. (2026) further pointed out that the coastal defense system possesses hierarchical and network characteristics [27,28]. In 1972, Kawagoe constructed the classic hierarchical framework of "garrison-fortress-camp" [29]. In recent years, the introduction of quantitative methods has deepened this understanding: Tan et al. (2021) used GIS minimum cost path analysis to verify the layout efficiency of "one fortress every seventy li" [30]. Liu et al. (2024) used long-term Japanese pirates (Wokou) data to reveal five phased adjustments of the Zhejiang defense system in response to the dynamic Japanese pirate's problem [3], correcting the traditional understanding of the static defense of garrisons.

However, macro-system studies often regard each garrison as a homogeneous node, focusing on explaining "why it was laid out here." But it is difficult to answer the question of "how it grows internally" in a single settlement, and the complexity and heterogeneity of its spatial evolution are obscured by the system framework.

- (2) Study individual morphology and city building system. At the individual and meso scales, researchers focus on the construction regulations and morphological characteristics of garrison cities. Studies have shown that the coastal defense city system of the Ming Dynasty provided a standardized construction template for the garrison, with the city walls, streets, and ancillary facilities all following a fixed form, presenting a highly modular street pattern [31]. In the study of international military architectural history, the innovation of firearms propelled European fortresses toward geometric and mathematical design, and military engineering technology spread widely with colonial activities [32–34]. Scholars clarified the design principles of bastions through geometric analysis [35,36] and completed the genealogy of European castles [37,38]. With urban expansion, traditional defensive buildings gradually integrated into urban spaces, evolving into urban landmarks and spatial skeletons [39].

Overall, existing research mostly focuses on interpreting the inherent form of the garrison, describing "what it looked like" rather than "how it evolved into this form." Therefore, existing results are insufficient to explain the transformation process from a single military fortress to a mixed residential settlement.

- (3) The introduction of quantitative methods. The introduction of methods such as GIS, spatial syntax, fractal theory, and principal component analysis has significantly improved the objectivity of the research. Zhou et al. (2024) used principal component analysis to assess the defensive effectiveness of garrisons [40]. Shen et al. (2023) used 3D point cloud models to quantify the blind spots of firepower in city walls and moats [41]. Domestic scholars have also conducted quantitative explorations of fractal and geometric indicators [42–44]. However, the quantitative objectives are still highly focused on static evaluations such as "defense effectiveness," and the changes in indicators have not been effectively linked to specific functional processes (such as land replacement and street widening). Methodological innovation has not simultaneously spurred discussions on the dynamic mechanisms of evolution.

In summary, existing research still has three shortcomings: First, it focuses on individual cases and static cross-sections, lacking multi-case long-term continuous analysis, making it difficult to distinguish between the particularity of individual cases and general laws. Second, the quantitative methods remain at the level of morphological description, failing to effectively connect functional transformation with spatial mechanisms. Third, urban morphology theory (especially the Conzenian School's "street-plot-building" framework) has not yet established a stable dialog with coastal defense garrison studies, and unique transformation processes such as "civilianization of military space" have not been incorporated into the morphological theory system for explanation.

1.3. Research Questions and Innovations

This study, within the framework of urban morphology theory, selects Puzhuang Fort, Hai'an Fort, and Jinxiang Garrison in Wenzhou, Zhejiang Province, China, as its research subjects. Based on observational data from seven time periods between 1969 and 2025, a morphological analysis system is constructed, encompassing four elements: buildings, plots, streets, and boundaries. Using quantitative indicators such as spatial syntax, morphological indices, and kernel density analysis, the study focuses on three key questions:

1. During the long-term urbanization process, do the morphological forms of buildings, streets, plots, and boundaries in coastal defense garrison exhibit a consistent evolutionary rhythm, or do they show asynchronous changes?
2. Under different levels of protection, location conditions, and development paths, does the morphological transformation of coastal defense garrison present identifiable differentiation types?
3. Which morphological indicators best characterize their functional transformation from a military defense space to a civilian settlement and heritage site?

The innovations of this study are mainly reflected in three aspects. First, a multi-period HGIS spatiotemporal database spanning 1969–2025 was constructed to provide fundamental support for long-term morphological evolution analysis. Second, a multi-dimensional index analysis framework of "building-plot-street-boundary" was established to identify the morphological differentiation patterns of coastal defense garrison under different evolutionary paths. Finally, the morphological differentiation characteristics of coastal defense garrison under three different evolutionary paths were compared to clarify the spatial logic and dynamic process of its transformation from a military settlement to a local town. This research can provide a reference analytical path for the spatial diagnosis of coastal defense garrison heritage and provide empirical support for enhancing its value recognition, formulating protection plans, and implementing revitalization and utilization.

2. Study Area, Methodology, and Data Sources

2.1. Study Area: Wenzhou City, Zhejiang Province

Southern Zhejiang was the core area for resisting Japanese pirates during the Ming Dynasty. The region boasts numerous Ming Dynasty garrison remains with significant differences in their preservation status, making it an ideal sample for studying the transformation of coastal defense settlements. This study selected three coastal defense garrisons—Puzhuang Fort, Hai'an Fort, and Jinxiang Garrison—located in Wenzhou, Zhejiang Province, China (Figure 1).

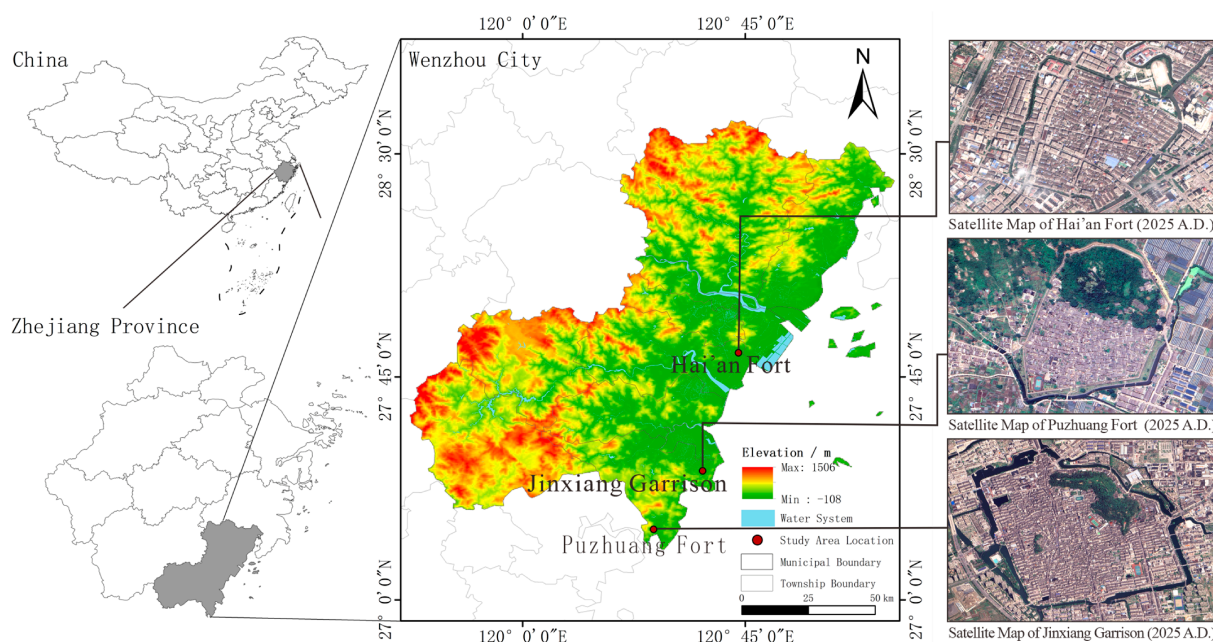


Figure 1. Location map of Puzhuang Fort, Hai'an Fort, and Jinxiang Garrison (Satellite Map source: National Geomatics Center of China; Map Approval No. GS (2024) 0650; URL: <https://cloudcenter.tianditu.gov.cn/administrativeDivision>, accessed on 18 March 2026) (Source: The author adapted the satellite map).

All three Coastal Defense Garrisons were built in the 20th year of the Hongwu reign (1387 A.D.) and were core defense nodes in the Ming Dynasty's southern Zhejiang coastal defense system. Table 1 provides detailed information on their latitude, longitude, area, shape, and status of protection.

Puzhuang Fort, Hai'an Fort, and Jinxiang Garrison share a common origin in their fortification but exhibit gradient differences in location, preservation status, and the impact of urbanization. They possess imagery data from seven time periods between 1969 and 2025, supporting long-term temporal morphological evolution research. To ensure the uniformity, standardization, and comparability of spatial morphological comparisons across multiple cases, this study adopts completely consistent boundary delineation rules for the three forts:

1. The core study area is limited to the area within the city walls and barbicans, excluding the moat, the buffer zone outside the city walls, and the built-up area outside the city.
2. Indicator statistics are only calculated within the city, strictly distinguishing them from the space outside the city.
3. The study boundaries are extracted from the outer contours of the city walls and barbicans, with completely unified scope, data units, and interpretation rules, ensuring consistency between long-term temporal analysis and horizontal comparison benchmarks.

Southern Zhejiang is located at the junction of Fujian and Zhejiang provinces, serving as a transitional zone in the Ming Dynasty's southeastern coastal defense system. Unlike the Fujian garrison settlements, which were mostly situated along mountains and coastlines, the garrison settlements in southern Zhejiang inherited the urban planning system of the Jiangnan plains while also incorporating features from the mountainous terrain of eastern Fujian. Influenced by topography, the military settlement system, and a cross-regional coastal defense policy, they developed a hierarchical defensive spatial form consisting of moats, city walls, and streets, while also serving production and living functions. This

case is a typical representative example in the study of the evolution of garrison structures during the Ming Dynasty.

Table 1. Comparison of core features of Jinxiang Garrison, Puzhuang Fort, and Hai’an Fort.

Comparison Dimensions	Puzhuang Fort	Hai’an Fort	Jinxiang Garrison
Latitude and Longitude	120.446° E, 27.234° N	120.732° E, 27.828° N	120.610° E, 27.432° N
Location Conditions	Coastal mountainous area	Coastal Plain	Coastal plain
Institutional Level	battalion-level administrative establishment (within the Ming guard system)	battalion-level administrative establishment (within the Ming guard system)	Guard-level administrative unit (within the Ming guard system)
Construction Time	Ming Dynasty, Hongwu 20th year (1387)	Ming Dynasty, Hongwu 20th year (1387)	Ming Dynasty, Hongwu 20th year (1387)
Initial Form Characteristics	Southern and northern circular, mountainous defensive type, complete crossroads	Square, cross-shaped symmetrical, with triple defense of walls, dikes, and moats, and a regular crossroads	Square-shaped, with a double-center cross street, integrating mountains, city, and water
Research Area	0.245 km ²	0.296 km ²	1.115 km ²
Military-to-Civilian Conversion Time	Tongzhi 11th year (1872)	Kangxi 11th year (1672)	Xuantong 2nd year (1910)

Source: the authors.

This study is based on two field surveys conducted in February and July 2025 at coastal garrison settlements in Fujian and Zhejiang. Taking into account the intensity of urbanization, the preservation of traditional urban fabric such as city walls, streets, and moats, and differences in location, three core coastal defense garrisons in southern Zhejiang were ultimately selected: Puzhuang Fort, built against mountains and with well-preserved traditional urban fabric, located on the coastal plain; Hai’an Fort, with a high degree of urbanization; and Jinxiang Garrison, where mountains, water, and city blend seamlessly and traditional urban fabric coexists with modern spaces. These three settlements exhibit significant differences in characteristics and can represent the main morphological evolution types of garrison settlements in southern Zhejiang.

2.2. *A Morphological Analysis Framework for Coastal Defense Garrison from a City Morphological Perspective*

Urban morphology emphasizes that urban space is composed of basic morphological units such as buildings, plots, and streets and forms a hierarchical spatial structure over a long historical process [45]. For historical settlements, streets reflect traffic organization and spatial order, plots embody land division and ownership usage, and buildings record construction intensity, functional carrying capacity, and textural density. This theory provides a basic analytical framework for explaining the transformation of a coastal defense garrison from a military settlement to a modern urban space.

However, coastal defense garrison differs from typical, naturally growing settlements. Its initial form was shaped from top to bottom by the Ming Dynasty’s coastal defense system. City walls, barbicans, city gates, and moats constituted strong boundary constraints, and cross streets and barracks together formed a highly regularized institutionalized spatial order. Therefore, in addition to the classic three elements of “street-plot-building,” the boundary itself is also a core variable that cannot be ignored in the morphological evolution of coastal defense garrison. Based on these factors, this paper constructs a four-

dimensional analytical framework of “building-plot-street-boundary.” The architectural dimension is used to identify building proliferation, density saturation, and space infill processes, reflecting the micro-manifestations of the transformation from military space to residential space. The plot dimension is used to characterize changes in land use ratios and land use structure, revealing the functional transformation of military land withdrawal, residential infill, and industrial implantation. The street and alley dimension is used to analyze changes in integration, selectivity, comprehensibility, and directionality, explaining the reorganization process of military order into a daily traffic network. The boundary dimension is used to assess the preservation, dissolution, and regularization of city walls, moats, and city outlines, reflecting the degree of transformation from closed defensive space to open urban space. Through the above four-dimensional framework, this paper further examines the response rhythms of different morphological elements and their interrelationships in long-term evolution (Figure 2).

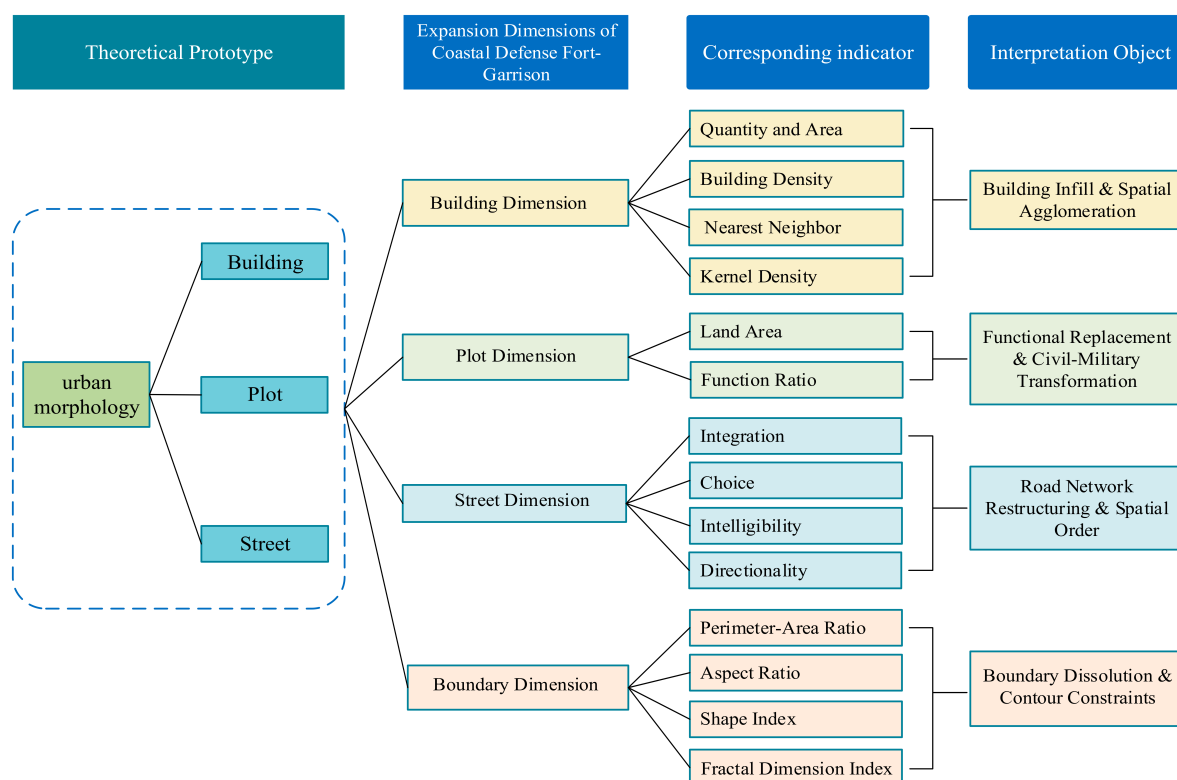


Figure 2. Analytical framework for the settlement morphology of Coastal Defense Garrisons based on urban morphology (Source: Drawn by the authors).

