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RESEARCH

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A study on the visual defensive system of the Moluo Tower Village, Western China, based on a multi-dimensional model

Wei Xiong[1], Licheng Wang[2], Mengyuan Tu[2], Xiang Li[2], Siwei Jiang[2] and Qinglin Liu[2*]

Abstract

Scientifically validating the value of rural heritage and exploring construction wisdom has emerged as a significant challenge in the study of rural settlements worldwide. Rural heritage shows significant differences according to the natural environment, history, culture, and socio-economic factors. However, the assessment of the authenticity and effectiveness of heritage values have yet to be quantified due to the difficulty in obtaining evidence directly from samples. By constructing a multi-dimensional model of villages for quantitative analysis, we proposed a multifaceted spatial visibility analysis method based on individual and combined defense structures to empirically study the remains of eight towers in Moluo village, western China. This study demonstrated that towers serve as regional defense structures and are essential for constructing a comprehensive and effective visual defensive system (VDS) in Moluo village, a typical military defense village. The effectiveness and coverage of the towers vary depending on their location, height, type, and other factors. They form a complementary and synergistic relationship, playing a dual mechanism of public and private, local and overall defense. In summary, this method enables the feasible quantification and analysis of the functional value of rural heritage through landscape visual analysis. It provides a new perspective for studying the authenticity of heritage functions.

Keywords Cultural heritage, Rural settlements, Visibility analysis, Defensive systems

Introduction

Background

Settlements have witnessed the development and evolution of history, culture, politics, and economy. They are an essential component of cultural heritage [1]. Settlement landscapes combine natural landscapes and cultural significance[2]. Traditional villages are formed early in history and are a rural heritage of precious traditional resources with nonrenewable historical, cultural, architectural, and research value [3, 4]. The concept of the universal value of heritage has facilitated the process of world heritage conservation and digitization [5, 6] as people's awareness of cultural heritage protection has increased.

The development of ethnic settlements in western China is attributed to the harsh natural and turbulent social environments of the time. Rural settlements are distributed on the banks of the Dadu River and the Minjiang River basin in high mountains and valleys; these areas are located at the intersection of Tibetan and Qiang ethnic cultures and have historically suffered from ethnic disputes and wars. The unique settlement pattern of tower (Diaolou) villages results from the area's complex historical and geographical environment. Towers serve as a visual marker of the settlement's construction. As early as in the "Northern History (北史)," the towers

*Correspondence:
Qinglin Liu
13854@sicau.edu.cn
[1] Department of Environmental Art and Design, Sichuan Agricultural University, Chengdu 611130, Sichuan, China
[2] College of Landscape Architecture, Sichuan Agricultural University, Chengdu 611130, Sichuan, China

were recorded as “stacked stones to serve as a nest to avoid suffering”. Its nest is as high as ten Zhang (Chinese unit of length, equal to 3.3 m), down to five or six Zhang…,To prevent thieves and robbers (垒石为巢，以避其患。其巢高至十余丈，下至五六丈……,以防贼盗)” [7]. The “Ancient History of Sichuan(四川上古史)” states that “Each village has a high tower to reach the height of seven, eight stories or even thirteen, fourteen stories for the defense of sight, command, and preparation for war” (各寨更有高碉达七八层或十三四层， 供防守眺望, 指挥备战之用) [8]. Towers have been used as defensive structures for thousands of years, and the corridor of the Tibet-Yi minority military architecture is a wonder in this regard [9]. These towers serve multiple functions, including lookouts, reserves, shelters, and defenses [10, 11]. They are also characteristic of settlements that prioritize defense [12]. Since 2014, the Chinese government has issued a series of policies aimed at revitalizing rural areas and protecting traditional villages. As of 2022, approximately 396 villages in Sichuan Province have been designated as conventional Chinese national villages. However, accelerating urbanization in China has significantly impacted rural settlement space [13]. Therefore, in the face of global habitat challenges, uncovering the value of cultural heritage hidden beneath the landscape's surface and revealing the wisdom of rural settlement construction can support the scientific conservation and sustainable development of rural settlements [14].

