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Evaluation of Chinese traditional military settlements' defensive capabilities via principal component analysis (PCA): a case study of coastal Wei forts in the Ming dynasty

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Abstract

Defensive capability is one of the essential attributes of traditional military settlements. In the Ming dynasty, coastal Wei fort was the one of the most functionally complex and wide-ranging fortifications in the military defense system of China. Because many factors affect their defensive capacities, including three dimensions: individual construction, synergistic links, and regional jurisdiction, it is not easy to compare different settlements' defensive capacities or to judge the degrees of different factors' influences. Through principal component analysis, this study determines the weights of each minor factor. It constructs a model for evaluating traditional Chinese military settlements' defensive capabilities, to quantify the defensive capability. The results show that the synergistic relationship between the settlements, especially settlement accessibility, has the most significant impact on defensive capability, much higher than a single castle's defensive construction. The defensive capability index of the Wei forts in Guangdong is the highest, consistent with the highest rate of victory in the wars fought on the coast during the Ming dynasty. The defensive capacity is directly proportional to the rate of victory, which validates this evaluation model's soundness. This study not only comprehensively evaluates the coastal Wei forts' defensive capacity in the Ming Dynasty, but also provides new methods for the quantitative or comparative analysis of military settlements at other temporal and spatial scales.

Keywords Defense capability, Traditional military settlements, Wei forts, Principal component analysis, The Ming dynasty

Introduction

Ancient China dedicated extensive efforts to the construction of military settlements for safeguarding its borders. In the early years of the Ming Dynasty (1368–1683), facing internal challenges and external threats, the imperial court placed significant emphasis on military defense in border regions. By the mid-Ming period, the construction of the Great Wall in northern China had reached its peak, and a comprehensive defense system had also been established along the eastern coastal areas [1]. However, under the turbulent international situation, continuous conflicts occurred in Japan and the Korean Peninsula, causing frequent disturbances along China's eastern coastal regions. In response to

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these challenges, the Ming Dynasty gradually strengthened its policy of isolation and reduced diplomatic or trade activities. At the same time, confronted with a large number of marauders arriving from the sea (倭寇Wokou), the Ming court strongly recognized the importance of constructing military defense systems in coastal areas. The Ming Dynasty experienced two large-scale phases of constructing maritime defense settlements, occurring in the early Ming period during the Hongwu-Yongle reigns (1368–1424) and in the mid-to-late Ming period during the Jiajing reign (1522–1566) [2]. These coastal defense military settlements were divided into seven major defense areas from north to south: Liaodong, North Zhili, Shandong, South Zhili, Zhejiang, Fujian, Guangdong. Although they did not have a continuous wall like the Ming Great Wall, they effectively formed a tight defensive belt along the eastern coastal regions of the Ming Dynasty.

The Du-Si-Wei-Suo (都司卫所) system was the fundamental military system of the Ming Dynasty in China, and it formed a defensive system adapted to local military needs in different regions. The coastal defense system was one of its important branches. In various coastal defense areas, there were Du-Si (都司) some regions referred to as Zhen forts (镇城) serving as administrative commanders. They were the largest military management institutions in each defense zone, with only one Du-Si (Zhen fort) per defense zone. These major command institutions typically did not engage in front line combat but rather operated from the rear, providing strategic direction. In order to defend against external threats landing on the eastern coastline, the Ming government established a tight network of military settlements for coastal defense in the region. Each defense area was mainly composed of Du-Si/Zhen Fort—Wei Fort (卫城)—Suo Fort (所城)—terminal defense facilities, such as XunJianSi (巡检司), Bao (堡), beacon towers or post stations were also distributed among the different levels of settlements to carry information and supplies (Fig. 1) [3]. The size of their settlements gradually decreased, and their functions became increasingly singular. The size of Wei Fort was smaller than Du-Si/Zhen Fort, and Suo Fort was smaller than Wei Fort.

Usually, Du-Si (Zhen Fort) were constructed together with the prefectural capital of the defense zone, while various terminal defense facilities were largely attached to local government offices and were not independently fortified. In contrast, fortresses at the level of Wei Fort and Suo Fort tended to be individually constructed military settlements. Typically, Wei Fort was larger in scale, and both military functions and the construction of military settlements were more comprehensive. So, the Wei fort was the largest fortification in this system that was directly involved in military activities, which was a kind of traditional settlement with a military role. Compared to the general castles, the coastal Wei forts had the social function of a fort with livelihood and cantonment. Unlike a typical village, coastal Wei forts had the military function of fighting and preparing for war. Moreover, compared with Suo forts or other small-scale defense facilities, Wei forts occupied the most military resources, which had most typical characteristics of the coastal military settlement. Therefore, this study chooses the Wei fort of the coastal defense system in the Ming Dynasty as the representative of Chinese traditional military settlement.

Initially, the exploration of traditional Chinese military settlements originated in historiography, primarily delving into their construction and developmental history [4–6]. Subsequently, archaeologists and heritage scholars employed novel investigative methods to analyze specific construction techniques and heritage preservation associated with these settlements [7–9]. In recent years, scholars specializing in architectural history and

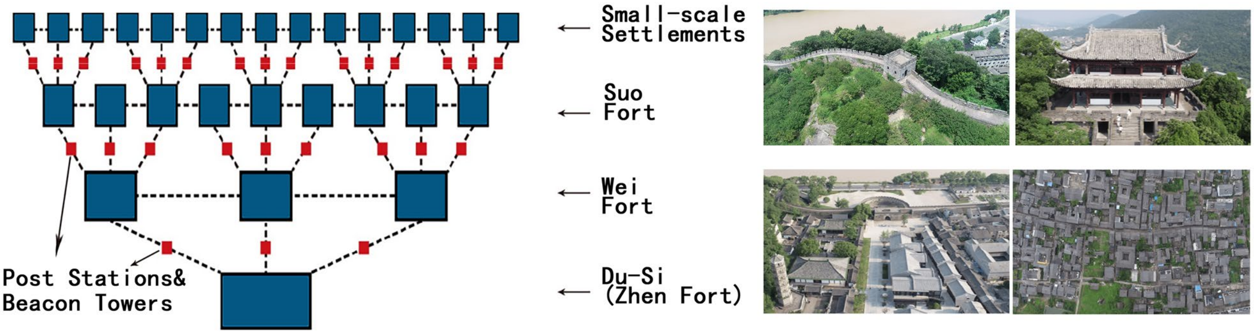


Fig. 1 Hierarchical system of coastal defense military settlements in Ming Dynasty (left), some examples of the Ming Dynasty coastal defense sites in Taizhou, Zhejiang, China (right)

urban development have applied systems thinking to systematically delineate complete military defense systems, such as the coastal defense system and the Great Wall defense system during the Ming Dynasty [10, 11]. The establishment of this system fosters interdisciplinary research, resulting in numerous case analyses. However, when considering traditional military settlements of the Ming Dynasty, their most notable distinction from general settlements lies in their military attributes, placing a significant emphasis on defensiveness. Various factors contribute to the defensive nature of military settlements, encompassing site selection, construction, supply, military command, and more. All these elements collectively shape the defensive performance of forts in actual combat. Military command and logistical supply, influenced by subjective judgments of decision-makers in different battles, exhibit a certain level of contingency. Conversely, objective factors such as geographical location, fortress construction, economic factors, population, etc., can represent the objective defensiveness of each military settlement to some extent. We term these factors as defensive capabilities. This defensive capability is a crucial attribute sought after in the construction of ancient Chinese military settlements, and it should also be a focal point of modern research.