The morphological analysis framework of this study is based on Conzen’s (1960) theory of town-plan analysis, decomposing urban form into three core elements: streets, plots, and buildings [46]. The specific indicators for each dimension of the framework are derived from existing research in urban morphology: (1) indicators for the building dimension—such as building density, nearest neighbor, and kernel density—draw upon comprehensive reviews by Gorjian (2025) and Li et al. (2024) [47,48]; (2) indicators for the plot dimension—specifically land area and functional proportions—refer to studies by Li et al. (2018) and Firmansyah et al. (2024) [49,50]; (3) indicators for the street dimension—including integration, choice, and intelligibility—originate from Hillier and Hanson’s (1984) space syntax theory and subsequent applied research [51,52], while the indicator for orientation draws on Boeing’s (2019) work [53]; and (4) indicators for the boundary dimension—namely shape index and fractal dimension—refer to studies by Chen (2011, 2022) [54,55].

For coastal defense garrisons, this paper proposes the hypothesis that morphological evolution is not a synchronous change in a single element but rather a differentiated response process of boundaries, streets, plots, and buildings at different time scales.

2.3. Research Methods

This study adopts a four-stage technical approach of “definition-quantification-comparison-analysis” to explore the long-term morphological evolution of Puzhuang Fort, Hai'an Fort, and Jinxiang Garrison. (1) Integrate multi-source historical and current data to uniformly define the comparable research scope. (2) Construct a morphological quantification index system from four dimensions: buildings, plots, streets and alleys, and boundaries. (3) Based on long-term image data from 1969 to 2025, conduct longitudinal evolution tracking and horizontal case comparison. (4) Based on the results of multi-dimensional analysis, summarize the evolution characteristics, analyze the driving mechanism, and form research conclusions and protection strategy recommendations (Figure 3).

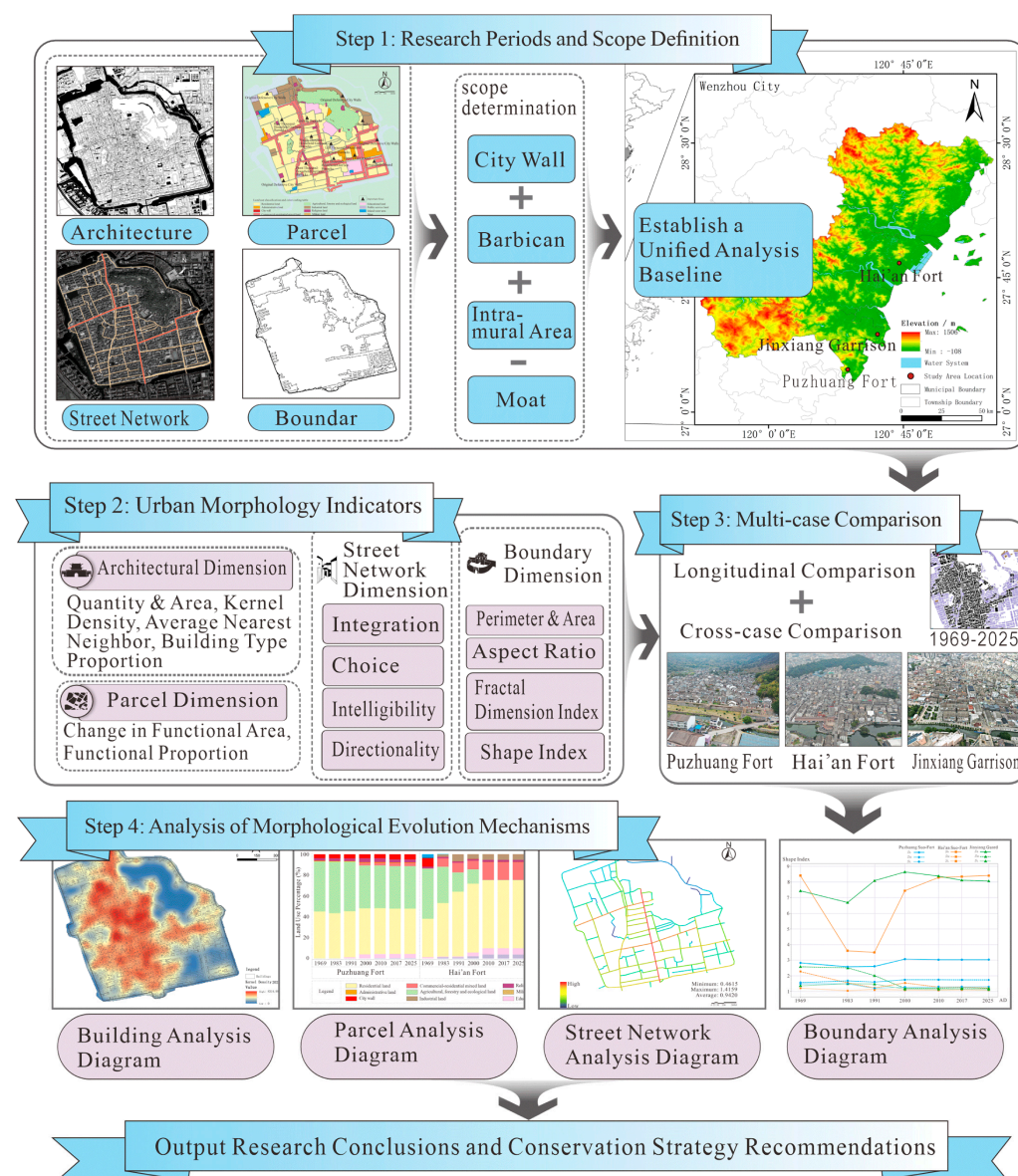


Figure 3. Framework for studying the morphological evolution of the Coastal Defense Garrison settlement (Source: Drawn by the authors).

2.3.1. Research Period Division

The study selected seven key years: 1969, 1983, 1991, 2000, 2010, 2017, and 2025. The selection of these points was based on data availability and took into account the correlation of major morphological changes (Table 2).

Table 2. Node Division in Long-Time Series Study of Coastal Defense Garrison.

Key Years	Stage Characteristics/Heritage Value	Corresponding Research Nodes
1969	Earliest clear image baseline period, reflecting the initial spatial pattern	Initial Morphological Baseline Period
1983	Demolition of city walls, a key node in boundary dissolution	Boundary Dissolution Period
1991	Early stage of urban expansion, the starting point for urban renewal	Urbanization Expansion Period
2000	Rapid urbanization, a key turning point in morphological evolution	Transformation Starting Point
2010	Slowing down of urban construction, the basic pattern has become fixed	Morphological Stability Period
2017	Intervention of protection policies and planning, the guiding role of control	Protection Intervention Period
2025	Current state section, the final form of settlement evolution and the effectiveness of protection	Current Status Observation Period

Source: the authors.

2.3.2. Building Quantitative Indicators

This study selects four quantitative indicators of architecture to analyze the architectural form of a garrison from four dimensions: scale, density, distribution pattern, and evolution direction. The specific formulas are shown in Table 3.

Table 3. Explanation of Building Quantitative Indicators.

Element Types	Research Indicators	Calculation Formula/Explanation	Processing Tools
Building	1. Number and Area (Maximum/Minimum/Average/Median)	Quantity: COUNT (Building Area Element) Area Statistics: MAX (Area), MIN (Area), AVG (Area), MEDIAN (Area)	ArcGIS Pro
	2. Building Density	$Building\ density = \left(\frac{\sum Area_{building}}{Area_{total}} \right) \times 100\%$	
	3. Average Nearest Neighbor	$ANN = \frac{\frac{1}{n} \sum_{i=1}^n d_i}{0.5 \times \sqrt{\frac{A}{n}}}$	
	4. Core Density Distribution	$f(s) = \sum (1/(h^2)) \times K((s - s_i)/h)$ (K is the kernel function, h is the search radius)	

Source: the authors. ArcGIS Pro (Chinese version), licensed for personal use; software obtained from the official ArcGIS website: <https://www.arcgis.com>, accessed on 20 March 2026.

1. Number and Area. The number of individual buildings and their base area within the statistical study unit are counted, including the maximum, minimum, average, and median values. This metric is used to identify the dispersion of building scale [56]. A large difference between the maximum and median indicates the emergence of high-density modern communities or large public buildings, disrupting the original homogeneous texture.
2. Building Density. The percentage of the total building base area to the total land area of the unit is used to measure the dynamic changes in spatial aggregation and diffusion [57]. An increase in the value accompanied by increased dispersion indicates the decline of the original residential area and the free dispersal of residential functions to the periphery.

3. Average Nearest Neighbor. The ratio of the measured average distance between each building and its nearest neighbor to the theoretically expected average distance (ANN value) [58] is used to determine the spatial distribution type of buildings. When $ANN < 1$, it is an aggregated distribution; when $ANN = 1$, it is a random distribution; and when $ANN > 1$, it is a uniform distribution.
4. Kernel Density Analysis. Using the kernel function as weight, density smoothing estimation is performed on building points within a given search radius [59]. It is used to reveal the patterns of architectural migration and can identify the paths and directions of spatial expansion, filling, and renewal.

2.3.3. Land Parcel Quantification Indicators

This study selects two quantitative indicators for land parcels to analyze the functional evolution of garrison land parcels from two dimensions: land use scale and structural ratio. The specific formulas are shown in Table 4.

Table 4. Explanation of Land Parcel Quantitative Indicators.

Element Types	Research Indicators	Calculation Formula/Explanation	Processing Tools
Land Parcel	1. Graphical representation of changes in the area of land parcels based on their functional attributes	$\Sigma \text{Area_class}$ (e.g., residential, commercial, military, administrative, public services) Rate of change = $\left(\frac{\text{Area}_{t2} - \text{Area}_{t1}}{\text{Area}_{t1}} \right) \times 100\%$	ArcGIS Pro
	2. Relationship of changes in the proportion of functional attributes	Proportion _{class} = $\left(\frac{\Sigma \text{Area}_{\text{class}}}{\Sigma \text{Area}_{\text{all}}} \right) \times 100\%$	

Source: the authors.

1. Changes in the area of land use functional attributes: The base area of various types of land uses in each period is statistically analyzed, and the rate of change between adjacent periods is calculated to visually present the growth and decline of land use areas [60]. The specific land parcels and their scales can be identified through area changes.
2. Proportional changes in functional attributes: The percentage of a certain type of land use area in the total land use area is used to reflect the degree of alienation in land use structure [61]. This metric is used to reveal the trend of functional reconstruction from traditional closed urban areas to modern open urban areas.

2.3.4. Street and Alley Quantitative Indicators

This study selects four quantitative indicators for streets and alleys to analyze the evolution of the morphology of garrison streets and alleys from four dimensions: accessibility, passage efficiency, spatial order and orientation consistency. The specific formulas are shown in Table 5.

Table 5. Explanation of Street and Alley Quantitative Indicators.

Element Types	Research Indicators	Calculation Formula/Explanation	Processing Tools
Street and Alley	1. Integration	$I_i = \frac{2(n-1)}{n \cdot TD_i} / \left[\frac{n}{2} \cdot \frac{1}{n-1} \right]$ Where n is the total number of axes, and TD_i is the topology depth value.	Depthmap-Beta 1.0

Table 5. Cont.

Element Types	Research Indicators	Calculation Formula/Explanation	Processing Tools
Street and Alley		$C_i = \frac{\sum_{j=1}^{j+1} \sum_{k=1}^{k+1} \sigma_{jk}(i)}{\sum_{j \neq i} \sum_{k \neq k} \sigma_{jk}}$ C_i: Choice value in space ii; σ_{jk}: total number of shortest paths from space jj to space kk; $\sigma_{jk}(i)$: number of shortest paths from space jj to space kk that pass-through space ii; numerator: sum of all shortest paths passing through space ii; denominator: sum of all possible shortest paths in the network.	Depthmap-Beta 1.0
	2. Choice		
	3. Intelligibility	$R = \text{Corr}(\text{Int_local}, \text{Int_global})$	
	4. Directionality	$SD = \sqrt{\frac{\sum_{i=1}^n (\theta_i - \theta_{\text{avg}})^2}{n}}$ (θ_i is the azimuth angle of a single street axis, and θ_{avg} is the average azimuth angle)	ArcGIS Pro

Source: the authors. Depthmap Beta 1.0 software source: Space Syntax Laboratory, University College London. Retrieved from <https://github.com/SpaceGroupUCL/Depthmap>, accessed on 20 March 2026.

1. Integration: The inverse weighted sum of the topological depths between a given axis and all other axes in the system, used to measure the topological accessibility and centrality of the road network [62]. A higher integration indicates a stronger locational advantage for the street within the overall network.
2. Choice: The percentage of times a given axis is traversed in all shortest paths, used to measure the traversal potential of the road network [62]. A higher choice indicates that the street is more likely to become a passageway, identifying key passages.
3. Intelligibility: The correlation coefficient between local integration and global integration, ranging from -1 to 1 , is used to measure spatial readability [63]. The closer the value is to 1 , the stronger the spatial readability, and the clearer and more easily perceived the spatial order.
4. Directionality: The standard deviation between the orientation angles of each street and alley and the average orientation angle, used to measure the consistency of the orientation of the street grid [53]. A smaller standard deviation indicates stronger orientation consistency, reflecting the rigid constraints of military planning.

2.3.5. Boundary Quantitative Indicators

This study selects three boundary quantification indicators to analyze the evolution of the garrison boundary from three dimensions: preservation status, outline regularity, and morphological complexity. In order to reveal the multi-scale response of the boundary morphology, this study selects three scales: 7 m (micro), 30 m (meso), and 100 m (macro) [64], calculates the shape index (S) and fractal dimension index (F), and combines them with the aspect ratio (λ) for analysis. The specific formulas are shown in Table 6.

1. Perimeter and Area Relationship (Wall Damage Rate): The percentage difference between the original wall perimeter and the existing wall perimeter relative to the original perimeter is used to quantify the physical preservation status of the wall boundary. A higher damage rate means that the historical boundary is more damaged, and vice versa.

2. Length-to-Width Ratio and Shape Index: The ratio of the longest axis to the shortest axis of the core area. The shape index is defined as the ratio of the boundary perimeter to the circumference of a circle of equal area [52]. It is used to determine the regularity of the boundary enclosure shape. By comparing the changes in the length-to-width ratio and shape index of the ancient and modern garrisons, the trend of the outline evolving from regular to irregular can be identified (Figure 4).

Table 6. Explanation of Boundary Quantification Indicators.

Element Types	Research Indicators	Calculation Formula/Explanation	Processing Tools
Boundary	1. Perimeter and Area Relationship Statistics	The wall damage rate = (original wall perimeter – current wall perimeter)/original wall perimeter × 100%	AutoCAD
	2. Aspect Ratio and Shape Index	The aspect ratio $\lambda = L/W$, the length of the longest axis (L)/the length of the shortest axis (W) of the bounded area; the morphological index $S1 = \frac{P}{(1.5\lambda - \sqrt{\lambda} + 1.5)} \sqrt{\frac{\lambda}{A\pi}}$, where P is the perimeter of the bounded area, λ is the aspect ratio, A is the area, and π is pi.	
	3. Fractal Dimension Index	Fractal dimension index: $F1 = 2\lg(0.25P)/\lg A$	

Source: the authors.

The long and short axes are determined based on the minimum bounding rectangle enclosing the outermost edges of the building footprint (indicated by the red dashed line in the figure); the longer orthogonal side of this rectangle represents the long axis, while the shorter side represents the short axis. These axes are perpendicular to each other and parallel to the sides of the rectangle. For the shape indices (boundary perimeter and area), the boundary patches are partitioned using grids of 7 m (micro-scale), 30 m (meso-scale), and 100 m (macro-scale); the perimeters and areas of all patches within each grid cell are aggregated, and these summed totals are used to calculate the indices.

3. Fractal Dimension Index: Based on the double logarithmic ratio of perimeter and area, it is used to measure the complexity of the boundary shape [52]. The higher the value, the more tortuous and complex the boundary, corresponds to the greater intensity of natural growth or human modification.