Visual analysis as an effective method for assessing the authenticity of cultural heritage

Residents' perceptions of their living environments form a unique value within rural landscapes [15], a value that is region-specific visual relationships between people and landscapes. Archaeological landscape research aims to explore the human–environment interactions [16], model site locations, evaluate site functions [17, 18], and explore the evolution of archaeological landscapes [19]. In archaeological GIS research, human visibility is still a focus topic [20]. Research on visual relationships focuses on the relationships between spatial and landscape elements. It conducts visibility analysis [21] and explores spatial visual features with simulation and digitization [22, 23]. This research is a critical aspect of human–environment interaction research [24]. Intervisibility analysis provides valuable insight into the sociocultural significance of archaeological features [25]. The visual relationships between point-to-surface and point-to-point can be analyzed through landscape modeling. This approach can explain defense functions [26] and provide a scientific basis for the authenticity of landscape heritage sites [27]. However, the analytical viewpoints, visual dominance, and visibility indices [28, 29] in the GIS planar view are not sufficient for illustrating the stereo-spatial relationships of landscapes. Therefore, we reconstructed a multi-dimensional spatial model and proposed a visual analysis method based on the relationships between individual and combined defense structures. It is an applied study of settlement areas and military contexts [30] to a more comprehensive and integrated assessment of the authenticity and likelihood of a landscape heritage [31, 32].

Study area and content

Study area

In the western Sichuan region, Tibetan and Qiang Tower (Diaolou) villages are commonly situated in river valleys that border perilous and narrow roadways. These villages can be classified into two types: valley-type and alpine-type. Danba is located in western Sichuan Province (330° 24′ to 31° 23′ N and 101° 17′ to 102° 12′ E), China. Moluo village in Danba is a typical example of a rural settlement in the area. The towers are well-preserved and contain the most excellent density of remains. Moluo village was inscribed on the Tentative List of World Heritage in 2012. [33]. The village is situated in a river valley, with mountains surrounding it on three sides and an altitude ranging from 1800 to 2100 m; the overall slope angle is between 0.00° and 82.18°; the slope changes significantly and has a steep slope topography. The land slopes from east to south, forming a natural protective barrier and providing an open range of views. The towers, which protrude vertically, offer a longer distance for observation [34, 35]. According to the Danba County Records, Moluo village originally had 21 towers. Based on the latest digital mapping, field research, and traditional village protection planning documents, we obtained the basic information of the village's eight existing towers (see Fig. 1 and Table 1). Towers ①–⑤ and ⑧ are relatively well-preserved, with no significant structural damage. In contrast, towers ⑥ and ⑦ collapsed, leaving only the foundation site. The ②, ⑤, ⑦, and ⑧ towers are village-towers (public property) located at the entrance and height of the village, with the ability to see into the distance. The village-tower is divided into the