On the one hand, in previous studies, scholars often examined individual variables, such as terrain and garrison strength [12, 13], which essentially involves analyzing the correlation between objective influencing factors and the defensive capabilities of these military settlements. Traditionally, these studies primarily concentrated on the specific construction features of each fortress, such as the height and thickness of fortress walls, and the number of troops stationed there. However, with an enhanced academic understanding of the defensive systems in Ming Dynasty military settlements, there is a growing recognition that true defensive capability extends beyond individual fortresses. It encompasses an interconnected overall defensive system formed by multiple fortresses. In addition to individual defensive capabilities, factors such as collaborative defense capabilities between fortresses and their impact on the social stability of an entire defense area are gaining significance and should be duly considered.

On the other hand, due to the multitude of factors involved in defensive capabilities, it is challenging to quantify the impact of each individual factor separately, and also hard to assess defense capabilities by a quantitative method. A comprehensive analysis of the mechanisms of multiple influencing factors simultaneously is a solution to tackle such complex issues. In recent years, a limited number of scholars have employed the Analytic Hierarchy Process (AHP) to have experts evaluate multiple factors, aiming to assess the significance of various influencing factors [14, 15]. For instance, some researchers concentrated on the efficiency of ancient information transmission systems by developing a hierarchical evaluation model [16]. Another notable study quantitatively examined the defensive efficiency of the coastal military settlement in Ningbo during the Ming Dynasty, utilizing the hierarchical analysis method to establish an AHP model [17]. Despite these efforts, these analyses encounter challenges, such as difficulties in horizontal comparisons due to varying quantification standards and issues related to the lack of scientific rigor in manually assigning weights. Additionally, some researchers have explored the use of methods like minimum cumulative resistance (MCR) and CRITIC to analyze the suitability of different Chinese traditional military settlements [18, 19]. Notably, these methods share commonalities, including the establishment of a multi-level and multi-indicator evaluation system, the formation of a quantitative description of evaluation indicators through scoring evaluation factors, and the construction of a comprehensive evaluation model. This study also adopted a similar strategy, but there were variations in the choice of research methods.

Regarding the defensive capability of Wei forts in the coastal defense military settlements of the Ming Dynasty, it involves numerous influencing factors, including the internal construction of forts, spatial distribution between forts, and regional socio-economic factors. We aim to assess which factors have a more significant impact on the defensive capability of Wei forts, achieving a preliminary quantification of their defensive capabilities through the construction of an evaluation system. This requires the hierarchical construction of a multi-indicator evaluation system and an attempt to determine the importance or weight of each indicator. Building upon previous research methods, this study introduces principal component analysis (PCA), which aims to address the problem of quantifying and assigning weights to the many factors affecting military settlement defense capabilities. PCA, an analytical method proposed over a century ago, has found widespread applications in multiple disciplines. This study employs PCA for the quantitative analysis of the defensive capability of traditional Chinese military settlements because, compared to the commonly used AHP method in existing research, PCA can mitigate the impact of subjective judgment on the analysis results and reduce the dimensionality of numerous influencing factors. The fundamental advantage of PCA lies in dimensionality reduction through the extraction of principal components from the original influencing factors, leading to a decrease in the number of variables [20]. This is particularly suitable for datasets with a large number of variables and unclear inter-variable correlations, making it more conducive to extracting data features.

After quantifying the defensive capabilities of military settlements, each Wei fort corresponds to an indicator representing its defensiveness, serving as a quantitative element for military settlements and participating in additional quantitative analyses. It becomes possible not only to compare the defensive abilities of the same military fortress at different historical periods but also to assess the differences in defensive capabilities among different military fortresses under the same criteria. This holds significant application value and contributes to the quantitative research of traditional Chinese military settlements.

Methods

Study area

The coastal military defense system in the Ming dynasty was divided into seven zones along the eastern coast of China. The spatial relationships of these defense areas in the historical maps of the Ming Dynasty are illustrated in Fig. 2. There were 4–11 Wei forts in each defense area, a total of 66 (Fig. 3).

Impact factors selection

In order to construct an evaluation model that can be used to quantify the defensive capabilities of military settlements, we first need to select the impact factors that affect these capabilities. The objectivity and comprehensiveness of the selected quantifying factors are directly related to the rationality of the evaluation model. If the number of factors is too small, the overall level of the defensive mechanism cannot be summarized; if the number of factors is too large, it covers duplicated information, which is more difficult to quantify [16]. Not all details are included as evaluation factors in the evaluation system. They should be selected according to the purpose of each level under the system framework. In addition to single forts, the synergy between a Wei fort and other military defense settlements under the whole coastal defense system should be taken into account, as well as the related economic and demographic factors.

There are three main aspects (Table 1): Single defensive capability (A), coordinated defensive capability (B), jurisdictional control capability (C). Each aspect is divided into several representative factors.

A. Single defensive capability represents the level of self-defense within a certain area of the settlement, including military strength (A_1) and the defensive construction (A_2). The level of military strength is expressed in terms of the number of troops. Although the standard number of troops for each Wei fort in the Ming Dynasty was as high as 5600, in reality, due to desertions and inadequate supplies, the actual number of troops ($A_{1\text{-}1}$) in each Wei fort was much lower than the designated quantity. Regarding the defensive construction of the fort, the actual factors influencing them varied significantly due to the different environments of each fort. To ensure that historical records related to all 66 Wei forts could be found, this study selected the most representative five factors ($A_{2\text{-}1}$, $A_{2\text{-}2}$, $A_{2\text{-}3}$, $A_{2\text{-}4}$, $A_{2\text{-}5}$).

B. Coordinated defensive capability signifies the interconnected relationships between a Wei fort and other military settlements, which this study categorizes into three aspects (B_1, B_2, B_3). First, given the limited number of regional military headquarters (Du-Si) in the Ming Dynasty coastal defense system and the relatively small scale of subordinate settlements like XunJianSi, Wei forts and Suo forts were the primary defensive entities in actual combat. The closest distance between the Wei forts ($B_{1\text{-}1}$), as well as between Wei forts and Suo forts ($B_{1\text{-}2}$), determines the ability of the neighboring Wei forts to rush to aid after a conflict. The closer the distance, the better the accessibility, and consequently, the stronger the collaboration. The nearest distance utilized here is determined by cost distance derived from DEM terrain data. Second, the quantity of terminal defense facilities is a crucial supplement to a Wei fort"s military support. The more terminal defense facilities under the jurisdiction of a Wei fort, the better its combat endurance. Given the diverse types of defense facilities among these 66 Wei forts, this study selected the most numerous and common ones, Bao ($B_{2\text{-}1}$) and XunJianSi ($B_{2\text{-}2}$). Lastly, the capacity for information and material transfer between Wei forts significantly impacts overall collaborative capability. The number of post stations ($B_{3\text{-}1}$) and beacon towers ($B_{3\text{-}2}$) between Wei forts determines the quality and speed of information and material exchange.