2.4. Data Sources and Processing

The data comes from four sources: (1) Historical documents. Information on the initial military spatial structure of the garrisons was obtained from local gazetteers such as the *Pingyang County Gazetteer* (平阳县志) and the *Ruian County Gazetteer* (瑞安县志), local cultural research documents such as *A Collection of Old Maps of Wenzhou* (温州古旧地图集) and *Famous Ming Dynasty Coastal Defense City: Jinxiang and Pucheng* (抗倭名城-金乡·蒲城), and exhibition materials from the Cangnan County Museum and the Ruian Museum (www.ruianmuseum.com, accessed on 2 May 2026). (2) Satellite remote sensing imagery. High-precision remote sensing imagery of the three garrisons was obtained through OMAP (www.ovital.com, accessed on 2 May 2026), Bigemap (www.bigemap.com, accessed on 2 May 2026), and O-map (www.o-map.cn, accessed on 2 May 2026). (3) Field survey data. Through field surveys, interviews, drone aerial photography, and street and alley mapping, we obtained real-world information on street and alley layouts, current building conditions, and functional distribution (March 2023; 12 July 2025; February 2026).

(4) Planning text data. We collected text data such as garrison plans and urban development plans from the Jinxiang Town Government, Pumen Community, and Tangxia Town Government, extracting morphological element information such as boundaries, buildings, road networks, and land use.

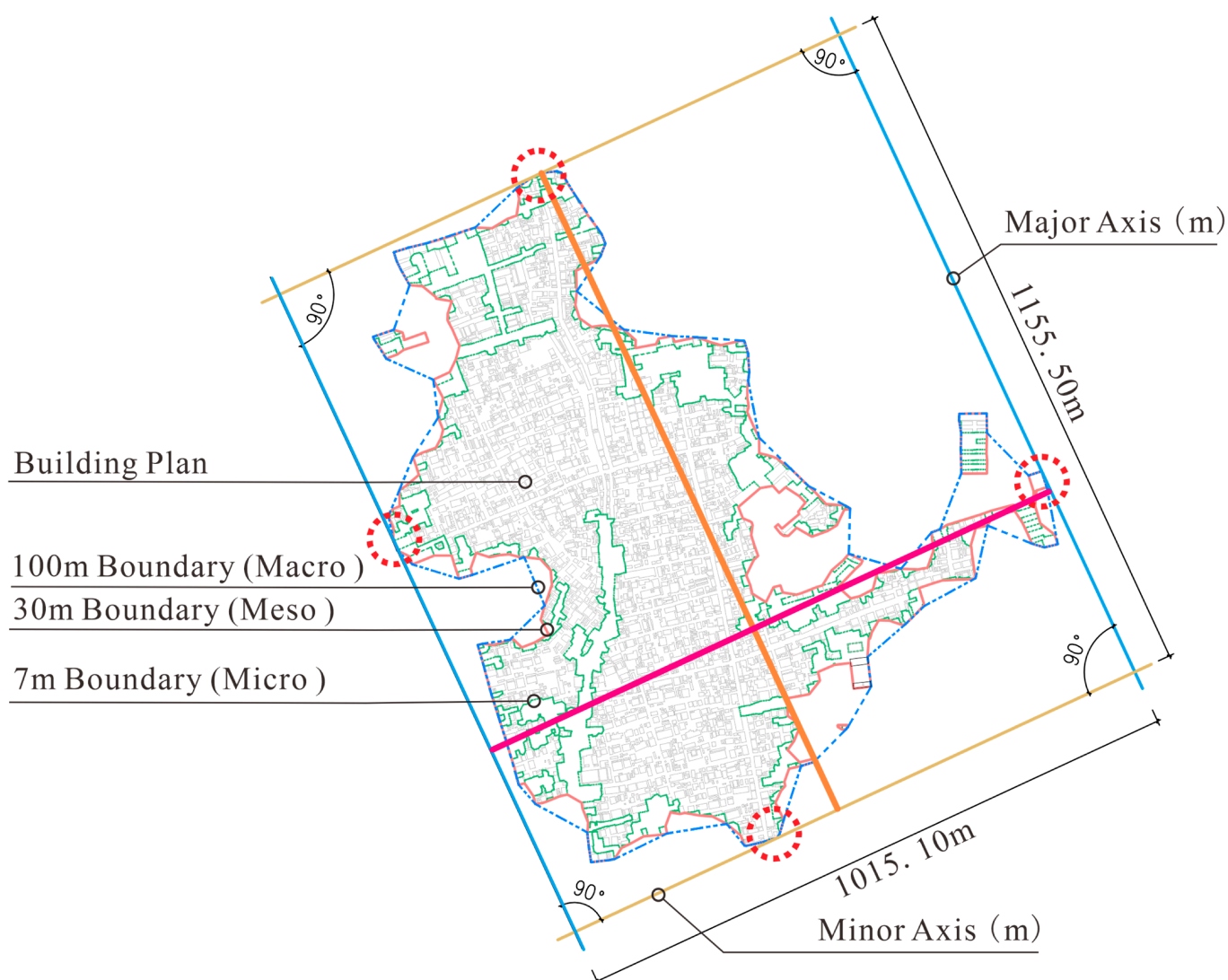


Figure 4. Schematic diagram illustrating the acquisition of data for aspect ratio and shape indices (boundary perimeter and area). (Source: Drawn by the authors).

Data processing flow: Based on the above four types of data, (1) we extracted satellite remote sensing image data of the three garrisons from 1969 to 2025. (2) Combining historical maps and field surveys, we performed geometric registration and deviation correction on the image data to ensure that the azimuth data at each time point basically corresponded. (3) We used AutoCAD 2026 version to draw spatial elements such as building foundations, road network patterns, boundary ranges, and rivers for different periods to obtain spatial data information of the three garrisons from 1969 to 2025, providing a basis for quantitative analysis. The quantitative results will be cross-validated with local historical records, current status surveys, and changes in key spatial nodes to reduce data errors from simple remote sensing interpretation and manual vectorization, ensuring the scientific reliability of subsequent quantitative analysis of settlement morphology (Figure 5).

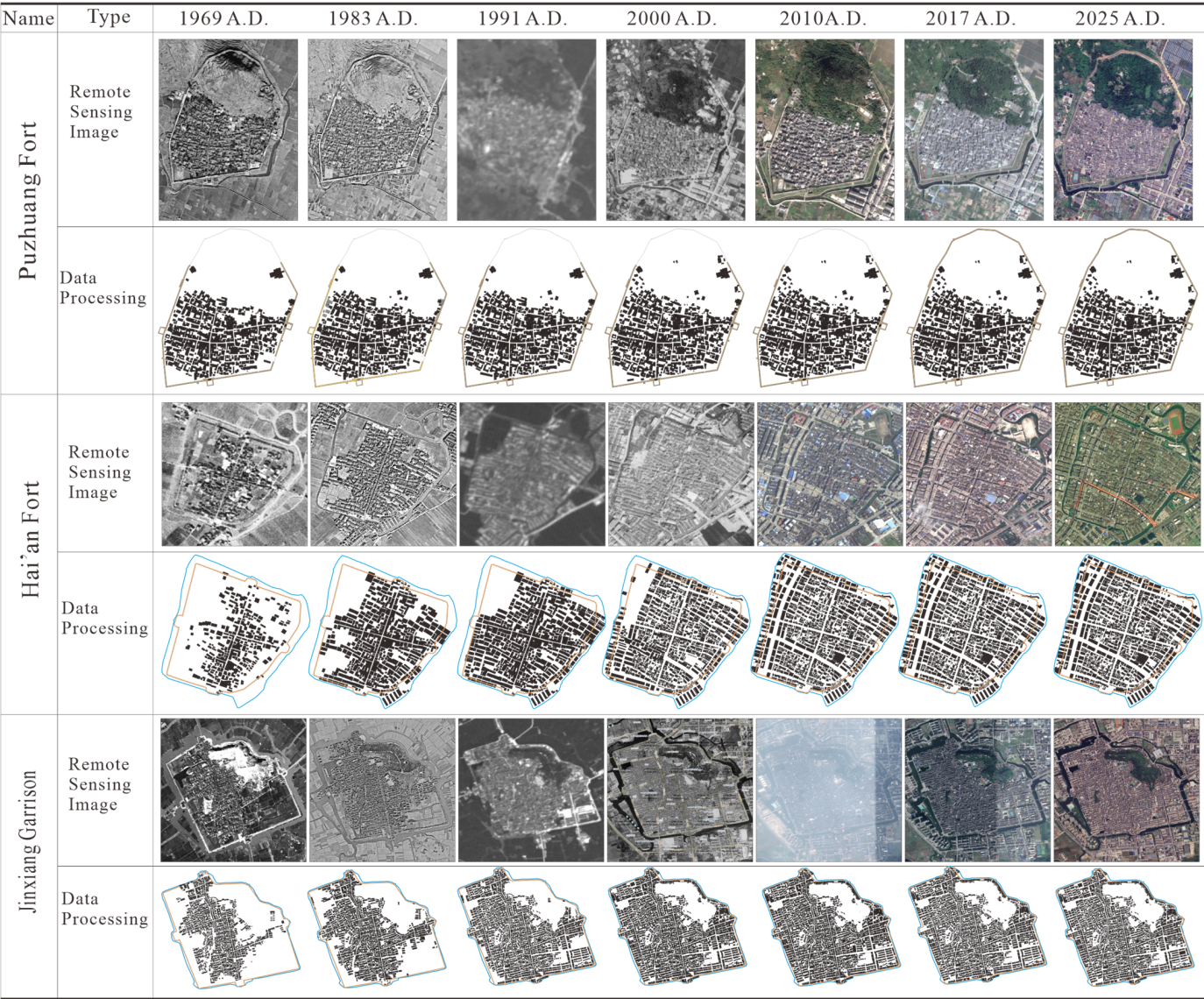


Figure 5. The architectural forms of the three Military Garrisons (1969 A.D.–2025 A.D.) (Source: Drawn by the authors).

3. Results

3.1. Building Scale Analysis

3.1.1. Number, Area, and Density of Buildings

The evolution of the number, area, and density of the three garrisons from 1969 to 2025 is shown in Table 7.

Table 7. Statistical Data on the Evolution of the Number and Area of Three Garrisons (1969 A.D.–2025 A.D.).

Name	Year	Number of Buildings	Minimum Building Area	Maximum Building Area	Total Building Area	Average Building Area	Standard Deviation of Building Area	Median Building Area	Building Density
Puzhuang Fort	1969	950	10.01	520.21	70,557.75	74.27	66.21	57.35	0.2880
	1983	981	10.01	520.21	72,973.89	74.38	66.01	57.54	0.2979
	1991	986	10.01	520.21	74,063.20	75.11	67.29	57.74	0.3023
	2000	1030	10.01	520.21	76,502.24	74.06	66.67	56.52	0.3123
	2010	1031	10.01	520.21	76,296.33	74.00	66.63	56.52	0.3114
	2017	1032	10.01	520.21	76,312.43	73.95	66.61	56.42	0.3115
	2025	1032	10.01	520.21	76,330.04	73.96	66.616	56.42	0.3116
Jinxiang Garrison	1969	2672	10.00	745.93	183,463.95	68.66	75.44	42.68	0.1628
	1983	3366	10.00	807.12	260,641.59	77.43	85.70	46.75	0.2313
	1991	4061	10.00	1485.05	343,243.34	84.52	100.09	47.99	0.3046
	2000	4397	10.00	1485.05	379,626.13	86.33	105.14	48.00	0.3369
	2010	4408	10.00	1485.05	382,081.83	86.68	104.74	48.18	0.3391
	2017	4383	10.00	1485.05	377,058.23	85.03	102.67	48.00	0.3347
	2025	4370	10.00	2144.68	379,877.04	86.93	111.73	48.00	0.3372
Hai'an Fort	1969	337	13.29	695.83	62,999.05	186.94	106.76	167.38	0.1720
	1983	612	13.99	1434.06	140,002.59	228.76	172.63	184.26	0.3823
	1991	729	10.50	1434.07	164,081.37	225.08	174.10	180.67	0.4481
	2000	1343	10.00	1447.63	131,811.96	98.15	126.52	50.62	0.3599
	2010	1367	10.00	2225.77	142,490.30	104.24	144.83	50.50	0.3891
	2017	1361	10.00	2225.77	145,522.24	106.92	148.66	51.75	0.3977
	2025	1349	10.00	2225.77	146,721.10	108.76	152.08	52.50	0.4007

Source: the authors.

The evolution of the three garrison towns can be divided into two stages:

1. Rapid Infilling Period (1969–2000)

From 1969 to 1991, the number of buildings in Puzhuang Fort increased from 950 to 986, and the building density rose from 0.288 to 0.302. The number of buildings in Hai'an Fort exploded from 337 to 729, and the building density jumped from 0.172 to 0.448. The number of buildings in Jinxiang Garrison increased from 2672 to 4061, and the building density rose from 0.162 to 0.305. During this stage, the three garrison towns primarily filled in vacant land, with building density increases of 4.9%, 160.5%, and 88.3%, respectively, leading to rapid saturation of buildable land within the towns.

2. Stable Stock Period (2000–2025)

After 2000, the building density of the three garrison towns tended to saturate, with an average fluctuation range of less than $\pm 5\%$. The Puzhuang Fort's building density remained stable at around 0.312, with a median building area of 56.42–57.74 square meters, indicating a consistent residential unit shape. Hai'an Fort's building density peaked in 1991 and then slightly decreased to 0.36, but the median unit area plummeted from 180.67 square meters in 1991 to 50.5 square meters in 2000. The original large units were replaced by modern, smaller units. After 2010, sporadic large-scale new buildings were added, resulting in a mixed form in Hai'an Fort characterized by a base of small units and heterogeneous large buildings. Jinxiang Garrison's building density remained stable at 0.34, with a median building area of 48 square meters. Its standard deviation steadily increased, reflecting the partial insertion of super-large buildings, while overall homogeneity remained excellent.

3.1.2. Average Nearest Neighbor

Between 1969 and 2025, with the continuous advancement of urban construction, the spatial agglomeration and differentiation among the three have continued to widen. The Puzhuang Fort nearest neighbor index changed from clustered to random and then returned to clustered. The Hai'an Fort nearest neighbor index has always been discrete, while the Jinxiang Garrison has gradually transitioned from clustered to discrete and random patterns. Specific parameters are shown in Table 8.

The nearest neighbor ratio of Puzhuang Fort rose from 0.957 to 0.976 and then fell back to 0.949, while the Z-value dropped from -2.51 to -1.47 and then recovered to -3.1 , exhibiting a “clustering-randomness-clustering” evolution trajectory. This indicates that after a brief period of loosening, the spatial order of the traditional military camp system re-established a stable clustering pattern after 2000.

The nearest neighbor ratio of Hai'an Fort consistently exceeded 1.0, and the Z-value remained above 10 for a long period, indicating a persistently dispersed spatial pattern. This suggests that intense urbanization dismantled the traditional military camp system's spatial order, with residential spaces freely scattering to the edges of streets and alleys, resulting in a long-term fragmented spatial pattern.

The nearest neighbor ratio of Jinxiang Garrison rose from 0.882 to 1.013, and the Z-value changed from -11.658 to 1.606. After 2000, the clustering effect continued to weaken, gradually evolving into a random distribution. Its traditional military camp system spatial order is now gradually disintegrating, with clustering and dispersion approaching equilibrium, and no drastic spatial fragmentation has occurred.

Table 8. Summary of the average nearest neighbor evolution of the three sanatoriums (1969 A.D.–2025 A.D.).

Garrison	Result	1969	1983	1991	2000	2010	2017	2025
Puzhuang Fort	Nearest Neighbor Ratio	0.957	0.974	0.976	0.952	0.949	0.949	0.950
	Z Score	−2.512	−1.567	−1.469	−2.958	−3.122	−3.113	−3.092
	<i>p</i> -value	0.012	0.117	0.142	0.003	0.002	0.002	0.002
	Clustering Results	Aggregation	Random	Random	Aggregation	Aggregation	Aggregation	Aggregation
Hai'an Fort	Nearest Neighbor Ratio	1.078	1.231	1.277	1.132	1.143	1.143	1.148
	Z Score	2.741	10.934	14.315	9.237	10.129	10.111	10.393
	<i>p</i> -value	0.006	0.000	0.000	0.000	0.000	0.000	0.000
	Clustering Results	Discrete	Discrete	Discrete	Discrete	Discrete	Discrete	Discrete
Jinxiang Garrison	Nearest Neighbor Ratio	0.882	0.926	0.975	1.0145	1.020	1.014	1.013
	Z Score	−11.658	−8.223	−3.102	1.814	2.528	1.772	1.606
	<i>p</i> -value	0.000	0.000	0.002	0.070	0.011	0.076	0.108
	Clustering Results	Aggregation	Aggregation	Aggregation	Random	Discrete	Random	Random

Source: the authors.