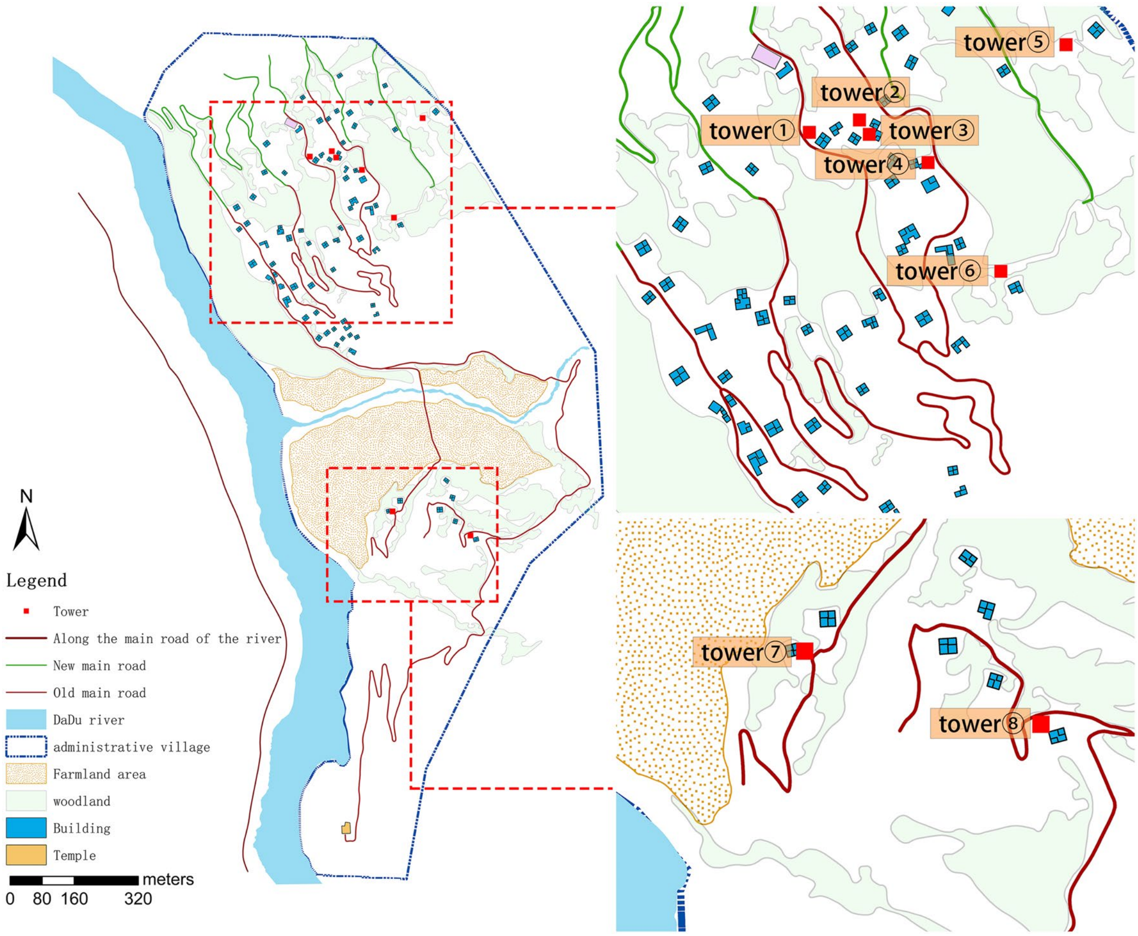


Fig. 1 The scope of the administrative village area and the location of the towers in Moluo village

Table 1 Basic information on the towers

Number	Type	Shape	Height of towers (m)	Altitude (m)	Length, width of the base (m)
Tower ①	Family-tower	Quadrangular	38.14	1991.58	7.21, 7.04
Tower ②	Village-tower	Octagonal	26.67	2006.36	6.69, 6.65
Tower ③	Family-tower	Quadrangular	36.02	2004.98	7.07, 6.69
Tower ④	Family-tower	Pentagonal	24.29	2015.21	7.08, 6.93
Tower ⑤	Village-tower	Quadrangular	22.67	2097.84	5.82, 5.02
Tower ⑥	Family-tower	Quadrangular	Approximately 22	2028.19	5.50, 5.00
Tower ⑦	Battle tower	Quadrangular	Approximately 22	1888.34	5.48, 5.00
Tower ⑧	Battle tower	Quadrangular	30.27	1949.57	6.52, 6.34

sentry tower, beacon tower, battle tower, watch-tower and other types the ①, ③, ④, and ⑥ towers are for the family-tower(private property), reflecting the identity and wealth of the owner.

Based on historical documents and field research, it has been determined that during the Second Battle of Jinchuan (1747–1749), the incoming enemy's main direction was from the north (Kangding) to the south