C. Jurisdictional control capacity measures the level of societal development in the region where each Wei fort was located. Ancient China was an agrarian civilization, and factors such as population (C_1), economics (C_2), and food (C_3) played crucial roles in the stable development of military settlements in the region. In previous studies, there has been a tendency to focus more on factors directly related to military settlements, often overlooking regional social issues. Actually, one of the purposes of establishing coastal defense military settlements was to safeguard the population, social stability, and economic development in coastal areas, and these social factors, in turn, can impact the defensive capabilities

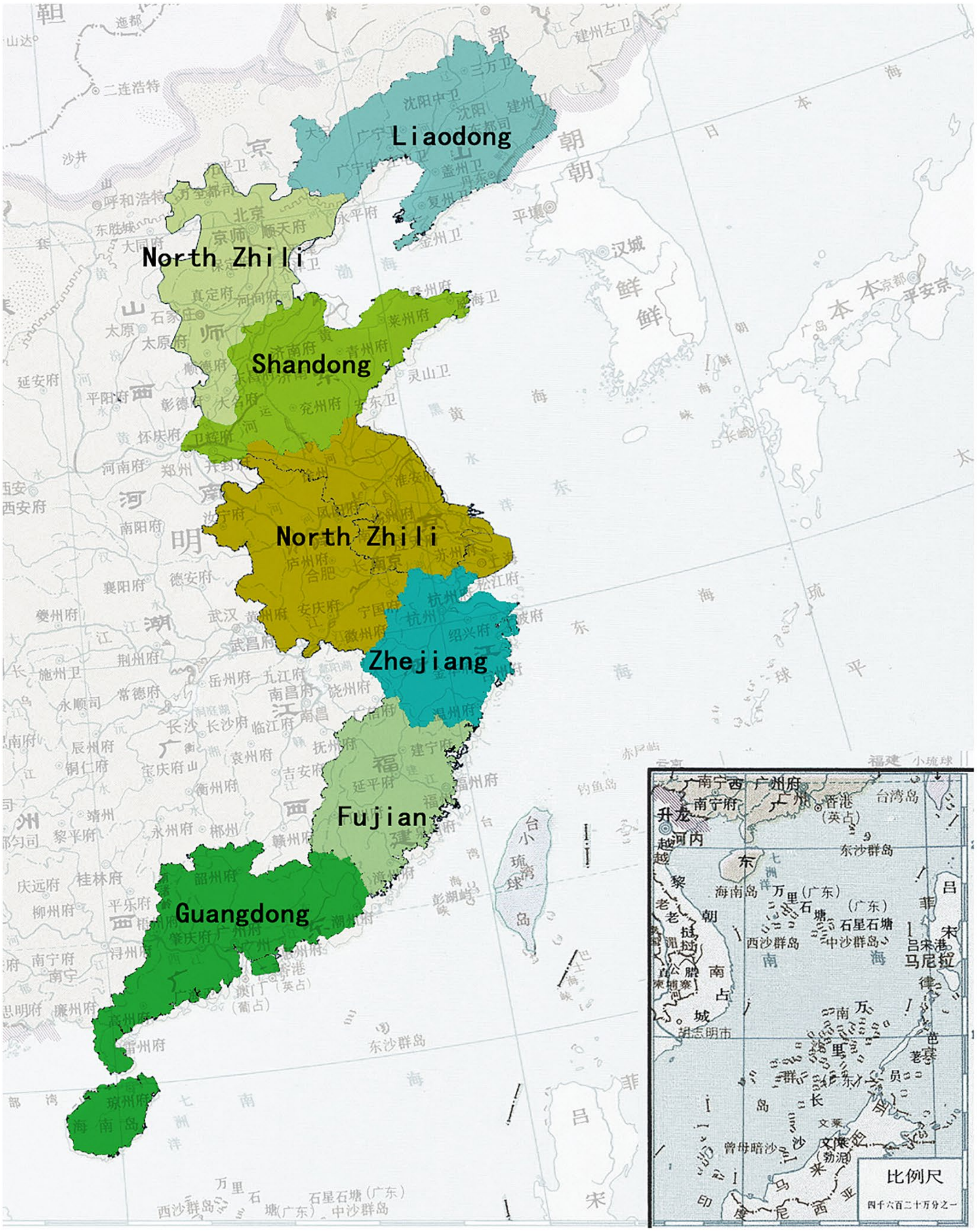


Fig. 2 The spatial distribution of the seven major coastal defense areas in the Ming Dynasty (the base map from the Historical Atlas of the Ming Dynasty in China [21])

of the forts. Typically, regions with dense populations and economic prosperity tended to have abundant manpower and resources, resulting in higher levels of fort defense, better weapon equipment, and superior construction standards. For instance, within the Fujian defense zone, Quanzhou Wei in Quanzhou Prefecture and Fuzhou Wei in Fuzhou Prefecture had average populations of 90,406 and 70,643, respectively (Table 2). The average tax levels were 655 and 429 liang (a unit of currency), and the average grain contributions were 54,925 and 34,626 shi (a unit of measurement for grain), respectively. The socioeconomic status of Quanzhou Wei was higher than that of Fuzhou Wei. Accordingly, the construction stand-

Fig. 3 The spatial distribution of 66 Wei forts in the Ming dynasty (the base map from ArcGIS Online, copyright © 2020 Esri)

Table 1 Classification and data sources of impact factors

Category		Impact factor	Description
Single defensive capability (A)	Military strength (A_1)	Number of troops(A_{1-1})	Historical information of the Wei fort
	Defensive construction (A_2)	Perimeter (A_{2-1})	
		Wall height (A_{2-2})	
		Wall thickness (A_{2-3})	
		The width of the moat (A_{2-4})	
		Number of gates (A_{2-5})	
Coordinated defensive capability (B)	Settlement accessibility (B_1)	The nearest distance between a Wei fort and other Wei forts (B_{1-1})	Calculated in ArcGIS based on the geographical location
		The nearest distance between a Wei fort and other Suo forts (B_{1-2})	
	Assistant settlements (B_2)	Number of Bao (B_{2-1})	Historical information of the Wei fort
		Number of Xunjiansi (B_{2-2})	
	Information and material transfer (B_3)	Number of post stations (B_{3-1})	
		Number of beacon towers (B_{3-2})	
Jurisdictional control capacity (C)	Population (C_1)	Population (C_{1-1})	The average for the state where the Wei fort is located. e.g. C_{1-1} = the population for the whole state/the number of Wei fort in this state
	Economics (C_2)	Tax (C_{2-1})	
	Food (C_3)	Grain output (C_{3-1})	

Table 2 The comparison between right Fuzhou Wei and Quanzhou Wei

	Population	Tax (Liang)	Grain output(Shi)	Perimeter (m)	Wall height(m)	Wall thickness(m)
Right Fuzhou Wei	70,643	34,627	430	5877.00	6.85	5.55
Quanzhou Wei	90,407	54,925	656	12,853.70	8.49	4.57

ards of Quanzhou Wei in terms of perimeter, wall height, and wall thickness were higher than those of Fuzhou Wei. One more thing is that we acknowledge using the economy as a factor, there are too many relevant evaluation indicators, and it is challenging to ensure that complete historical information is available for all 66 Wei forts. This study utilizes tax revenue to represent the local economic level because it is a well-documented and easily accessible factor. After careful consideration, we have chosen three representative and easily quantifiable elements: Population (C_{1-1}), Tax (C_{2-1}), and Grain output (C_{3-1}) to indirectly reflect the level of societal prosperity and stability in the region where the Wei forts are situated.