3.1.3. Spatial Kernel Density Distribution

The three garrison buildings were concentrated at the intersection of the main cross street in the city. As the buildings expanded, the high-density built-up area showed a pattern of first filling the center and then spreading outward layer by layer (Figure 6).

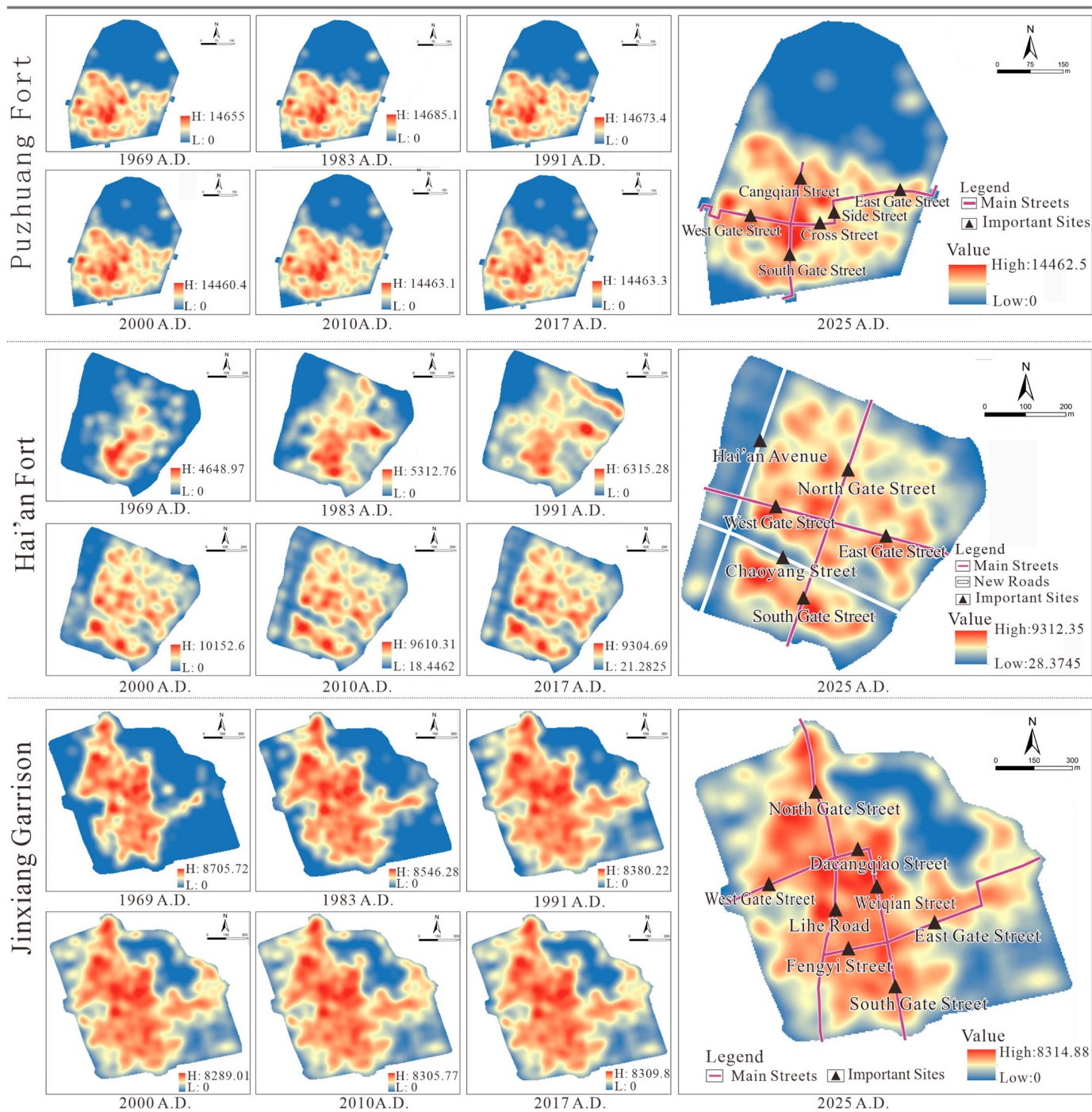


Figure 6. Kernel density evolution of the three Military Garrisons (1969 A.D.–2025 A.D.) (Source: Drawn by the authors).

From 1969 to 1991, the high-density area of the Three Garrisons only saw minor infilling of the core streets and alleys, with large areas of low-density blue open space on the periphery. After 2000, the high-density area of the core streets and alleys reached saturation, and hot spots began to spread outwards along the main and secondary streets. From

2010 to 2025, large secondary high-density areas appeared on the periphery, and the focus of building infill shifted from buildings within the old city to outward expansion along the streets.

Comparing the core density distribution from 1969 to 2025, it is clear that the core hot zone of the crossroads has never completely disappeared, and the historical street and alley framework has long constrained the core area of building expansion. All newly added high-density patches in the Three Garrisons are linearly distributed along the main streets, with streets and alleys serving as the core corridors for building expansion. The lack of road access to these areas has resulted in a consistently low development intensity.

The annual color changes in the Three Garrisons visually reflect these trends: the blue low-density area has been continuously shrinking, while the high-intensity construction areas represented by red and yellow have been expanding, indicating that the overall development intensity has increased year by year along with the urbanization process. After 2000, the peak building density and spatial distribution pattern of the three garrisons stabilized, and the transformation of settlement space based on building infill was basically finalized. The high-density hotspot of Puzhuang Fort was long confined within traditional cross-street lanes, maintaining a stable single core and a spatial pattern of dense development in the west and sparse development in the east. Hai'an Fort experienced intense street and lane redevelopment; the construction of Chaoyang Avenue and Hai'an Avenue in 2000 (shown by the white line in Figure 5 for 2025 A.D.) spurred the development of large areas of surrounding land but also fragmented the original high-density patches. The widening and redevelopment of internal streets and lanes resulted in multiple dispersed high-density patches within the city, with a significantly fragmented internal spatial fabric. The high-density hotspot of Jinxiang Garrison has consistently developed in a balanced manner around its core streets and lanes, achieving a relative balance between urban renewal and the preservation of traditional street and lane fabric. Spatial development shows a stable core area where buildings are slowly spreading out.

3.2. Plot Scale Analysis

3.2.1. Changes in Area Diagram of Plot Functional Attributes

1. Gradual Withdrawal of Defensive Function

In 1969, the three garrisons site maintained its original military function. By 1991, the reduction or disappearance of defensive elements such as military sites, city walls, and waterways occurred as buildings filled in vacant land. The three garrisons thousand-household garrisons and barracks were transformed into residential functions, and the Jinxiang Garrison Upper and Lower School sites were divided into residential, educational, and administrative functional sites. At this point, the three garrison's site's function entirely changed from military to civilian (Figure 7).

The area occupied by the Jinxiang Garrison city wall decreased from 6.63 hectares to 0.01 hectares, a reduction of 99.8%, with military land decreasing from 6.58 hectares to zero. The area occupied by the Hai'an Fort city wall decreased from 2.29 hectares to 0.02 hectares, a reduction of 99.1%, with the water area within the city completely disappearing. Puzhuang Fort was the only exception, with its city wall area increasing from 0.85 hectares to 1.09 hectares, an increase of 26%, but its defensive function was substantially weakened. The withdrawal of defensive functions freed up space for subsequent land use replacements; specific parameters are detailed in Appendix A (Tables A1–A3).



Figure 7. Land parcel evolution of the three Military Garrisons (1969 A.D.–2025 A.D.) (Source: Drawn by the authors).

2. The Rapid Infilling Phase of Residential and Industrial Land

After 1991, residential and industrial land continued to expand, and by 2025, the proportion of residential land in the three garrison areas tended to stabilize. Puzhuang Fort maintained 44–46%, Hai'an Fort 65.3%, and Jinxiang Garrison 54%, with residential land dominating the evolution of garrison land use. Development has continuously encroached upon agricultural and forestry ecological land, the natural foundation of the garrison areas. The more urbanized an area is, the less it loses. For example, Hai'an Fort lost 99.4% of its area, Jinxiang Fort lost 72.2%, and Puzhuang Fort lost 15.2%.

Industrial land is a key variable in the differentiation of the garrison area's morphological evolution. In Hai'an Fort, industrial land developed from scratch, intertwined with commercial and residential land. After 2000, the two combined accounted for 20%, driving the overall restructuring of land functions. In Jinxiang Garrison, industrial land was systematically established, accounting for approximately 8.74%, mainly located in peripheral clusters and not encroaching on the old town core. Commercial and residential land in the old town grew rapidly, accounting for 17%. Puzhuang Fort, however, had no industrial land at all and only a small amount of modern functions, such as commercial, residential, and educational facilities, totaling less than 5%.

3. Alleviating the functional load on the old town core plots.

The rapid influx of residential and industrial land has continuously increased traffic pressure between plots. After 1991, Hai'an Fort initiated a project to improve the accessibility of the site, demolishing existing buildings to free up road space, widening and straightening streets and alleys, and planning the construction of Hai'an Avenue and Chaoyang Avenue to improve traffic connectivity between the sites. In the 1980s, Jinxiang Garrison experienced rapid industrial and commercial development, and the core area's building and industrial and commercial development became saturated. This forced the government to delineate functional zones for the outer areas of the core area, expand the supporting road network, release idle land such as agricultural, forestry, and water areas, accommodate the spillover of industrial and commercial activities, divert pedestrian and industrial demand from the core area, and alleviate the pressure on the core area's land use.

3.2.2. Proportional Changes in Functional Attributes

From the perspective of the changes in land use ratio, after 2000, the three garrisons entered the stock optimization stage, and the differentiation path of functional ratio became clearer (Figure 8).

Hai'an Fort has a combined residential and commercial/residential ratio of 82.3%, forming a "residential + industrial + commercial/residential" structure. Jinxiang Garrison has a combined residential and commercial/residential ratio of 67.1%, with industrial, educational, and administrative land uses increasing simultaneously, forming a "residential + industrial + commercial/residential + public service" structure, and the functional attributes of the plots are becoming more complete. Puzhuang Fort has a "residential + agricultural, forestry, and ecological" ratio of 84.3%, with the land used for the city wall remaining stable at 3.8–4.8%, making it the only case among the three garrison areas that retains military defense space. Detailed data results can be found in Appendix A (Table A3).

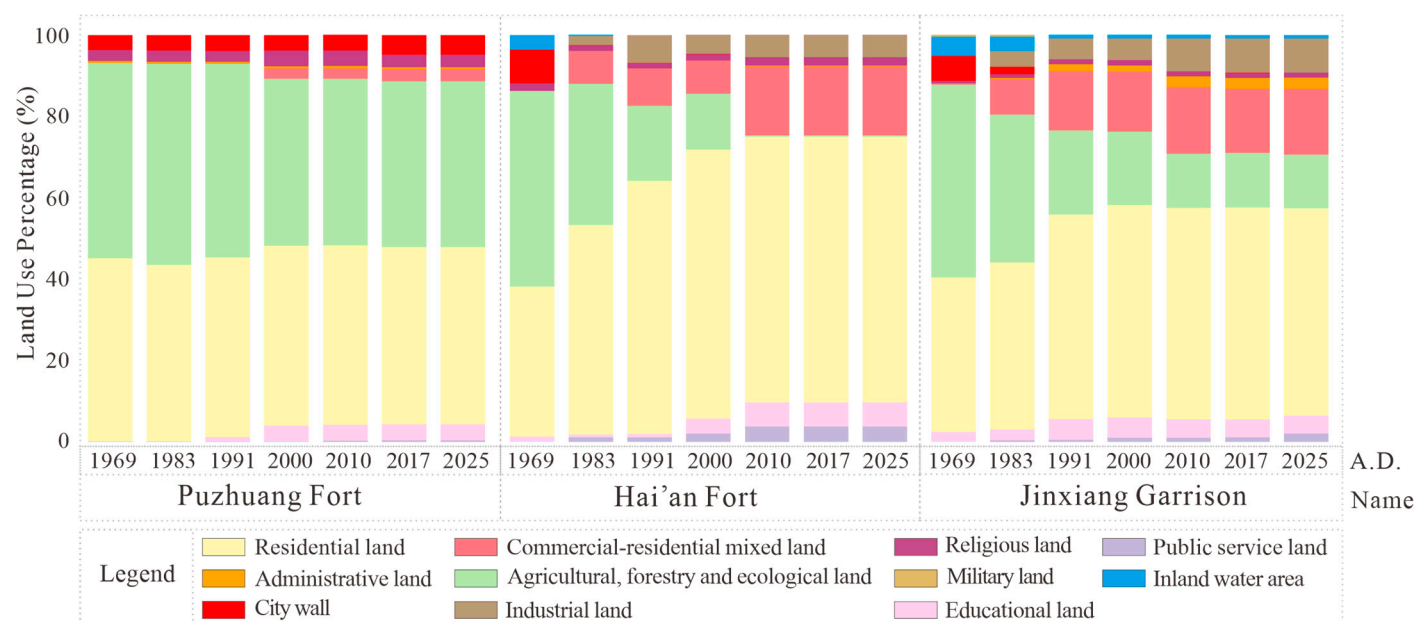


Figure 8. Proportion of different types of land parcels in the three Military Garrisons (1969 A.D.–2025 A.D.) (Source: Drawn by the authors).

3.3. Street and Alley Scale Analysis

3.3.1. Integration, Choice and Intelligibility

1. Global Integration

The original street and alley framework of the three garrisons dominated the evolution of global integration, exhibiting a temporal evolution characterized by main street agglomeration and overall equalization. From 1969 to 1991, the high integration areas of the three garrisons were concentrated on the main streets connecting the four city gates, while the accessibility of streets and alleys near the city walls and waterways was relatively low, resulting in significant spatial differentiation in street and alley vitality. From 2000 to 2010, through street and alley renovation and road network construction, the homogenization level of the road network continuously improved, the integration of branch roads gradually increased, and the differences in street and alley vitality levels continued to narrow. After 2010, the road network renovation was basically completed, and the integration of streets and alleys within the city tended to be balanced (Figure 9).

The three garrison areas show significant differences in their integration. Puzhuang Fort Integration has remained consistently low at 0.74–0.82. Within the main cross-shaped street network, Nanmen Street, Ximen Street, Cangqian Street, Shizi Street, and Heng Street have consistently shown high integration, while Dongmen Street's integration has been declining. Overall, the street network exhibits weak centrality, with the city wall significantly inhibiting outward expansion of activity, resulting in pronounced spatial polarization.

Hai'an Fort Integration has consistently been greater than 1.0, and the value has been steadily increasing over the years. Within the main cross-shaped street network, Nanmen Street and Beimen Street have consistently maintained high integration. As the road network has expanded annually, the integration of Dongmen Street and Ximen Street has continuously strengthened. High integration has evolved from an early north–south single axis to a highly integrated area covering the main cross-shaped street network, with the radiation layer continuously expanding outward, ultimately forming a modern road network structure with a single center and progressively expanding layers.