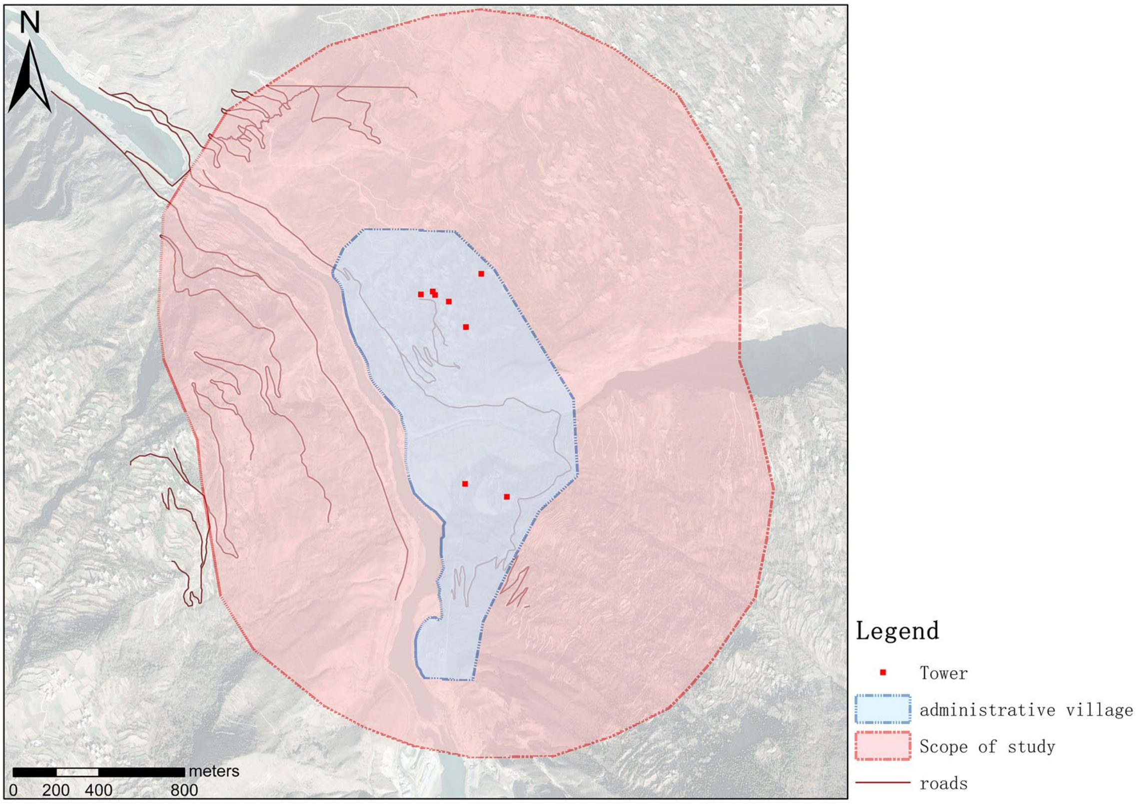


Fig. 2 Map of the tower (Diaolou) village research area scope

(Danba). Additionally, according to oral history, the southwest of the village was the main entrance and exit during that time.[1] The battle towers are built at the main intersection of the village mountainside and the main road with good vision [11]. The ⑦ and ⑧ towers were further subdivided into battle towers. The farthest view distance of the towers is 1200 m, within which the roads and rivers around the village can be effectively seen. Each tower has a 1200 m view distance as a radius to perform the buffer zone, which forms the largest visual coverage for external observation and defense; that is the study area of this paper. Furthermore, the administrative village domain covers the inside space of the tower (Diaolou) villages. (see Fig. 2).

Posing problems

This article aims to explore the role of visual defense and the functionality of towers by using towers with visual prominence and absolute vertical height as observation points. It intends to determine the historical function of the visual features of the towers by answering the following four questions and to provide scientific support for the authenticity of the defense function of the tower heritage.

(1) How effective is the visual control exerted by the towers on the surrounding environment of the village?
(2) How are the visual coverage and monitoring capabilities of the towers for internal spaces and different types of roads in the village? Is there a potential relationship between the towers and the military preparatory buildings? (ravuze: the name of military preparatory buildings, it is a transliteration of a Chinese term.)
(3) How can the location of multiple towers and the line of sight (LOS) relationship between the construction of a timely communication network and a visual surveillance network facilitate the transfer of information?
(4) How does the visual relationship of the tower (Diaolou) village landscape reflect the wisdom of settlement construction? What beneficial insights can it provide for the protection and development of contemporary rural settlements?