Materials

The data in this study is mainly extracted from historical documents, including general histories [22–26], local chronicles [27–31], and the thematic chronicles of coastal defense [32–34]. All raw data is recorded in Additional file 1: Table S1, Additional file 2: Table S2, Additional file 3: Table S3). Category A pertains to internal features within each fort, with information sourced from local chronicles of various defense areas. Since the number of troops has experienced prolonged dynamic changes, this study adopts the number in the early stage of the establishment of each Wei fort. Additionally, for data such as wall height and circumference, which may involve unit conversion issues, this study uniformly converts them into modern units of meters. It is shown in Additional file 1: Table S1. Category B includes distances between settlements, involving spatial information related to Wei forts, subordinate Suo forts, XunJianSi fort, etc. This data is derived from long-term compilation of literature and on-site surveys, contributing to the establishment of a geographical information database for coastal defense military settlements of the Ming Dynasty. The nearest distance between settlements($B_{1)}$ is calculated based on the ASTER GDEM China 30 m precision elevation data, and obtained as the cost distance by ArcGIS. Category C encompasses the economic status of local governments where these Wei forts were situated, primarily sourced from *Accounting Records of Wanli in the Ming Dynasty*. As Wei forts were large settlements second only to Du-Si and their fortifications continued to be utilized after the Ming Dynasty, records are relatively rich and detailed. This is also one of the reasons why this study chose Wei forts as its research focus.

The main sources for records of conflicts in the coastal regions during the Ming Dynasty in this article are specialized historical works [22, 23, 35, 36] in ancient China focusing on Wokou, the marauders arriving from the sea. Such historical materials typically document significant incidents and conflicts with larger impacts, while often omitting details of localized or minor disturbances. Considering that smaller-scale disturbances, usually attributed to pirates or a small group of individuals, are characterized by their occasional and unorganized nature, this section of the study chooses to overlook this aspect. Additionally, due to the generalized nature of the records, it is challenging to compare the intensity of wars based on uniform indicators such as military strength, combat capability, weapon scale, and duration. Therefore, this section relies solely on statistics related to the location, frequency, and outcomes of these conflicts.

Min–max scaling

Before PCA, the indicators from these historical information sources exhibit diverse directions and magnitudes. In the case of defensive elements for military settlements, some factors indicate better defensive capabilities with higher value, while others indicate the opposite. Also, the data directions need to be aligned. The maximum-minimum scaling method, often referred to as Min–Max scaling, is a common approach to normalization. Specifically, the Max–Min scaling involves a linear transformation for each feature, scaling it to a specific range, typically [0, 1]. Forward indicators utilize the Maximum scaling method, while reverse indicators use the Minimum scaling method.

$$\begin{aligned} x &= \frac{x_0 - x_{\min}}{x_{\max} - x_{\min}} \\ x &= \frac{x_{\max} - x_0}{x_{\max} - x_{\min}} \end{aligned} \tag{1}$$

x is the normalized data, x_0 is the original value, x_{max} and x_{min} are the minimum and maximum values, respectively.

Principal component analysis (PCA)

PCA is a relatively objective method that is applied to multivariate statistical analysis. Its basic principle is to analyze the characteristic values of the sample data, calculate the mutuality among the factors, and extract the main components of the sample factors that can express the information of all factors. By reducing the dimensionality, multiple variables are reduced to several principal components (PCs) with as little loss of information as possible. It means that fewer PCs are used to summarize the original variables [37–40]. Instead of the original variables we can calculate the scores and loadings. The data matrix **X** can be decomposed as,

$$\mathbf{X} = \mathbf{TP} + \mathbf{E} \tag{2}$$

X is the normalized data matrix, **T** is the scores matrix of (number of objects) × (number of PCs), **P** is the loadings matrix of (number of PCs) × (number of variables), and **E** is the residual matrix, which is part of **X** but can not be explained by **TP**.

Every PC can represent Y% of original variable. The PCA calculation for this research is completed by SPSS via NIPALS algorithm. In order for variables to be reduced to a smaller number of PCs, we can decide on the number of PCs to keep via the scree plot by SPSS. The dividing point is the point before where the curve flattens. In addition, the interpretation rate of each original variable should be greater than 50%. After screening, there are n PCs, PC_1, PC_2, ... PC_n, which corresponds to Y_1, Y_2, ... Y_n. The sum of Y represents the percentage of original variables that can be explained by these PCs.

Loadings serve as a valuable tool for discerning the individual contributions of variables within a dataset. Through the calculation of the absolute sum of loadings for each principal component (PC), we derive the cumulative significance of each original variable, denoted as L_1, L_2, ... L_n. In this study, these values are transformed into percentages, thereby establishing them as weights. Consequently, we ascertain the weight assigned to each original variable, thereby elucidating its significance within the original dataset.

$$L = \sum |\text{Loadings}| \tag{3}$$

$$\text{Weight} = \frac{L_{\text{n}}}{\sum L} * 100\% \tag{4}$$

Results

Among the above factors, the number of gates ($A_{2\text{-}5}$) and the settlement accessibility factors ($B_{1\text{-}1}$ and $B_{1\text{-}2}$) negatively correlate with the defense capability. The more gates of the Wei forts there are, the more vulnerable breakthroughs there are. And the higher values of $B_{1\text{-}1}$ and $B_{1\text{-}2}$, the poorer abilities of military settlements to aid each other, and the weaker defense capabilities of the Wei forts. Other factors are positively correlated with the defense capability. The higher the value of factors, the stronger the defense capability of the Wei fort. We collect the historical documents' data for each impact factor, and unify their magnitudes and directions using the Min–Max scaling method to obtain the normalized impact factors (Additional file 4: Table S4).

By Extracting PCs, the eigenvalues are shown in the Table 3 and the scree plot is shown in Fig. 4. In the scree plot, there is a clear break between PC$_3$ & PC$_4$, PC$_6$ & PC$_7$, and PC$_{10}$ & PC$_{11}$. Usually, the scree plot is used to assist in determining the number of principal components to extract. When the steep slope suddenly becomes flat, the corresponding number of PCs from steep to flat can be considered as a reference for extracting the PCs. In this case, the cumulative variance of the first three PCs is only 48.186%, even less than 50%, which is not enough to represent the whole data matrix. The cumulative variances of the first six PCs = 73.005% > 70%. Therefore, The first six PCs are a more reasonable choice. The first six PCs have a significant effect on the defensive capability of the Wei forts, which can replace the original 15 impact factors.