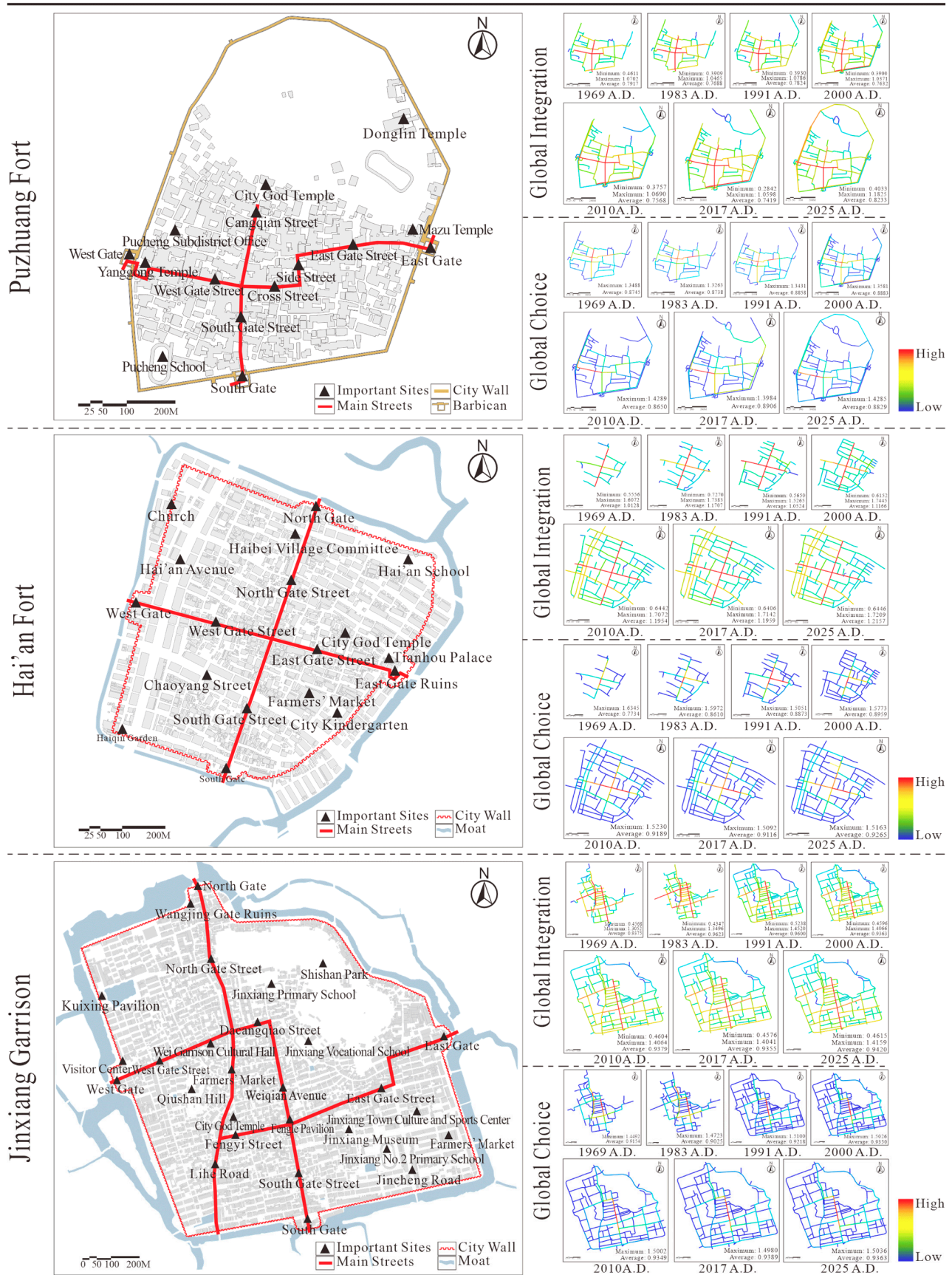


Figure 9. Integration and choice evolution of the three Military Garrisons (1969 A.D.–2025 A.D.) (Source: Drawn by the authors).

Jinxiang Garrison remains within a balanced range of 0.93–0.98. With the expansion of the road network around the core area, Nanmen Street and Weiqian Avenue have consistently maintained a high integration advantage, while the integration of Beimen Street, Dongmen Street, Dacangqiao Street, Fengyi Street, and Lihe Road has continued to decline. The high-integration street pattern has gradually evolved from the “井”-shaped double cross core pattern in 1969 to a “干”-shaped structure, exhibiting a multipoint, dispersed distribution. The original single core has dissolved, ultimately forming a multi-center networked street spatial structure. Specific parameters are shown in Table 9.

Table 9. Statistical analysis of Space Syntax results for the three Garrisons (1969–2025).

Name	Year	Number of Axes/Line	Integration		Choice		Intelligibility (R ²)	Spatial Relevance
			Maximum Value	Average Value	Maximum Value	Average Value		
Puzhuang Fort	1969	69	1.0701	0.7917	1.3488	0.8745	0.3748	Low Relevance
	1983	79	1.0465	0.7688	1.3263	0.8738	0.2832	Low Relevance
	1991	79	1.0786	0.7824	1.3431	0.8858	0.2553	Low Relevance
	2000	113	1.0371	0.7632	1.3581	0.8883	0.3380	Low Relevance
	2010	117	1.0690	0.7568	1.4289	0.8650	0.3343	Low Relevance
	2017	129	1.0598	0.7419	1.3984	0.8906	0.2592	Low Relevance
	2025	136	1.1825	0.8233	1.4285	0.8829	0.4293	Medium Relevance
Hai'an Fort	1969	28	1.6072	1.0128	1.6345	0.7734	0.6741	High Relevance
	1983	48	1.7383	1.1707	1.5972	0.8610	0.5686	Medium Relevance
	1991	64	1.5265	1.0254	1.5051	0.8873	0.6172	High Relevance
	2000	89	1.7445	1.1166	1.5773	0.8959	0.5122	Medium Relevance
	2010	112	1.7073	1.1954	1.5230	0.9189	0.4965	Medium Relevance
	2017	113	1.7142	1.1959	1.5092	0.9116	0.4971	Medium Relevance
	2025	113	1.7209	1.2157	1.5163	0.9265	0.4827	Medium Relevance
Jinxiang Garrison	1969	125	1.3052	0.9750	1.4492	0.9154	0.5497	Medium Relevance
	1983	150	1.3496	0.9623	1.4723	0.9025	0.5074	Medium Relevance
	1991	219	1.4520	0.9600	1.5100	0.9218	0.3789	Low Relevance
	2000	235	1.4066	0.9363	1.5026	0.9350	0.3246	Low Relevance
	2010	238	1.4064	0.9379	1.5000	0.9349	0.3294	Low Relevance
	2017	235	1.4041	0.9355	1.4980	0.9389	0.3301	Low Relevance
	2025	242	1.4159	0.9420	1.5036	0.9363	0.3328	Low Relevance

Source: the authors.

2. Global Choice

The street layout of the three garrisons determined the pedestrian flow pattern, with the core passageway of choice remaining stable at the main cross street for a long time. From 1969 to 1991, only the main street exhibited a high-choice warm color, while side streets and periphery streets rarely served cross-area passage functions. After 2000, the traffic flow of secondary grid side streets gradually increased, and pedestrian flow began to disperse to side streets around the main street. After 2010, the road network system was improved, and cross-area passage paths became more diversified. By 2025, the average global choice of the three garrisons will have settled in the range of 0.88–0.94, showing

an overall evolution trend of traffic flow from a single main street to a distributed network across the entire area. With the continuous increase in the number of axes, the characteristic of traffic concentration on a single main street in the military defensive city weakened, and road network traffic was dispersed to streets and alleys at all levels, forming a homogeneous, multi-center road network pattern adapted to modern life.

The global choice of the three garrisons shows significant differences. Puzhuang Fort's average choice value remains stable between 0.87 and 0.89. Limited by its single cross-shaped street network, its traffic distribution capacity is insufficient, with the main east–west street consistently bearing the majority of through traffic. Hai'an Fort saw the largest increase in its average choice value, rising from 0.77 to 0.93. The warm-colored area along its main cross-shaped street continues to expand, significantly enhancing its hub-and-spoke functionality. Jinxiang Garrison's average choice value remains stable between 0.90 and 0.94. Its grid-like structure offers advantages in multi-path traffic distribution, with the north–south main street serving as the core corridor. Lateral grid branches evenly distribute vehicle and pedestrian traffic, preventing excessive congestion on any single street. Overall, the higher the complexity of the street grid, the weaker the monopolistic effect of Main Street through traffic. With continuous street network updates, the constraints imposed by traditional boundary elements such as city walls and moats on cross-area through traffic paths are gradually decreasing.

3. Intelligibility

Puzhuang Fort's R^2 remained at a low correlation of 0.25–0.43 for a long period, only rising to 0.4293 in 2025, reaching a medium correlation. The overall pattern is difficult to infer from local street and alley spaces, retaining a maze-like defensive characteristic. Hai'an Fort's Intelligence R^2 remained stable in the 0.48–0.67 range, with spatial correlation mainly at a medium to high level. Its initial R^2 reached 0.6741, exhibiting the best spatial identifiability. After street and alley renovations in 1991, the value gradually decreased year by year, falling to 0.4827 in 2025. Increased road network complexity slightly weakened spatial readability, but the overall topological order of the town remained relatively clear. Jinxiang Garrison's R^2 declined from 0.55 to around 0.33 year by year, experiencing fluctuations from clear spatial identification to chaotic topological structure and then stabilizing at a low level. This reflects that after 1991, peripheral expansion disrupted the original road network topology, leading to a continuous weakening of overall spatial readability.

3.3.2. Street and Lane Directionality

From 1969 to 2025, the extreme values of street and lane directionality in the three garrison areas decreased synchronously, and the evolution trends were similar, but three different types of spatial paths were formed based on the original foundation (Figure 10).

Common patterns: First, the directional orientation of the main streets and alleys continuously weakens. As shown in Figure 10a, the maximum directional value of the streets and alleys in each garrison area decreased year by year and tended to stabilize after 2010. The main streets of the military-regulated crossroads and the border city walls have significant spatial orientation, and continuous street and alley renewal has weakened their spatial dominance. Second, road network orientation tends to be more balanced. In Figure 10b, the median value dropped from 6 to 9 to 4–5, and the overall street and alley network developed from a single main axis pattern to a multi-directional balanced network. Third, the density of the street and alley network becomes polarized. Figure 10c shows that the minimum value of Puzhuang Fort and Jinxiang Garrison City has been at a low level of 0.25 for many years, and their low-directional branch alleys are denser. The minimum value of Hai'an Fort shows a U-shaped trend, and after 2010 it stabilized in the range of

1–1.25. After the widening and straightening of streets and alleys, the overall orientation of the street and alley network is more open.

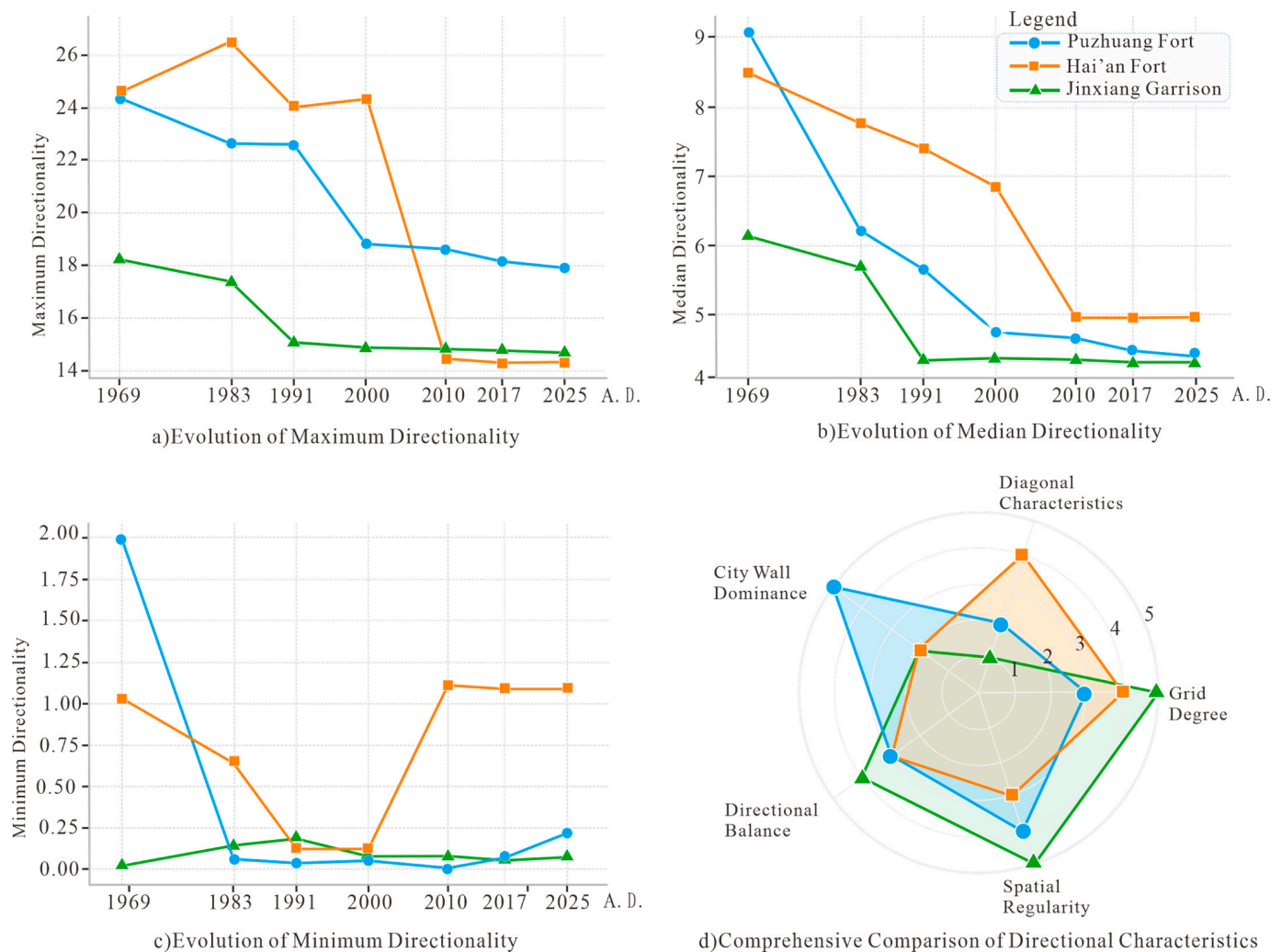


Figure 10. Temporal changes in street direction of the three Military Garrisons (1969 A.D.–2025 A.D.) (Source: Drawn by the authors).

Characteristics of individual garrison areas: The maximum and median values of Puzhuang Fort steadily decreased, with the median value decreasing by 51.40%. From 1969 to 1983, numerous small alleyways were added, causing the minimum value to drop from 1.99 to 0.22, a decrease of 89.04%. After 1990, the city wall and inner ring road were repaired and connected, resulting in a slight increase in the minimum value. Highly directional streets and alleys shifted towards the city wall boundary, the dominance of cross streets decreased, and the balance was maintained by the city wall, resulting in a road network pattern of dense boundaries and sparse interior.

Hai'an Fort initially had a maximum value of 24.62, ranking first among the three. From 1969 to 1991, rapid building construction drove the expansion of diagonal main roads, raising the maximum value to a peak of 26.43, while street and alley renovation lagged behind. From 2000 to 2010, grid-based renovations were implemented, causing the maximum and median values to plummet by 40.50% and 27.37%, respectively. The minimum value remained above 1.0, with the interior filled with regular, medium-directional branch roads. After 2010, the index stabilized, control of the original diagonal arterial roads weakened, and the overall directionality tended toward balance.

The maximum value of Jinxiang Garrison decreased by only 19.29%, while the median decreased by 29.57%. All three values stabilized as early as 1991, indicating an early start in street and alleyway evolution. The median value was consistently the lowest across the region, stabilizing first at 4.31, with the orthogonal grid-like road network ensuring a high degree of directional balance. The minimum value remained consistently low, indicating continuous densification of streets and alleyways, resulting in optimal grid regularity and balance.

Figure 10d shows three unique evolutionary paths for the three garrison cities:

Puzhuang Fort exhibits a strong dominance of its city walls, with further reinforcement of its boundary orientation after renovation. Internal street and alleyway modifications are limited. Although it retains the framework of Ming Dynasty Street and alleyway regulations, the street and alleyway orientations are singular, with the weakest diagonal characteristics, failing to improve spatial directional balance. The overall structure presents a binary, solidified spatial structure with strong outer boundaries and a weak inner grid.

Hai'an Fort exhibits prominent diagonal street and alleyway characteristics, with a high degree of diagonal features and grid formation. Street and alleyway renewal relies on the original diagonal main axis layout. Subsequent grid-based construction of streets and alleyways failed to form an orthogonal street and alleyway pattern. The maximum value of street and alleyway directionality has remained consistently high, and the overall regulation and directional balance of the streets and alleyways are significantly weak.