[1] Derived from the field work and oral history accounts of the village of Moluo by this research team.

Table 2 The sources of primary data for the study area

Datatype	Data sources	Data use
Digital orthophoto map (DOM) of Moluo village	UAV tilt photography (5 m resolution)	Physical spatial elements of the village
3D modeling of Moluo village	UAV tilt photography	Modeling of landscapes, towers, houses, etc
Digital elevation model (DEM) of Moluo village	UAV-mounted LiDAR (5 m resolution)	Spatial analysis of the village
DEM of Moluo village and surrounding area	Geospatial data cloud https://www.gscloud.cn/search (30 m resolution)	Spatial analysis around the village
Historical information on towers and villages	Traditional village protection planning, field mapping, and oral history recording	Characteristics, evolution, and development of the defensive system

Research data and methodology

Data sources

Digital Elevation Models (DEMs) based on airborne laser scanning flights are among the most commonly used data for analyzing terrain differences and archaeological landscapes [36]. This paper utilizes UAV tilt photography and airborne LiDAR mapping to collect precise coordinates using GPS-RTK. The acquired data are then processed to obtain DEM and Digital Orthophoto Map (DOM) and create a 3D real-world model (Table 2). DOM presents the authentic appearance of the settlement surface, effectively identifying the features of buildings, trees, roads, and other features. A seamless DEM model represents the village's environmental data, reflecting the three-dimensional information of the surface. The historical information of Tower Village is based on the results of the traditional village protection planning survey, field mapping, and oral history records of Danba County.

Multi-dimensional model construction

We used ArcGIS 10.4 to simulate the spatial interaction between towers, buildings, and the surrounding terrain in Moluo village. According to the results of the statistical value of the ratio of the floor area to the height of the four corner towers, the ratio of the two is 0.7–0.8, which was then combined with on-site vegetation, surface cover, and the sheltering relationship with the tower, resulting in 22 m as a model parameter of the collapsed tower height. In this paper, cubical objects such as buildings do not have a complete three-dimensional form in the DEM and are, therefore, defined as 2.5D models. A 2.5-dimensional raster and 3D scene model of Moluo village and its surrounding environment were constructed. These models were used to analyze the visual relationship between natural and artificial elements of the village from the perspective of the tower (see Fig. 3). Combined with the historical documents describing the natural environment of the village, it is evident that the local vegetation is sparse and significantly shorter than the towers. This information has little effect on the visual analysis, so no additional vegetation information was added to the model.

In the 2.5-dimensional field of view, visual buffer zones and viewing directions are divided to assess the effectiveness of the towers in controlling the surrounding landscape's visual elements. The degree of visual prominence and interconnections between the village's internal and external spaces and roads are assessed through visibility, a single field of view, and a cumulative field of view. The 3D field of view was used to determine the towers' intervisibility in 3D space. This was done to explore the information communication network's composition and the specific information dissemination path.

The viewpoint position of the tower

The eight existing towers have multiple triangular stone protrusions at the top. They were combined with the results of the internal structure of the towers, which was in the ideal state of maximizing the overlooking ability. According to the average vertical height of human eyes above the ground, the tower viewpoint is set at a height of 1.6 m from the ground at the tower's highest floor. The lowest point of the U-shaped height of the towers above the ground is the same (see Fig. 4). Changes in the height of triangular protruding objects (0.4–0.6 m) may have negligible effects on visual field analysis. Therefore, the viewpoint location in the model is set as the lowest position of the U-shaped top of the tower in the plane polygon center, which accurately provides viewpoint height information as a unified standard for location.