Table 3 Total variance explained

	Initial Eigenvalues		
	Total	% of variance (Y)	Cumulative%
PC$_1$	2.753	18.354	18.354
PC$_2$	2.414	16.09	34.444
PC$_3$	2.061	13.742	48.186
PC$_4$	1.424	9.495	57.681
PC$_5$	1.185	7.903	65.585
PC$_6$	1.113	7.42	73.005
PC$_7$	0.87	5.799	78.804
PC$_8$	0.723	4.819	83.622
PC$_9$	0.621	4.139	87.762
PC$_{10}$	0.619	4.125	91.887
PC$_{11}$	0.374	2.493	94.38
PC$_{12}$	0.325	2.167	96.547
PC$_{13}$	0.243	1.623	98.169
PC$_{14}$	0.2	1.332	99.501
PC$_{15}$	0.075	0.499	100

Next, we acquire the loadings of these six PCs (Table 4). Through the summation of the absolute values of these principal component loadings, we derive the value of L for each impact factor, resulting in a cumulative sum of 19.319. Following this, in accordance with Eq. (4), we compute the weights assigned to each factor, along with the average weight.

The weight calculation results indicate that in the evaluation system of Wei fort defensive capabilities, Category B has an average weight of 7.21% > Category C with an average weight of 6.44% > Category A with an average weight of 6.24%. This indicates that the data presentation of Category B variables in the dataset is markedly higher than that of Category A and Category C. It suggests that the difference of defensive mechanism tends to rely on collaborative operations, followed by the regional jurisdictional control capacity. Their importance slightly surpasses that of the construction

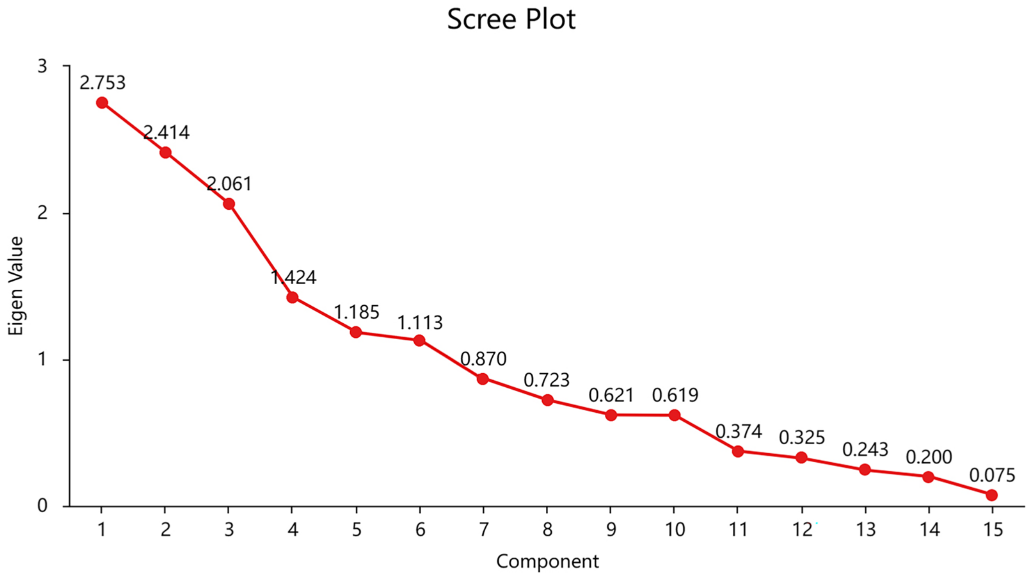


Fig. 4 Scree plot of the PCs

Table 4 Loadings

Impact factor	Loadings							Weight	Average weight	
	PC_1	PC_2	PC_3	PC_4	PC_5	PC_6	Sum of the absolute values (*L*)			
$A_{1\text{-}1}$	−0.043	0.376	0.35	0.209	−0.06	−0.039	1.077	5.57%	5.57%	6.24%
$A_{2\text{-}1}$	0.124	0.383	0.24	0.076	0.214	0.096	1.133	5.86%	6.37%	
$A_{2\text{-}2}$	0.069	−0.005	0.299	−0.341	−0.523	−0.247	1.484	7.68%		
$A_{2\text{-}3}$	0.245	0.207	−0.005	−0.007	−0.423	−0.215	1.102	5.70%		
$A_{2\text{-}4}$	0.129	0.408	0.136	0.036	−0.293	0.252	1.254	6.49%		
$A_{2\text{-}5}$	0.105	0.137	−0.38	−0.077	0.177	0.307	1.183	6.12%		
$B_{1\text{-}1}$	0.344	−0.231	0.138	0.278	−0.109	0.371	1.471	7.61%	7.74%	7.21%
$B_{1\text{-}2}$	0.307	−0.342	0.149	0.352	−0.139	0.232	1.521	7.87%		
$B_{2\text{-}1}$	0.229	−0.335	−0.03	0.22	0.007	−0.338	1.159	6.00%	6.85%	
$B_{2\text{-}2}$	0.181	0.348	0.018	0.463	0.277	−0.203	1.490	7.71%		
$B_{3\text{-}1}$	0.151	−0.234	0.495	−0.152	0.178	0.171	1.381	7.15%	7.03%	
$B_{3\text{-}2}$	−0.063	−0.021	0.466	−0.339	0.401	0.044	1.334	6.91%		
$C_{1\text{-}1}$	0.424	0.066	−0.217	−0.412	0.037	0.151	1.307	6.77%	6.77%	6.44%
$C_{2\text{-}1}$	0.342	−0.046	0.028	−0.039	0.264	−0.568	1.287	6.66%	6.66%	
$C_{3\text{-}1}$	0.519	0.137	−0.125	−0.231	0.099	0.025	1.136	5.88%	5.88%	