Jinxiang Garrison features a regulated orthogonal grid with optimal grid formation and regulation and the lowest median value of directionality. It was the first to complete its pattern formation. It gradually expanded from a double-cross main axis to a regular chessboard road network, with east–west and north–south main streets and alleys maintaining a stable layout and small side roads evenly filling the blocks. The overall space is regular and balanced, without obvious diagonal or boundary-dominated features.

3.4. Boundary Scale Analysis

3.4.1. Perimeter and Area Relationship Statistics

1. Evolution Characteristics of 7 m, 30 m, and 100 m Boundaries

From 1969 to 2000, the perimeters of the three garrisons increased simultaneously at 7 m, 30 m, and 100 m. Puzhuang Fort, constrained by the city wall boundary, had long-term high overlap between the 30 m and 100 m boundaries. Before 1991, Hai'an Fort and Jinxiang Garrison were mainly filled with internal buildings, and the 30 m and 100 m boundaries slowly became more regular; after 1991, construction broke through the original city wall, and the moat became the constraining boundary, further regularizing and overlapping the 30 m and 100 m outlines.

The 7 m fluctuations in Puzhuang Fort were long concentrated at the edge of the city wall, and the street and alley texture remained stable. After 1991, Hai'an Fort underwent large-scale street and alley renovations, and the newly built road network increased the complexity of the 7 m boundary. In Jinxiang Garrison, 7 m changes occurred more frequently in newly built areas outside the traditional blocks. As can be seen, with the filling of building land, the 30 m and 100 m boundaries tend to overlap, while the 7 m scale boundary changes are always higher than those at the 30 m and 100 m scales. Furthermore, with the widening and renovation of streets and alleys and the increase in newly built roads, the 7 m boundary becomes more complex and diverse (Figure 11).

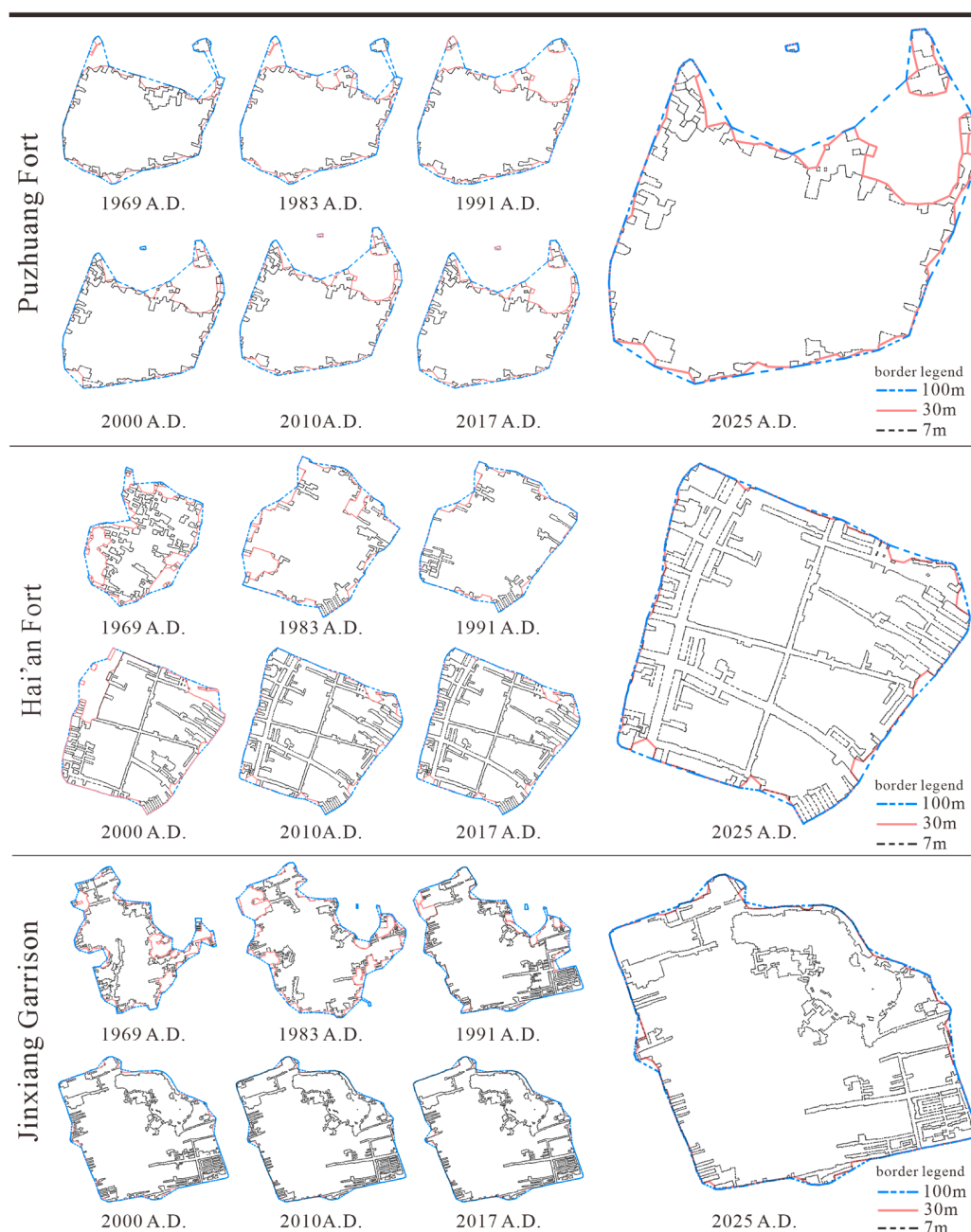


Figure 11. Evolution of boundary morphology at 7 m, 30 m, and 100 m for the three Military Garrisons (1969 A.D.–2025 A.D.) (Source: Drawn by the authors).

2. Statistical Results of the Relationship between Wall Damage Rate, Perimeter, and Area

The damage rate of the Puzhuang Fort city wall decreased from 24.47% in 1969 to 0% in 2017, indicating that the wall has been repaired and remains stable. The 7 m perimeter fluctuated only slightly from 3400.26 m in 1969 to 3772.2 m in 2025. During the same period, the area increased only slightly from 0.1132 km² to 0.1191 km². The area and perimeter at the 30 m and 100 m scales also showed slight increases, stabilizing after 2000. The increase was concentrated within the city wall, exhibiting characteristics of boundary constraints and internal infill. Specific parameters are shown in Table 10.

Table 10. Statistics on the existing city walls of the Three Garrisons, their major and minor axes, and their lengths of 7 m, 30 m, and 100 m (1969–2025 A.D.).

Name	Year	Existing City Wall (m)	Major Axis (m)	Minor Axis (m)	7 m		30 m		100 m	
					Perimeter P (m)	Area A (km ²)	Perimeter P (m)	Area A (km ²)	Perimeter P (m)	Area A (km ²)
Puzhuang Fort	1969	1553.7	541.4	443.0	3400.26	0.1132	2002.99	0.1268	2002.39	0.1406
	1983	1560	541.4	442.5	3172.62	0.1176	2162.92	0.1295	2056.74	0.1454
	1991	1560	532.3	442.8	3186.63	0.1166	2065.24	0.1288	1747.48	0.1602
	2000	1560	595.9	443.2	3838.6	0.1197	2344.5	0.1372	1877.4	0.1643
	2010	1560	575.6	442.8	3772.2	0.1192	2317.7	0.1363	1865.1	0.1628
	2017	2057	575.6	442.8	3772.2	0.1191	2317.7	0.1363	1865.1	0.1628
	2025	2057	575.6	442.8	3772.2	0.1191	2317.7	0.1363	1865.1	0.1628
Hai'an Fort	1969	1667.87	595.3	480.5	8824.1	0.0859	3223.3	0.1559	1966.2	0.2035
	1983	24.82	623.1	601.6	5970.3	0.2185	2976.5	0.2424	2113.6	0.2755
	1991	24.82	623.0	612.1	6281.0	0.2554	2343.4	0.2812	2177.2	0.2934
	2000	24.82	666.2	624.3	12,643.9	0.2339	3049.9	0.3012	2278.1	0.3415
	2010	24.82	676.6	624.3	14,620.4	0.2468	2654.9	0.3371	2325.1	0.3496
	2017	24.82	676.6	624.3	14,624.7	0.2437	2653.2	0.3372	2325.2	0.3497
	2025	24.82	676.6	624.3	14,840.7	0.2484	2542.9	0.3393	2325.7	0.3493
Jinxiang Garrison	1969	4031.65	1155.4	1015.1	16,647.4	0.3944	6536.4	0.4986	4576.3	0.5887
	1983	1552.35	1229.6	1145.7	17,801.0	0.5511	7266.6	0.6483	4809.5	0.7632
	1991	23.89	1298.5	1147.3	23,844.1	0.6870	6658.9	0.8477	5064.7	0.9123
	2000	23.89	1298.5	1147.3	27,165.3	0.7798	4405.9	1.0635	4207.0	1.0781
	2010	23.89	1298.5	1147.3	26,568.2	0.7960	4411.3	1.0646	4203.1	1.0797
	2017	23.89	1298.5	1147.3	25,826.9	0.7983	4484.0	1.0594	4231.7	1.0767
	2025	23.89	1298.5	1147.3	25,599.0	0.7963	4419.9	1.0639	4205.9	1.0797

Source: the authors. Note: (1) In AutoCAD, draw the boundary patches corresponding to the 7 m, 30 m, and 100 m scales, respectively. (2) Use AutoCAD to sum the edge lengths of all patches within the same grid; the aggregated total (in meters) represents the Perimeter (*p*) value in table. (3) Use AutoCAD to sum the areas of all patches within the same grid; the aggregated total (in m²) is converted to km² using the formula $A(\text{km}^2) = \frac{A(\text{m}^2)}{10^6}$ to obtain the Area (*A*) value in the table.

The wall damage rate at Hai'an Fort increased from 26.8% in 1969 to 98.9% in 1983, with the wall boundaries nearly completely disappearing. The 7 m perimeter reached a high of 8824.1 m in 1969, decreased to 5970.3 m in 1983, then surged again to 12,643.9 m in 2000, before declining and stabilizing, indicating drastic micromorphological adjustments. The 30 m and 100 m perimeters, however, continued to increase, while the area increased from 0.0859 km² to 0.2484 km² during the same period, showing a significant increase in both perimeter and area at the 30 m and 100 m scales. Its spatial expansion broke through the original wall boundaries, exhibiting an outward-expanding and open-form characteristic.

The wall damage rate at Jinxiang Garrison increased from 11.43% in 1969 to 99.5% in 1991, with the wall boundaries nearly completely disappearing. The period from 1969 to 2000 was a period of rapid expansion, during which the 7 m perimeter increased from 16,647.4 m to 27,165.3 m, and the area increased simultaneously from 0.3944 km² to 0.7798 km². The perimeter and area at the 30 m and 100 m scales also increased significantly. After 2000, the expansion stagnated, with the perimeter slightly decreasing to 25,599.0 m and the area stabilizing at around 0.7963 km². Its spatial expansion broke through the original city wall boundaries, exhibiting a phased characteristic of initial expansion followed by boundary solidification.

3.4.2. Aspect Ratio (λ), Shape Index, and Fractal Dimension Index

1. Aspect Ratio (λ) and Shape Index

Puzhuang Fort λ remained stable at 1.22–1.34 for a long period and then stabilized at 1.30 after 2010; Hai'an Fort λ fluctuated slightly, briefly dropping to 1.04 in 1983 before rebounding; Jinxiang Garrison λ remained stable at 1.07–1.14 for a long period, with a consistently balanced aspect ratio. The aspect ratio of the three sanitary sites remained generally stable in the range of 1.0–1.35, all exhibiting a balanced clustered shape. Specific parameters are detailed in Appendix B (Table A4).

The shape indices S_L and S_M of the three sanitary sites became highly similar after 2000, stabilizing at the clustered settlement threshold of 1.4–1.6. The weighted average of the comprehensive shape index $S1/sub>$ also stabilized synchronously. The microscale (7 m) S_S of the three sanitary sites continued to rise overall. Puzhuang Fort's S value rose slightly from 2.83 to 3.04; Hai'an Fort's S value experienced a sharp drop followed by a sharp rise, first dropping from 8.42 to 3.60 and then rising back to 8.43; Jinxiang Garrison's S value rose from 7.45 to 8.07 (Figure 12a).

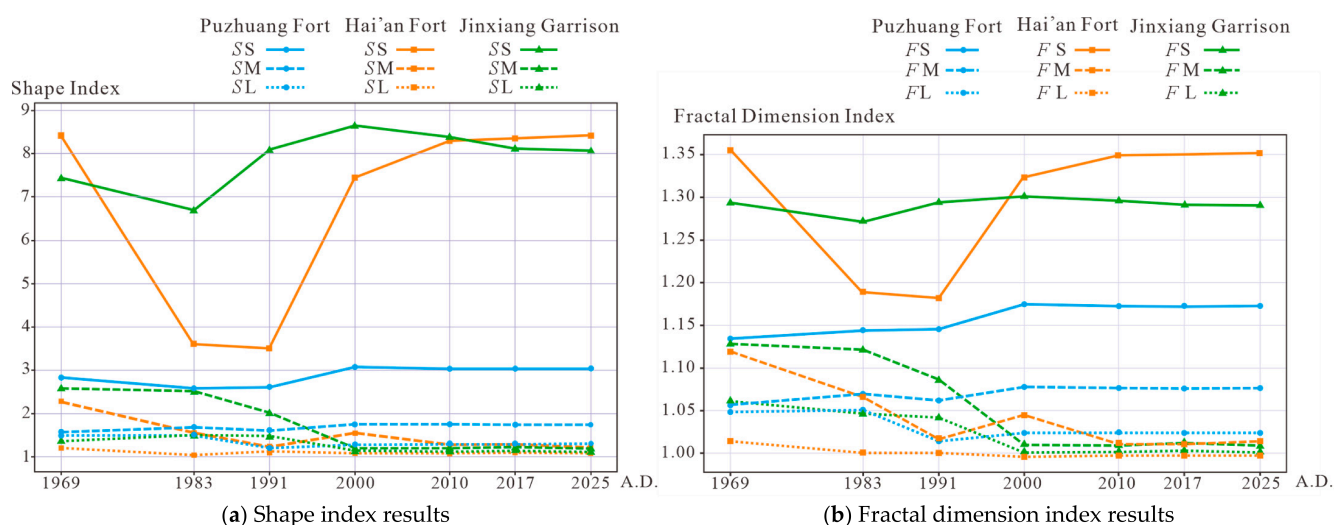


Figure 12. Comparison of shape index and fractal dimension index of the three Military Garrisons (1969 A.D.–2025 A.D.). (Source: Drawn by the authors).

2. Fractal Dimension Index

The fractal dimensions F_L and F_M of the three garrisons continued to decline, approaching the standard geometric threshold of 1.0 (Figure 12b). The F_L of Puzhuang Fort decreased from 1.05 to 1.02, the F_L of Hai'an Fort decreased from 1.01 to 0.998, and the F_L of Jinxiang Garrison decreased from 1.06 to 1.002. The average weighted comprehensive fractal dimension $F1$ also declined synchronously. The overall microscopic (7 m) F_s of the three garrisons continued to climb and remained at a high level. The F_s of Puzhuang Fort rose slightly from 1.135 to 1.172. The F_s of Hai'an Fort fluctuated significantly in the range of 1.19–1.36 and is expected to remain at a high level of 1.35 in 2025. The F_s of Jinxiang Garrison has remained stable in the high range of 1.27–1.30 for a long time; specific parameters are shown in Appendix B (Table A5).

4. Discussion

4.1. Hierarchical Rhythm and Functional Transformation

The evolutionary rhythm of Coastal Defense Garrison differs fundamentally from that of naturally growing and administratively evolved settlements. Clans, markets, and agricultural production primarily drive naturally growing settlements, expanding from the bottom up [65,66]. Traditional prefectural and county towns, on the other hand, undergo multiple functional shifts, including administration, commerce, and transportation [67]. Coastal defense garrisons, however, are institutionally planned military settlements, exhibiting a strong uniformity in their initial boundaries, streets, barracks, and defensive facilities [68]. This top-down, one-time planning characteristic determines the uniqueness of their transformation path.