Research methods

Visibility

The extent of visual coverage of the surrounding area and directionally visible analyses [37, 38] are crucial factors in determining the placement of defensive structures. To examine the visual coverage capabilities of towers, visibility is utilized to evaluate the degree of control over the viewpoint's visibility within its area and assess the

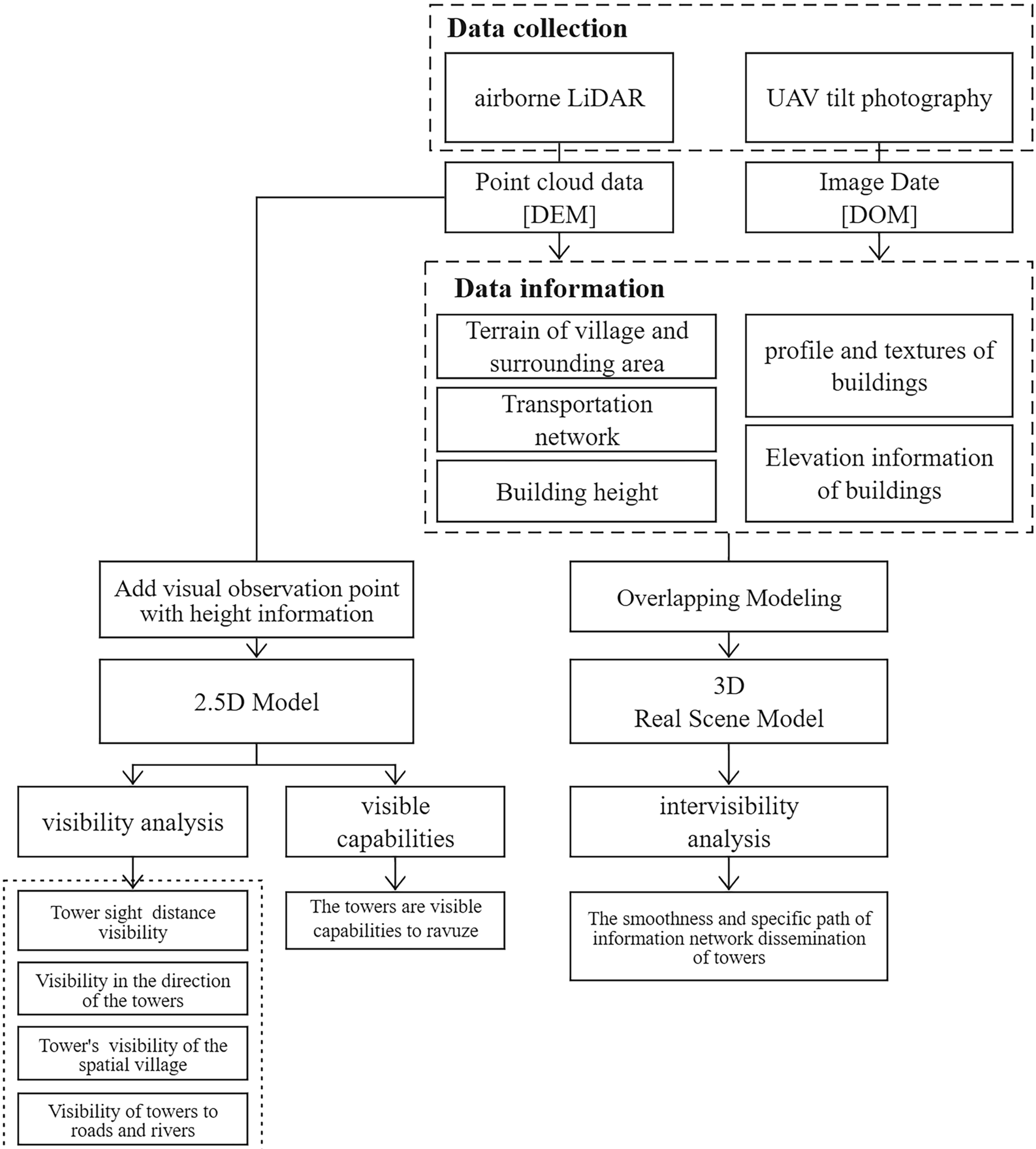


Fig. 3 Methodology

correlation between the visual range and adjacent roads and rivers [31, 39]. In our study, visibility refers to the percentage of the total visual area visible to the observation point within the selected range of the field of view, which quantifies the towers' visual control capabilities.