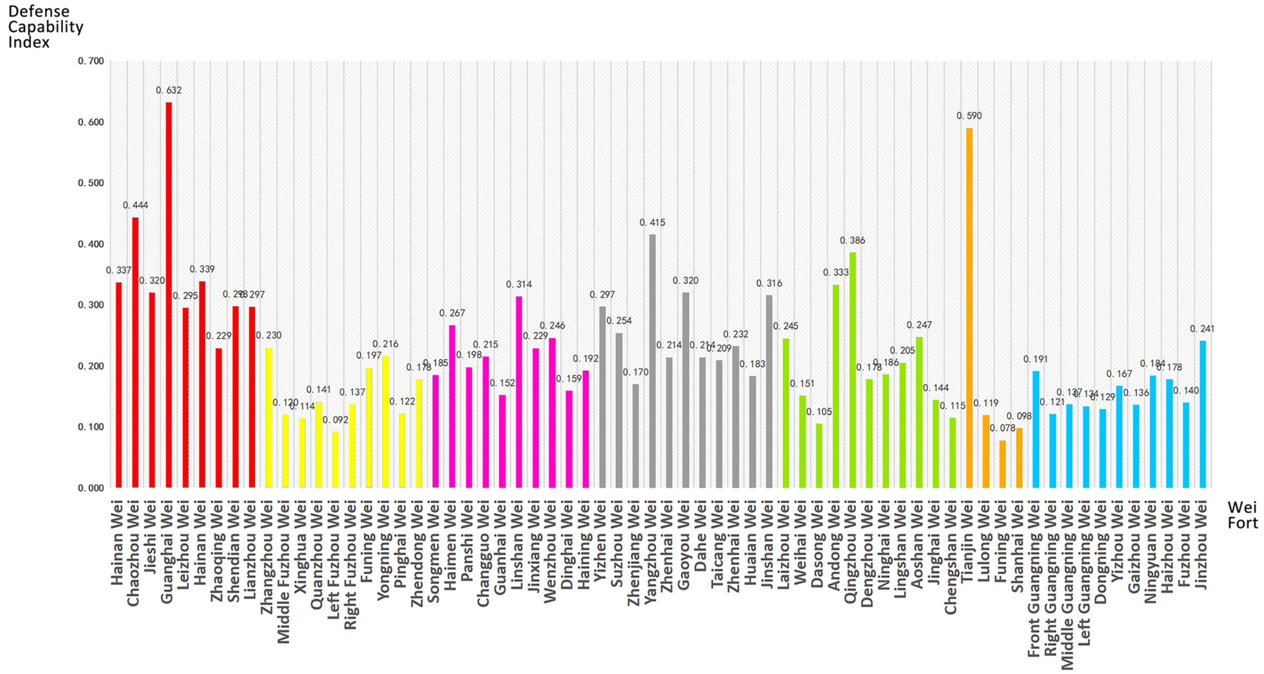
characteristics of individual settlements. Comparing the average weights at the next level, the order is as follows: $B_1 > B_3 > B_2 > C_1 > C_2 > A_2 > C_3 > A_1$. Particularly noteworthy are the two factors with the higher weights: $B_{1\text{-}1}$(the nearest distance between a Wei fort and other Wei forts) and $B_{1\text{-}2}$(the nearest distance between a Wei fort and Suo forts). This signifies that the mutual reinforcement distance between Wei forts and between Wei and Suo forts shows significant variability in the overall defensive capability of the settlements in the coastal defense system. As a comprehensive system, the spatial layout and relationships between core fortresses within the coastal defense settlements are crucial for the effectiveness of the entire system.

Defense capability index

Based on the weight, we calculate the comprehensive defensive capability index of the 66 Wei forts from the 7 defense areas. We define the defensive capability index as the weighted sum of the above 15 impact factors, and the results are presented in Fig. 5. Guanghai Wei and Tianjin Wei obtained the highest scores, and their defensive capabilities are particularly outstanding because they are both located within the castles of the state capitals. The Wei forts in Guangdong have the highest average score and median, followed by South Zhili and the Zhejiang defense area. As a whole, the southern Wei forts' defensive capabilities are higher than the north.

Discussion

In theory, the greater the comprehensiveness and granularity of factors considered in constructing the defensive capability assessment model, the higher the credibility of the resulting model. Although the inclusion of more factors implies dealing with a larger dataset, the application of the PCA method facilitates the extraction of principal components, streamlining the computational process. However, due to the challenging task of quantifying numerous factors associated with ancient Chinese military settlement construction and ensuring data completeness, this study has focused on extracting only the most representative ones. For instance, certain Wei forts featured the unique Ming Dynasty coastal settlement type known as "Shuizhai Fort (水寨)," designed for maritime patrols [41]. Additionally, in regions like south Zhili and Zhejiang, an extensive network of "Haitang(海搪)" defensive structures was established along the Yangtze River mouth, forming a continuous line to repel Wokou attempting to land and regroup [42]. Wei forts equipped with Shuizhai fort and Haitang structures should exhibit higher defensiveness. However, the lack of precise information regarding maritime patrol routes for Shuizhai fort and the construction lines for Haitang poses a challenge in determining which Wei forts could benefit from these defense strategies. The selected impact factors in the preceding sections have shifted the focus from exclusively considering the internal defense of individual forts to emphasizing the synergy between settlements. The obtained weights are intended for broad comparisons



Defense Area	Guangdong	Fujian	Zhejiang	South Zhili	Shandong	North Zhili	Liaodoong
Average index	0.355	0.155	0.216	0.257	0.209	0.221	0.160
Median index	0.320	0.139	0.207	0.232	0.186	0.109	0.140

Fig. 5 Defense capability index of each Wei fort

among categories, emphasizing the significance of spatial relationships between settlements, rather than ranking the importance of each individual factor.

Given the constraints imposed by the partial lack of historical data, it is imperative to validate the effectiveness of the defensive capability indices from alternative perspectives. We sought to correlate these indices with the actual battle outcomes around the Ming Dynasty coastal defense Wei forts. The defensive capability index of these forts serves as a representation of their military readiness. Generally, a higher index suggests superior defensive capabilities across various aspects, indicating better performance in real warfare and an increased likelihood of victory. It is crucial to acknowledge that myriad factors contribute to the outcome of a battle, and shifts in the political landscape during different historical periods significantly impact the results of military conflicts. For instance, during the mid to late Ming Dynasty, specifically in the Jiajing era (1522–1566), coastal fortification had fallen into disrepair, with a high incidence of desertion. The eastern coastal regions faced severe incursions from Wokou, leading to successive defeats of Ming forces. The situation began to improve gradually when the renowned military commander Qi Jiguang assumed office. During this period, the defensive capabilities of Wei forts might not have been a decisive factor in determining the outcomes of warfare. In future research, it is imperative to extract influencing factors in a time-specific manner to conduct a specific assessment of defensive capabilities. However, it can be affirmed that over the nearly three centuries of the Ming Dynasty's history, there is undoubtedly a correlation between the defensive capabilities of military settlements and the probability of victory. For the battle outcomes around the Wei forts, we gathered records from historical documents, extracting geographical coordinates for the locations of battles and victories (detailed data available in Additional file 5: Table S5). The coordinates of battle locations, along with the battle count and outcomes, were extracted, and the kernel density distribution is depicted in Fig. 6.