Research has found that the modern transformation of coastal defense garrisons is not simply driven by functional replacement but rather by a phased, asynchronous coupling between building infill, functional replacement, and road network adjustments. Building density saturation often precedes the reorganization of the street system, with a time lag of approximately 10–15 years between the two. Between 1969 and 1991, after the military functions were phased out, the garrisons prioritized addressing population and housing needs through “filling vacant land, increasing residential land density, and replacing buildings,” rather than immediately modifying the road network—because the city walls and the framework of the cross-shaped streets and alleys still physically and institutionally constrained spatial behavior. Only when building density approached saturation and traffic pressure and mixed-use demands significantly increased did infrastructure adjustments such as widening, connecting, and straightening of streets and alleys begin, marking the beginning of the second stage of spatial evolution.

The intensity of street and alley renovation is a core indicator for judging whether the historical fabric is preserved; the extent of renovation directly determines the state of preservation. As the spatial framework of historical settlements, any alteration to the layout of streets and alleys causes irreversible damage to the traditional fabric, while changes to land use at the building level (such as converting residential to commercial/residential) have a relatively limited impact on the overall appearance.

Meanwhile, the continuous constraints of the boundary dimension constitute the third evolutionary rhythm. This study found that even though the city walls almost completely disappeared between 1980 and 1990, the moat and the outline of the city continued to function as “morphological inertial lines”—indirectly curbing the disorderly spread of the built-up area through topographic barriers, property division, and road layout.

Based on the evolutionary rhythms arising from the asynchronous coupling of the aforementioned four-dimensional elements, one can identify key morphological indicators characterizing the transformation of defense garrisons (Wei-Suo) from military defen-

sive spaces into civilian settlements and heritage sites. Indicators related to streets and alleys serve as the primary criteria; metrics such as the standard deviation of street orientation, integration, and choice quantify the shift from a regimented military road network to a network serving daily traffic, while the extent of street modification—which directly impacts the preservation of the traditional urban fabric—acts as the foremost basis for distinguishing between different transformation patterns. The proportions of residential and industrial land use serve as significant indicators; shifts in land-use structure intuitively reflect the reduction in military land and the continuous integration of civilian functions, thereby illustrating the fundamental functional evolution of settlement. Characteristics of boundary preservation play a supplementary role: the degree of city wall preservation and boundary complexity determine the recognizability of the garrison's military outline—distinguishing defensive heritage sites from ordinary towns—while simultaneously constraining urban expansion over the long term. Indicators such as building density, which primarily reflect the infilling of open spaces, offer limited explanatory power regarding the overall functional transition between military and civilian uses and thus serve only as supplementary references. Consequently, combining street modification metrics with land-use functional proportions effectively characterizes the process of spatial functional transformation in these garrison settlements.

4.2. Three Types of Transformation Paths and Their Formation Mechanisms

This study uses the intensity of street and alleyway renovation and the preservation of historical fabric as the core judgment criteria, and the degree of industrial and commercial/residential land intervention, the city wall preservation rate, and boundary complexity as auxiliary judgment criteria. Combining the explanatory variables from three levels—the intensity of cultural heritage protection control, urbanization pressure, and industrial placement methods—it identifies three differentiated spatial morphological evolution paths.

Path 1: Gradual Preservation (Puzhuang Fort). Puzhuang Fort is constrained by cultural heritage protection policies, resulting in a low-density building scale and a relatively stable total area. At the plot scale, the land use structure is stable, with no industrial development and only scattered commercial/residential buildings. At the street and alley scale, the maximum directional value of streets and alleys decreased by 26.34%; the high-guiding framework of the city wall was completely preserved; and the original spatial pattern was fully retained. At the boundary scale, the city wall boundaries remained intact, and the clustered settlement form was consistently maintained.

Path 2: Radical Reconstruction (Hai'an Fort). Hai'an Fort features high-density saturation at the building scale; at the plot scale, agricultural and forestry spaces are largely exhausted, industry is interspersed within the built-up area, and commercial and residential areas fill the old town in contiguous clusters. After straightening and grid-based transformation of the street and alleyway network, the maximum directional value of streets and alleyways decreased by 45.88%. The secondary road network drastically dissolved the original cross-shaped main axis, leading to the near disappearance of the traditional street and alleyway pattern. At the boundary scale, the city wall boundaries were extremely simplified, and the form tended to be regular.

Path Three: Balanced Regular Type (Jinxiang Garrison). At the Jinxiang Garrison building scale, the intensity of filling is moderate, and the scale is relatively stable. At the plot scale, agricultural and forestry spaces were significantly reduced, commercial and residential areas were extended into the old city, and industries were concentrated on the periphery. Renewal only adjusted the functions of the plots. At the street and alleyway scale, the maximum directional value of streets and alleyways decreased by 29.5%. Or-

thogonal grids developed evenly, and the directional distribution was regular. Street and alleyway renewal preserved the original street and alleyway network. At the boundary scale, the boundaries were moderately simplified, and the form tended to be the original state, achieving a coexistence of old and new in the old city's appearance (Figure 13).

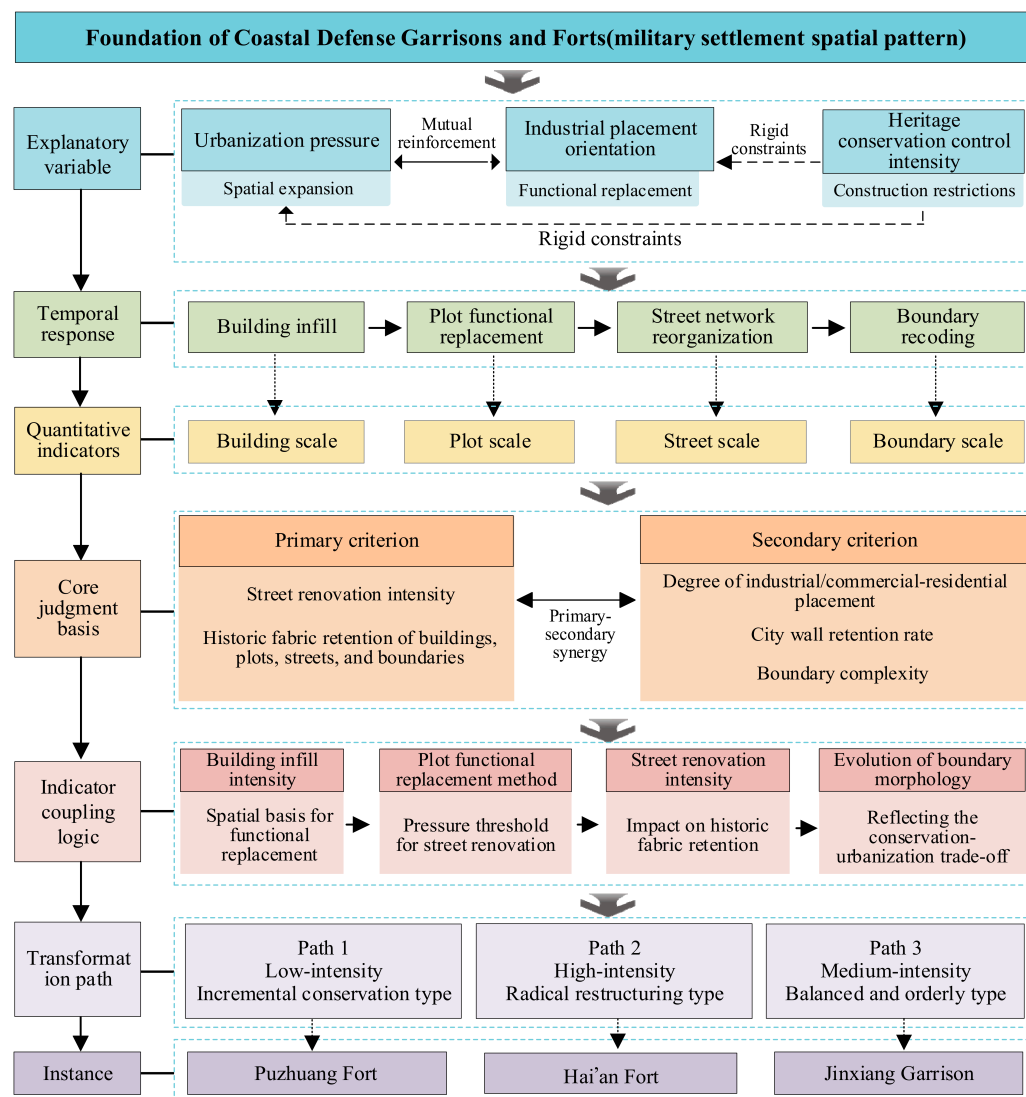


Figure 13. Three types of transformation paths and their formation mechanisms (Source: Drawn by the authors).

Currently, the transformation results of Hai'an Fort are easily regarded as a negative case, while Puzhuang Fort is considered the best model for protection and renewal. However, from the perspective of urban and rural planning, the three transformation paths are not just differences in good and bad but reflect the differentiated results of different development pressures, location conditions, and governance goals. Therefore, Hai'an Fort should not be regarded as a failure case. It reflects the systematic rewriting of historical military settlements by modern transportation and industrial functions under the pressure of high urbanization. Jinxiang Garrison embodies the balance between functional renewal and the continuation of traditional streets and alleys. Puzhuang Fort shows that strong cultural heritage protection and control can maintain the integrity of the pattern but may also face problems such as insufficient revitalization and lagging public service renewal.

It can be seen that when the pressure of industrial implantation and road reconstruction exceeds the threshold that local cultural inertia and traditional usage habits can bear,

the framework of streets and alleys will undergo irreversible structural changes. This result supports the hypothesis that “transportation and industrial technology iteration drives urban transformation” [67,69], while also putting forward limiting conditions for the view that “cultural inertia can effectively delay the decline of spatial structure” [70]—its effectiveness requires that the intensity of institutional development does not exceed the critical value.

4.3. Formation Mechanism of Boundary Morphology with Simple Outer and Complex Inner Surface

The boundary morphology of the three garrisons exhibits significant reverse evolution characteristics at both macro and micro scales. The shape index and fractal dimension index show that the outline regularity at the macro (100 m) and meso (30 m) scales continue to improve, converging towards a clustered settlement pattern. However, at the micro (7 m) scale, irregularity and fragmentation continue to intensify, resulting in a spatial variation of “simple on the outside and complex on the inside”.

The moat is not only a physical water body but also a “morphological inertia line” left over from the historical defense system. Even after the military function is phased out, the moat continues to influence the construction boundary through topographic barriers, property division, road layout, and landscape perception. Although the city walls are almost gone, after the building land breaks through the city walls, its expansion ultimately ends at the moat, and it cannot form a finger-like or radial, disorderly spread. This phenomenon is in stark contrast to the “extensional expansion of the city walls” in medieval Western towns [71] and also different from the “finger-like spread guided by the water network” [67] in the water towns of Jiangnan (Figure 14).

Compared to other military settlements in China during the Ming Dynasty, Tianjin Garrison (Figure 14a), located on the northern plains, lost its city walls and was no longer constrained by a moat. Its streets and alleys extended outwards, merging with the city’s road network. Changcheng Fortress in Hexi, Gansu Yongtai (Figure 14b), in arid mountainous terrain, lacked a moat and water system. Its rammed earth walls remained intact, but long-term isolation from construction activities led to stagnation.

In contrast, Wenzhou Ancient City in Jiangnan (Figure 14c), with its dense water network as its spatial framework, saw its waterways replace roads after the city walls disappeared, transforming into main urban thoroughfares. Buildings sprawled freely along the waterways, filling in city gate nodes, and the walls no longer controlled expansion boundaries.

A quadrilateral rammed earth wall built on a hillside enclosed the modern defensive military stronghold of Macau Mount Fortress (Figure 14d). The city’s development is centered spatially on the fort, with an irregular network of streets and alleys expanding outward in concentric layers. In medieval Western European military towns, such as the Elvas Fortress in Portugal and the Carcassonne Fortress in France (Figure 14e,f), city walls served as the boundaries for town construction and control, with towns expanding outwards along these walls.

A comparative analysis of various case studies reveals that the boundary evolution of the coastal defense garrison in southern Zhejiang differs from the outward expansion of northern garrisons without moats, the wall-constrained renewal of northwestern fortresses, and the linear extension guided by waterways in Jiangnan water towns. It also differs from the expansion beyond walled boundaries of medieval European fortresses and the concentric expansion of point-like fortresses in Macau. Instead, it represents a “renewal within an enclosure” constrained by both defensive water bodies and the outline of the old town. Thus, the “moat” is not merely a spatial barrier but becomes a constraining institutional boundary in modern urbanization.



Figure 14. Current status of military fortification development in different regions. (Source: Author's own drawing; (a–c,e) are from omap: www.ovital.com, accessed on 19 May 2026; (e,f) are from Google Maps: <https://www.google.com/maps>, accessed on 19 May 2026).

The increasing complexity of the garrison's micro-boundaries primarily stems from the widening of internal streets and alleys, the fragmentation of historical sites by new roads, and the uneven interfaces created during architectural renewal. Some of these micro-complexities arise from the subdivision of historical sites, the turning points of traditional streets and alleys, and the interfaces of daily life—all carriers of historical information. Some micro-level complexities arise from disorderly demolition and reconstruction, road cutting, and large-scale development—results of destructive alteration.

In general, the “simplicity” of boundary forms does not equate to the loss of historical value, nor does the “complexity” of micro-textures equate to the enhancement of spatial vitality. In conservation practice, it is crucial to distinguish between “beneficial complexity” and “harmful fragmentation,” avoiding the conflation of the two.

4.4. Evolution of the Spatial Form of Garrison Dwellings at the Micro Level

Micro-scale renovations of residential dwellings provide tangible, observable evidence of the morphological indicators characterizing the functional transformation of these former military garrison settlements. The shift in street-facing interfaces from enclosed to open states serves as a micro-level manifestation of changes in street and alley connectivity. Traditionally, dwellings relied on *taimen* (gated entrances) to link streets with inner courtyards, while street-facing walls remained enclosed to meet historical military defense requirements. With the introduction of commercial activities, street-facing courtyard walls

and structures were the first to be converted into shops, and *taimen* steps were removed to improve accessibility. This opening of the interface mirrors the transition from a defensive, cul-de-sac-dominated road network to one designed for civilian thoroughfares.

The subdivision and reconstruction of courtyard spaces tangibly demonstrate the functional mixing of land use. Renovations extended from street-facing areas into inner courtyards, with buildings filling the open spaces. Residential functions shifted toward the rear of the courtyards and upper building levels, evolving into “shop-front/home-rear” or “shop-below/home-above” mixed-use patterns; in the garrison towns of Haian and Jinxiang, layouts further evolved into “shop-front/workshop-rear” or “workshop-below/home-above” configurations, reflecting a shift away from original military land-use attributes toward commercial, residential, and industrial functions.

Significant changes occurred in building construction and scale: the traditional *taimen*-courtyard layout gave way to contiguous rows of individual units, and building heights increased from a single story to between two and seven stories. The reconfiguration of floor plans and vertical expansion altered building density and footprint coverage across the area. Variations in the spatial distribution of buildings—ranging from sparse to dense—influenced “nearest neighbor” indices and kernel density values, thereby disrupting the original, low-profile character of the streetscape. By incorporating building-level indicators, one can discover micro-scale evidence of the functional shifts driven by the restructuring of street networks and land-use patterns, thereby refining the morphological criteria used to identify the transformation of military garrisons into civilian settlements and heritage sites (Figure 15).

4.5. Coastal Defense Garrison Protection and Utilization Strategies

1. Puzhuang Fort focuses on micro-updates and functional continuity. It involves low-intensity building renovations, avoiding large-scale demolition and reconstruction. It maintains the continuity of traditional streetscapes. It preserves the natural subdivision of historical sites, avoiding forced mergers and preventing large-scale functional replacements due to tourism or commercial development. It uses city walls and moats as boundary constraints to control the orderly integration of public service facilities (Figure 15).
2. Hai'an Fort focuses on the reconstruction of streetscapes and the restoration of boundary memories. It organizes the remaining streetscape framework, marking historical intersections and turning points. It restores the architectural style of important nodes, regulates the boundaries between industrial and commercial/residential sites, and curbs further fragmentation of the urban fabric. It uses the remaining city gate ruins and moat as boundaries for the memory landscape, reconstructing fragmented spatial narratives.
3. Jinxiang Garrison focuses on preserving the scale of streets and alleys and continuing the site layout. It maintains the double-cross streetscape, limits the widening of old city roads, and constrains building height and volume to avoid high-intensity development. It preserves the traditional site scale and street orientation, selectively optimizes traffic, and balances modern traffic needs with the protection of the traditional fabric. The foundations of the city walls and the moat serve as boundaries for spatial growth, preventing high-density construction from eroding the historical outline.