$$V = \frac{S1}{S2},$$

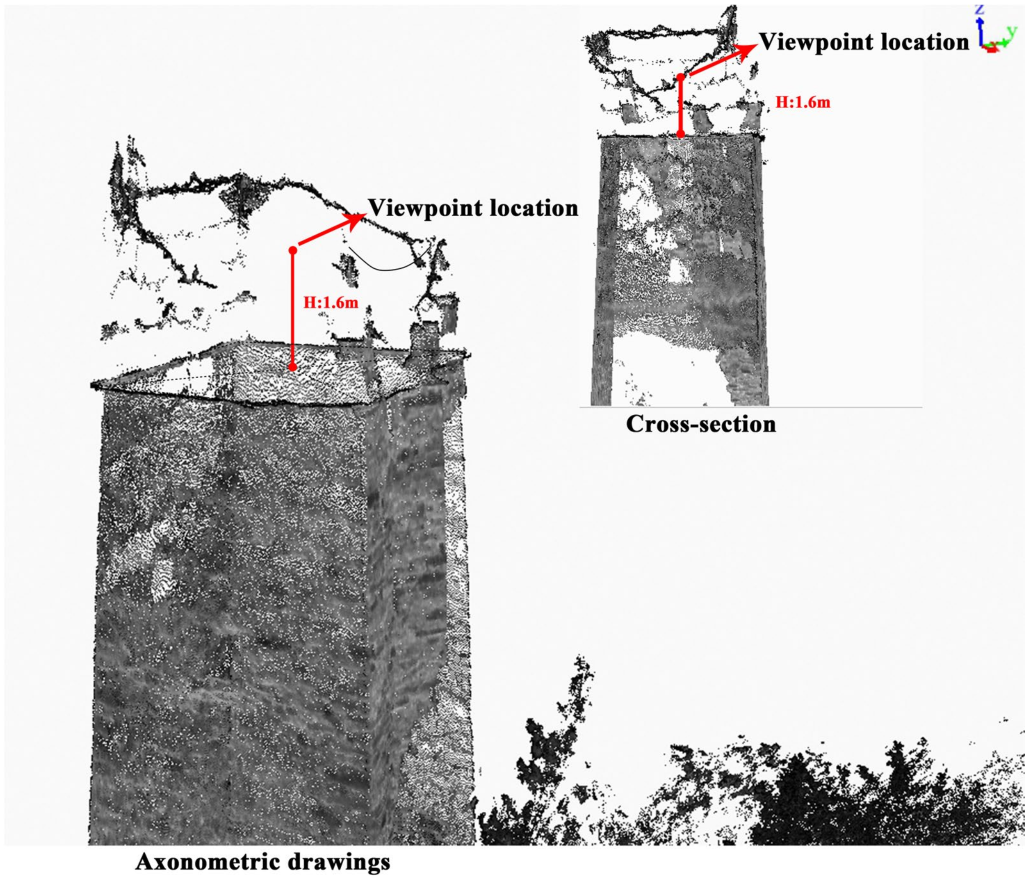


Fig. 4 Tower viewpoint location

Fig. 5 Image of Ravuze

V represents visibility, S1 represents the total number of visible rasters, and S2 represents all raster cells within the study area.

Visible capabilities

Ravuze is a type of family-tower typically used for military preparation and refers to the specific locations where towers used to exist or should have been constructed (see Fig. 5). The analysis of visible capability mainly explores whether there is a synergistic visual relationship between the ravuze and the towers, and how such capabilities affect visual command [29], and clarifies whether the ravuze is an important component in the visual relationship of the towers. The degree of complete visibility versus partial visibility is taken into account.