In accordance with the division by defense zones revealed by the kernel density distribution, regions experiencing a higher frequency of invasions were primarily concentrated in Zhejiang and south Zhili. Following closely were Fujian, Guangdong, and Shandong, while Liaodong and north Zhili witnessed remarkably few instances of warfare. Upon calculating the victory rate by dividing the number of victorious battles in each defense zone by the total number of battles and comparing it with the previously obtained defensive capability index (as shown in Fig. 7), several observations can be made. Firstly, Guangdong exhibited the

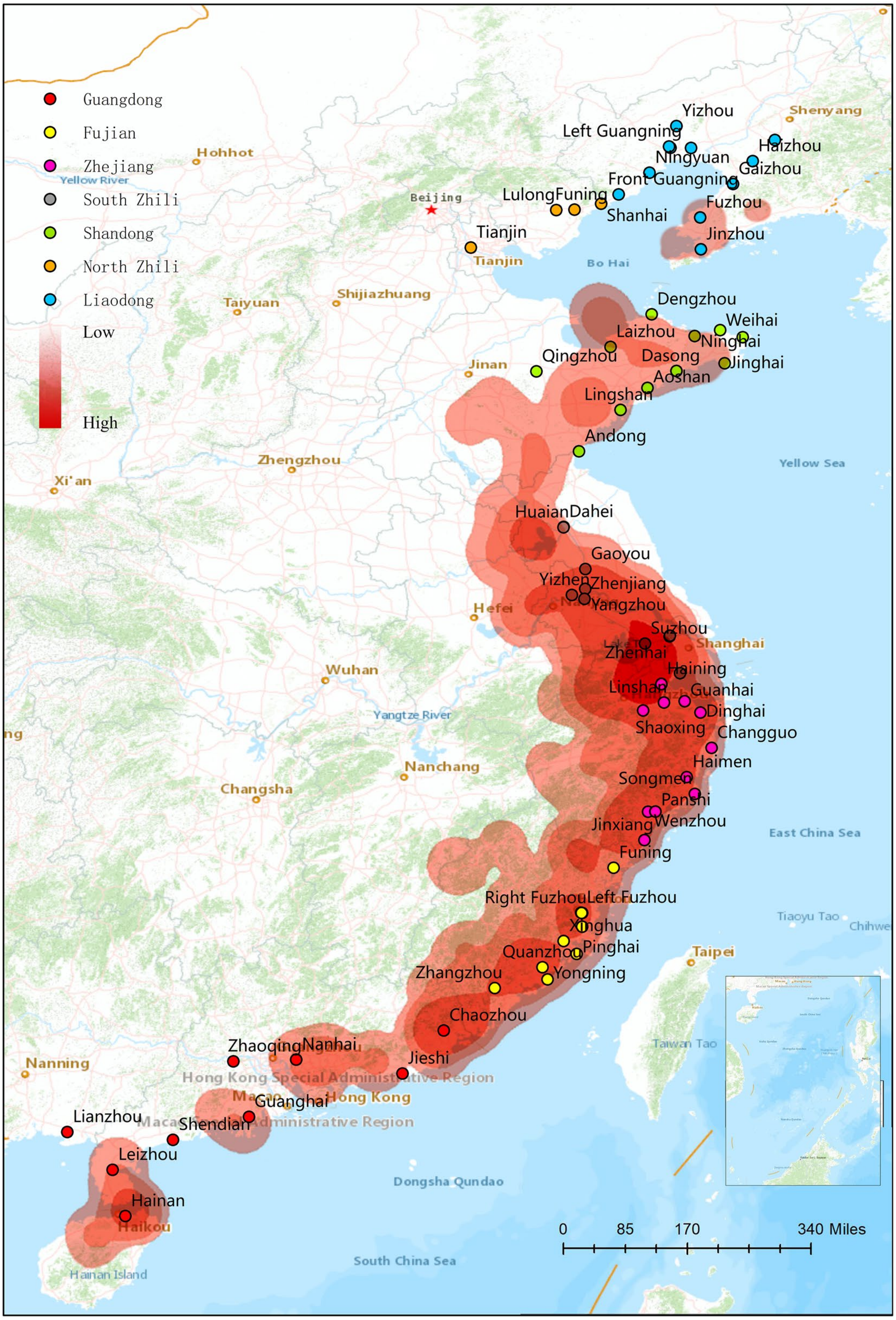


Fig. 6 The kernel density distribution of the battles in coastal region during the Ming dynasty (the base map from ArcGIS Online, copyright © 2020 Esri)

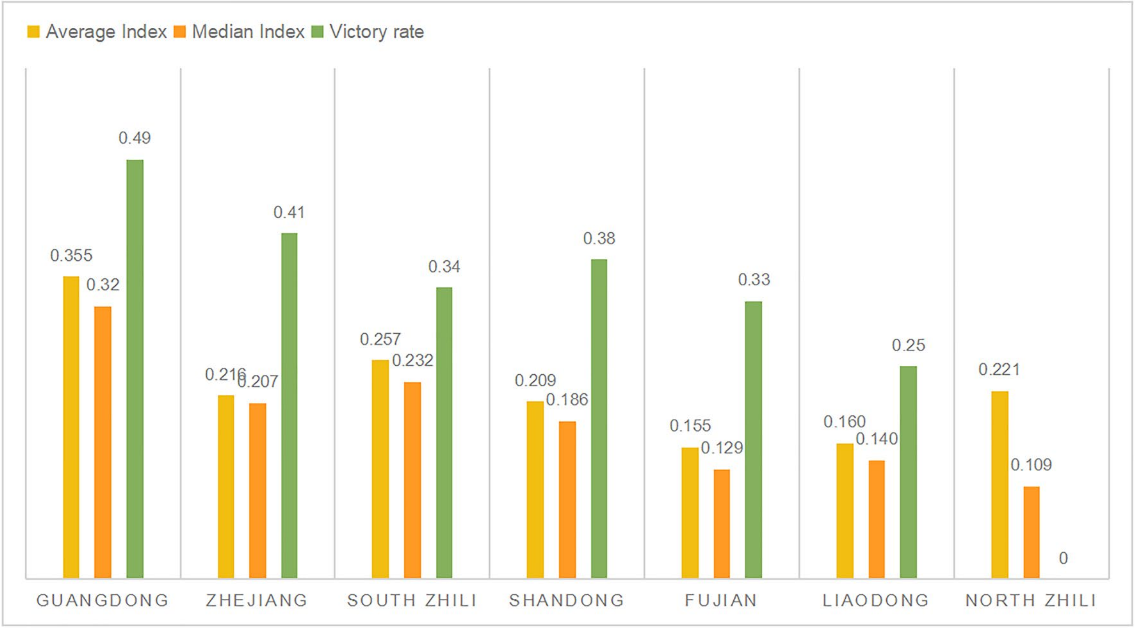


Fig. 7 Defensive capability index and victory rate

highest victory rate, aligning with the highest average defensive capability index. This indicates that among the seven coastal defense areas, Guangdong's Wei forts showcase the strongest defensive capabilities, resulting in a higher victory rate in actual warfare. Secondly, the central regions, encompassing Fujian, Zhejiang, southern Zhili, and Shandong, displayed a lower but consistent victory rate, corresponding with the average and median values of the defensive capability index. Thirdly, Liaodong had the lowest victory rate, corresponding to the lowest defensive capability index, suggesting a correlation between defensive capability and victory rate. It is noteworthy that due to the protective positioning of the Liaodong and Shandong peninsulas, North Zhili faced minimal maritime invasions, resulting in no significant warfare. Therefore, this study does not statistically analyze the victory rate of North Zhili.