Figure 15. Evolution of the spatial form of residential buildings in three military garrisons (Source: Drawn by the authors).

The common principle of the three strategies is to preserve the street and alleyway framework as the core, to constrain the inertia of boundary utilization, and to use the gradual renewal of buildings and plots as a flexible adjustment variable. Land use can

be changed without damaging the historical character, but once the streets and alleys are structurally altered, their historical value suffers irreversible loss.

4.6. Limitations

Although this paper constructs a four-dimensional quantitative analysis framework for buildings, land parcels, streets, and boundaries based on multiple periods of remote sensing imagery, historical maps, local documents, and field survey data from 1969 to 2025, certain limitations still exist. First, the limited resolution, clarity, and geometric registration accuracy of early remote sensing images may affect the identification of small-scale buildings, narrow alleys, courtyard boundaries, and remnants of city walls. Manual vectorization can also introduce errors in the measurement of building area, street axes, and boundary perimeters. Second, some historical land use functions require comprehensive interpretation in conjunction with local chronicles, planning documents, image features, and interview data; classification uncertainties still exist between residential, mixed-use, and public service types. Third, GIS, spatial syntax, shape indices, and fractal dimension indices primarily reveal physical spatial structure and are insufficient to fully explain deeper mechanisms such as population migration, property rights changes, policy intervention, and local governance. Spatial syntax indicators cannot be entirely equated with actual traffic flow and resident activities. Finally, this paper only selects three typical military garrisons in Wenzhou, and the conclusions mainly reflect the characteristics of the modern transformation of the coastal areas of southern Zhejiang. In the future, it is still necessary to expand to the coastal military garrisons in Fujian, Guangdong, Shandong, and other places and combine ancient maps, cadastral data, street view data, and social surveys to further verify the universality of the type framework.

5. Conclusions

This paper takes three Ming Dynasty coastal defense garrisons in Wenzhou as examples and constructs a four-dimensional morphological analysis framework of “building-plot-street-boundary” based on long-term spatial data from 1969 to 2025 to reveal the morphological mechanism of their transformation from military defense spaces to modern towns and heritage sites.

The evolution of the garrisons exhibits a hierarchical response pattern of “building first, road network lagging, and boundary constraints.” Urbanization is first manifested in building densification and land replacement, followed by street and alley reorganization, while historical boundaries such as moats maintain macroscopic outline stability after the dissolution of city walls. The three garrisons form three paths: radical reconstruction, balanced regularization, and gradual preservation, reflecting the different roles of urbanization intensity, industrial implantation, and cultural heritage management. Among them, the intensity of street and alley renovation is a key variable for identifying the degree of preservation of historical textures and transformation types. Multi-scale analysis further reveals the spatial fingerprint of “simplicity on the outside and complexity on the inside,” that is, macroscopic boundaries tend to be regularized, while microscopic textures continue to become more complex. Therefore, the protection of Coastal Defense Garrison should move beyond the restoration of individual remains and towards the holistic maintenance of the streetscape, plot scale, boundary inertia, and continuity of living functions. This article can provide a reference for the morphological diagnosis, typological identification, and dynamic renewal of coastal defensive settlement heritage.

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Data Availability Statement: The original data presented in this study are held by Yuhao Huang, who organized and conducted the investigation. If you are interested, please contact u24092120176@cityu.edu.mo (Y.H.) for further information.

Conflicts of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Appendix A

Table A1. Statistics on the Changes in Land Area Used by the Three Garrisons (1969–2025) (Unit: Hectares).

Name	Land Use Types	1969	1983	1991	2000	2010	2017	2025
Puzhuang Fort	Residential Land	10.14	9.50	9.67	9.98	9.98	9.91	9.91
	Agricultural and Forestry Ecological Land	10.81	10.81	10.41	9.25	9.25	9.25	9.25
	Commercial and Residential Land	0	0	0	0.59	0.59	0.66	0.66
	Public Service Land	0.02	0.04	0.04	0.04	0.06	0.10	0.10
	Educational Land	0	0	0.23	0.88	0.88	0.88	0.88
	Administrative Land	0.12	0.12	0.12	0.12	0.12	0.12	0.12
	Religious Land	0.59	0.59	0.59	0.87	0.87	0.71	0.71
	City Wall	0.85	0.85	0.86	0.86	0.86	1.09	1.09
Hai'an Fort	Industrial land	0	0.70	2.00	1.40	1.45	1.45	1.45
	Residential land	10.14	15.94	18.12	19.78	17.36	17.36	17.36
	Agricultural, forestry, and ecological land	13.25	10.73	5.36	4.10	0.09	0.09	0.09
	Commercial and residential land	0	2.50	2.66	2.43	4.51	4.51	4.51
	Public service land	0	0.34	0.34	0.62	1.01	1.01	1.01
	Educational land	0.38	0.22	0.22	1.11	1.57	1.57	1.57
	Administrative land	0	0	0	0.01	0.05	0.05	0.05
	Religious land	0.51	0.40	0.37	0.47	0.54	0.54	0.54
	City walls	2.29	0.03	0.03	0.01	0.01	0.01	0.01
	Waterways within the city	0.99	0.08	0	0	0	0	0
Jinxiang Garrison	Industrial land	0	4.03	5.33	5.49	8.33	8.74	8.74
	Residential land	40.80	42.49	51.67	53.82	53.69	53.75	53.17
	Agricultural and forestry ecological land	50.94	37.65	21.24	18.56	13.74	13.74	13.74
	Commercial and residential land	0.35	9.01	15.10	15.25	16.80	16.29	16.92
	Public service land	0.06	0.44	0.59	1.05	1.05	1.14	2.13
	Military land	0.52	0.52	0	0	0	0	0
	Educational land	2.60	2.73	5.21	5.21	4.64	4.64	4.64
	Administrative land	0	0.35	1.61	1.61	2.73	2.73	2.81
	Religious land	0.60	0.93	1.25	1.35	1.35	1.35	1.35
	Urban water area	5.04	3.57	0.85	0.87	0.87	0.87	0.87
	City walls	6.63	1.87	0.01	0.01	0.01	0.01	0.01

Source: the authors.

Table A2. Statistical table of changes in the percentage of various types of land parcels in the three garrison areas (1969–2025).

Name	Land Use Types	1969	1983	1991	2000	2010	2017	2025	Trends (1969 → 2025)
Puzhuang Fort	Public Service Land	0.09	0.17	0.17	0.16	0.28	0.42	0.42	Slight growth
	Educational Land	0.00	0.00	1.06	3.89	3.89	3.87	3.87	From nothing to something
	Residential Land	45.00	43.36	44.13	44.19	44.15	43.63	43.63	Basically stable
	Agricultural and Forestry Ecological Land	48.00	49.36	47.49	40.94	40.88	40.72	40.72	Slow decline
	Commercial and Residential Land	0.00	0.00	0.00	2.62	2.62	2.89	2.89	Slow growth
	Administrative Land	0.53	0.54	0.54	0.53	0.53	0.52	0.52	Basically stable
	Religious Land	2.62	2.70	2.70	3.87	3.87	3.14	3.14	Rise then fall
	City Wall	3.76	3.87	3.91	3.80	3.79	4.80	4.80	Full recovery
Hai'an Fort	Industrial Land	0.00	2.26	6.86	4.69	5.44	5.44	5.44	Rise then stabilize
	Residential Land	36.80	51.52	62.25	66.07	65.32	65.32	65.32	Significant rise
	Agricultural and Forestry Ecological Land	48.06	34.68	18.42	13.69	0.32	0.32	0.32	Sharp decline
	Commercial and Residential Land	0.00	8.09	9.15	8.13	16.96	16.96	16.96	Significant growth
	Public Service Land	0.00	1.11	1.18	2.08	3.81	3.81	3.81	Steady growth
	Educational Land	1.38	0.71	0.75	3.71	5.89	5.89	5.89	Rise then rise
	Administrative Land	0.00	0.00	0.00	0.03	0.20	0.20	0.20	From nothing to something
	Religious Land	1.85	1.29	1.28	1.58	2.02	2.02	2.02	Basically stable
	Urban Water Area	3.60	0.27	0.00	0.00	0.00	0.00	0.00	Completely disappear
Jinxiang Garrison	City Wall	8.31	0.09	0.09	0.04	0.05	0.05	0.05	Almost disappear
	Industrial Land	0.00	3.89	5.18	5.32	8.07	8.46	8.37	Significant growth
	Residential Land	37.95	41.02	50.23	52.14	52.02	52.06	50.93	Steady rise
	Agricultural and Forestry Ecological Land	47.38	36.35	20.65	17.98	13.31	13.31	13.16	Significant decline
	Commercial and Residential Land	0.33	8.70	14.68	14.78	16.28	15.78	16.21	Significant growth
	Public Service Land	0.06	0.42	0.57	1.02	1.02	1.10	2.04	Steady growth
	Military Land	0.48	0.50	0.00	0.00	0.00	0.00	0.00	Complete exit
	Educational Land	2.42	2.64	5.07	5.05	4.50	4.49	4.45	Rise then stabilize
	Administrative Land	0.00	0.34	1.57	1.56	2.65	2.64	2.69	From nothing to something
	Religious Land	0.56	0.90	1.22	1.31	1.31	1.31	1.29	Slight growth
	Urban Water Area	4.69	3.45	0.83	0.84	0.84	0.84	0.83	Obvious decline
	City Wall	6.17	1.81	0.01	0.01	0.01	0.01	0.01	Almost disappear

Source: the authors.

Table A3. Trends in the proportion of land used by the three sanitation stations (1969–2025).

Indicators	Puzhuang Fort	Hai'an Fort	Jinxiang Garrison
Residential Land	45.0% → 43.6%	36.8% → 65.3%	38.0% → 50.9%
Agricultural and Forestry Ecological Land	48.0% → 40.7%	48.1% → 0.3%	47.4% → 13.2%
Industrial Land	0% → 0%	0% → 5.4%	0% → 8.4%
Commercial and Residential Land	0% → 2.9%	0% → 17.0%	0.3% → 16.2%
Public Services	0.09% → 0.42%	0% → 3.8%	0.06% → 2.0%
Education	0% → 3.9%	1.4% → 5.9%	2.4% → 4.5%
Administration	0% → 0.52%	0% → 0.2%	0% → 2.7%
Religion	2.62% → 3.14%	1.85% → 2.02%	0.56% → 1.29%
City Walls	3.8% → 4.8%	8.3% → 0.05%	6.2% → 0.01%
Water Areas	/	3.6% → 0%	4.7% → 0.8%

Source: the authors.

Appendix B

Table A4. Statistics on the shape index of three garrisons (1969–2025 A.D.).

Name	Year	Length and Width Ratio (λ)	S _{Small}	S _{middle}	S _{large}	S1 Weighted Average ^(a)	Boundary Morphological Characteristics
Puzhuang Fort	1969	1.2220	2.8299	1.575	1.495	1.6756	Clustered settlements
	1983	1.2235	2.5907	1.6824	1.5101	1.6990	Clustered settlements
	1991	1.2021	2.616	1.613	1.224	1.5774	Clustered settlements
	2000	1.3445	3.0796	1.7568	1.2853	1.7367	Clustered settlements
	2010	1.2999	3.0432	1.7482	1.2873	1.7277	Clustered settlements
	2017	1.2999	3.0437	1.7482	1.2873	1.7278	Clustered settlements
	2025	1.2999	3.0437	1.7482	1.2873	1.7278	Clustered settlements

Table A4. Cont.

Name	Year	Length and Width Ratio (λ)	S _{Small}	S _{middle}	S _{large}	S1 Weighted Average ^(a)	Boundary Morphological Characteristics
Hai'an Fort	1969	1.2389	8.4186	2.2835	1.2191	2.0062	Finger-shaped settlements with a tendency towards clustering
	1983	1.0358	3.6032	1.5592	1.0579	1.3284	Clustered settlements
	1991	1.0178	3.5057	1.2465	1.1337	1.1920	Clustered settlements
	2000	1.0671	7.4435	1.5602	1.0988	1.5514	Clustered settlements
	2010	1.0838	8.2913	1.2883	1.1078	1.4645	Clustered settlements
	2017	1.0838	8.3475	1.2873	1.1078	1.4671	Clustered settlements
	2025	1.0838	8.4275	1.2246	1.1078	1.4401	Clustered settlements
Jinxiang Garrison	1969	1.1382	7.4547	2.603	1.407	2.1734	Finger-shaped settlements with a tendency towards clustering
	1983	1.0732	6.7000	2.5435	1.5155	2.1545	Finger-shaped settlements with a tendency towards clustering
	1991	1.1318	8.092	2.0343	1.4916	1.9517	Clustered settlements
	2000	1.1318	8.6531	1.2018	1.1397	1.4490	Clustered settlements
	2010	1.1318	8.3765	1.2026	1.1378	1.4337	Clustered settlements
	2017	1.1318	8.1311	1.2254	1.1472	1.4349	Clustered settlements
	2025	1.1318	8.0693	1.2054	1.1386	1.4187	Clustered settlements

Source: the authors. (a) S1 weighted average algorithm: $S1 = S_{large} \cdot \frac{S_{middle}}{S_{large}} \cdot 0.25 + S_{middle} \cdot 0.5 + S_{Small} \cdot \frac{S_{middle}}{S_{Small}} \cdot 0.25$.

Table A5. Fractal dimension index statistics for three garrisons (1969–2025 A.D.).

Name	Year	F _{small} (7 m)	F _{middle} (30 m)	F _{large} (100 m)	F1 Weighted Average ^(b)	Boundary Morphological Characteristics
Puzhuang Fort	1969	1.1347	1.0580	1.0487	1.0636	Complete pattern
	1983	1.1436	1.0692	1.0503	1.0717	Slight regularization
	1991	1.1455	1.0619	1.0147	1.0592	Slight regularization
	2000	1.1745	1.0776	1.0240	1.0762	Slight regularization
	2010	1.1720	1.0765	1.0243	1.0751	Stable form
	2017	1.1721	1.0765	1.0243	1.0752	Continuous stability
	2025	1.1721	1.0765	1.0243	1.0752	Stable form

Table A5. Cont.

Name	Year	F _{small} (7 m)	F _{middle} (30 m)	F _{large} (100 m)	F1 Weighted Average ^(b)	Boundary Morphological Characteristics
Hai'an Fort	1969	1.3553	1.1194	1.0141	1.0944	Complex boundary
	1983	1.1889	1.0666	1.0011	1.0313	Rapid regularization
	1991	1.1821	1.0159	1.0008	1.0045	Slight regularization
	2000	1.3228	1.0448	0.9962	1.0459	Complex boundary
	2010	1.3484	1.0110	0.9978	1.0346	Rapid regularization
	2017	1.3501	1.0108	0.9978	1.0348	Regularity solidification
	2025	1.3517	1.0134	0.9979	1.0365	High regularity
Jinxiang Garrison	1969	1.2936	1.1281	1.0603	1.1013	Complex boundary
	1983	1.2710	1.1216	1.0472	1.0907	Rapid decrease in complexity
	1991	1.2936	1.0866	1.0411	1.0756	Rapid decrease in complexity
	2000	1.3008	1.0095	1.0018	1.0284	Tend to stability
	2010	1.2956	1.0094	1.0016	1.0272	Fine-tuning improvement
	2017	1.2911	1.0125	1.0028	1.0281	Significant regularity
	2025	1.2904	1.0097	1.0017	1.0263	Tend to stability

Source: the authors. (b) F1 Weighted Average Algorithm: $F1 = F_{large} \times \frac{F_{middle}}{F_{large}} \times 0.25 + F_{middle} \times 0.5 + F_{small} \times \frac{F_{middle}}{F_{small}} \times 0.25$.

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