Due to the extensive distribution of coastal defense forts and the dispersed nature of war outbreaks, it is necessary to preliminarily delineate the control range for each fort. Previous studies based on Ming Dynasty military records suggest that the average daily distance covered by Ming Dynasty cavalry was approximately 60 km, while infantry covered about 30 km. Although coastal defense settlements had some naval forces, naval marches were slower. Considering that these forts were primarily manned by infantry, with some having a small cavalry contingent, we have set a threshold of 60 km for a march within 2 days. It's important to clarify that we are not defining the actual reinforcement distance for each fort. Due to historical variations, accurately determining the jurisdiction of each fort poses a challenge. In real combat scenarios, when one location was attacked, it was not just the nearest fort that responds, but a network of nearby military settlements. Therefore, we have chosen a relatively larger range.

Then, we count the battles and wins within the 60 km radius of each Wei fort and then we compare this with the defensive capacity [43]. Considering that the number of battles within a 60 km radius of some Wei forts is 0 or 1, it makes the victory rate of high occasionality. Therefore, the 52 Wei forts with more than one battle are finally selected. Then, coupling analysis is performed, with the victory rate and the defense capability index of each Wei fort (Table 5).

To verify the correlation between the defensive capability index and the victory rate, we use the Pearson's correlation coefficient (r_p). As per the result in Table 6, $r_p = 0.726$, this indicates a significant positive correlation. It proves that the higher the defensive capability index of the Wei fort, the higher the rate of them winning the war, which also reviews the rationality of this defensive capability evaluation model.

Conclusion

This study aims to address questions surrounding the factors influencing defensiveness and their impact on the practical defensive effectiveness of settlements, particularly quantifying the defensive capabilities. The

Table 5 The correlation between the Wei forts defense capabilities and the victory probabilities

Wei fort	Number of wars	Number of victories	Defensive capability index	Victory rate (V)
Taicang Wei	72	21	0.209	0.292
Zhenhai Wei	72	21	0.232	0.292
Huaian Wei	17	7	0.183	0.412
Jinshan Wei	98	36	0.316	0.367
Songmen Wei	27	12	0.185	0.444
Haimen Wei	34	14	0.267	0.412
Panshi Wei	27	10	0.198	0.370
Changguo Wei	26	8	0.215	0.308
Guanhai Wei	55	22	0.152	0.400
Linshan Wei	53	23	0.314	0.434
Lingshan Wei	5	2	0.205	0.400
Aoshan Wei	4	2	0.247	0.500
Jinghai Wei	3	1	0.144	0.333
Chengshan Wei	3	1	0.115	0.333
Dasong Wei	5	2	0.105	0.400
Yongning Wei	24	9	0.216	0.375
Pinghai Wei	12	4	0.122	0.333
Zhendong Wei	16	7	0.178	0.438
Hainan Wei	14	7	0.337	0.500
Chaozhou Wei	38	17	0.444	0.447
Jieshi Wei	2	1	0.320	0.500
Guanghai Wei	2	2	0.632	1.000
Leizhou Wei	2	1	0.295	0.500
Middle Fuzhou Wei	14	5	0.120	0.357
Xinghua Wei	11	4	0.114	0.364
Quanzhou Wei	25	9	0.141	0.360
Left Fuzhou Wei	14	5	0.092	0.357
Right Fuzhou Wei	15	6	0.137	0.400
Fujing Wei	14	4	0.197	0.286
Dinghai Wei	44	12	0.159	0.273
Haining Wei	70	23	0.192	0.329
Suzhou Wei	35	14	0.254	0.400
Yangzhou Wei	14	9	0.170	0.643
Zhenhai Wei	37	21	0.415	0.568
Gaoyou Wei	11	6	0.214	0.545
Dahei Wei	16	6	0.320	0.375
Dengzhou Wei	5	3	0.214	0.600
Ninghai Wei	3	1	0.186	0.333
Jinzhou Wei	5	3	0.241	0.600
Nanhai Wei	3	1	0.339	0.333
Shendian Wei	2	1	0.298	0.500
Zhangzhou Wei	26	12	0.230	0.462
Zhenyi Wei	16	9	0.297	0.563
Andong Wei	7	3	0.333	0.429
Left Qingzhou Wei	2	1	0.386	0.500
Laizhou Wei	5	2	0.245	0.400
Weihai Wei	5	1	0.151	0.200
Wenzhou Wei	28	12	0.246	0.429
Tianjin Wei	6	4	0.590	0.667
Lulong Wei	3	1	0.119	0.333
Funing Wei	3	1	0.078	0.333
Shanhai Wei	2	1	0.098	0.500

Table 6 Pearson's correlation coefficient

	Defensive capability index	Victory rate
Defensive capability index		
Pearson correlation	1	0.726**
Sig. (2-tailed)		0.000
N	52	52
Victory rate		
Pearson correlation	0.726**	1
Sig. (2-tailed)	0.000	
N	52	52

** Correlation is significant at the 0.01 level

construction of Wei forts is influenced by numerous factors. Acknowledging the holistic nature of the Ming Dynasty coastal defense system, we introduced two additional significant factors—Coordinated Defensive Capability (B) and Jurisdictional Control Capacity (C)—in addition to the common factors categorized as Single Defensive Capability (A). Leveraging the PCA method for principal component extraction, we obtained weights for each impact factor. Results indicate that within the Ming Dynasty coastal defense, operating as a systemic and integrated defense system, settlement accessibility emerges as the most crucial factor influencing the defensive capabilities of Wei forts. Contrary to expectations, the defensive capabilities of individual forts play a relatively minor role in the overall defense level. Consequently, the defensive capabilities of Wei forts are more determined by the overall coordination of the coastal defense system than the individual fort's defensive capacity.

Based on the weights assigned to each impact factor, this study establishes a comprehensive quantitative model for assessing the defensive capabilities. The calculated defensive capability indices reveal that, overall, the southern coastal region are generally higher than those in the northern region, with Guangdong showing the highest defensive capability and Liaodong the lowest. This result is coupled with the distribution of battles in the coastal region during the Ming Dynasty. The coupling analysis shows a positive correlation between the victory rate and the defensive capability index. Moreover, higher defensive capabilities of Wei forts are associated with a greater probability of victory in battles occurring within the controlled territory of each Wei fort. This confirms the significant positive impact of the construction of the coastal defense. Additionally, it validates the rationality of the evaluation model and suggests potential applications in the study of other Chinese traditional military defense systems.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s40494-024-01209-1.

Additional file 1: Table S1. The original value of the impact factors A.

Additional file 2: Table S2. The original value of the impact factors B.

Additional file 3: Table S3. The original value of the impact factors C.

Additional file 4: Table S4. Classification and data sources of impact factors.

Additional file 5: Table S5. The temporal and spatial distribution and the outcomes of major military conflicts in the coastal defense areas during the Ming Dynasty.

Author contributions

JZ and YJ wrote the main manuscript text. JL prepared Figs. LM collected the data and revised the text. LT provided the fund and managed the whole project. All authors reviewed the manuscript.

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Availability of data and materials

The original contributions presented in the study are included in the article and supplementary material, further inquiries can be directed to the corresponding authors.

Declarations

Competing interests

The authors have no competing interests as defined by Springer, or other interests that might be perceived to influence the results and/or discussion reported in this paper.

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