$$R = \frac{C}{N} \times 100\% + \frac{A}{N} \times 50\%,$$

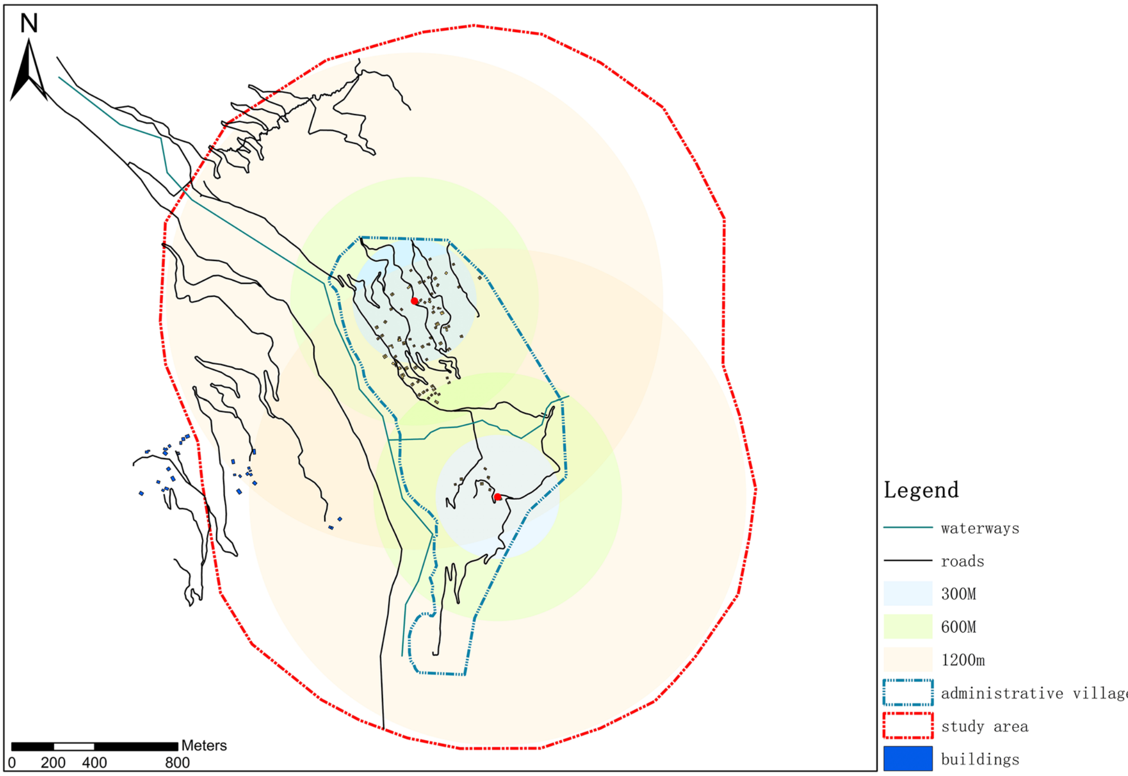


Fig. 6 300 m, 600 m, and 1200 m buffer area maps

R is the visible capability of the ravuze, C is the number of fully visible ravuze, N is the total number of ravuzes, and A is the number of partially visible ravuzes. The coefficients of 100% and 50% represent the capability of the tower viewpoint to see a single complete ravuze and to see only part of the ravuze, respectively.

3D spatial intervisibility analysis

Linear intervisibility analysis creates a LOS from the observation point to the observation target and determines any visibility issues along the line [40]. Intervisibility analysis in 3D space is a processing method to optimize the surrounding terrain, environment, buildings, and other obstacles, and obstacles to accurately reflect the 3 spatial relationships and occlusion of the LOS between two or more points. We can comprehensively consider whether there are obstacles in the LOS propagation between two or multiple points and accurately reflect the 3D spatial relationship and the occlusion of the LOS. It is important for interpreting information dissemination from towers and exploring how information exchange is achieved between defensive systems [28].

Table 3 Tower visibility at various viewing distances

	300 m	300–600 m	600–1200 m
Tower ①	0.945	0.727	0.549
Tower ②	0.934	0.575	0.481
Tower ③	0.925	0.639	0.528
Tower ④	0.804	0.450	0.464
Tower ⑤	0.916	0.548	0.403
Tower ⑥	0.899	0.502	0.573
Tower ⑦	0.821	0.750	0.599
Tower ⑧	0.859	0.834	0.638

Analysis

Analysis of tower visibility

Analysis of tower visibility based on different distances

The defense process involves knowing the direction and distance of the enemy in advance to provide adequate early warning and to gain initiative in the war. View distance analysis is essential for clarifying the tower's main monitoring range. Based on observations of the

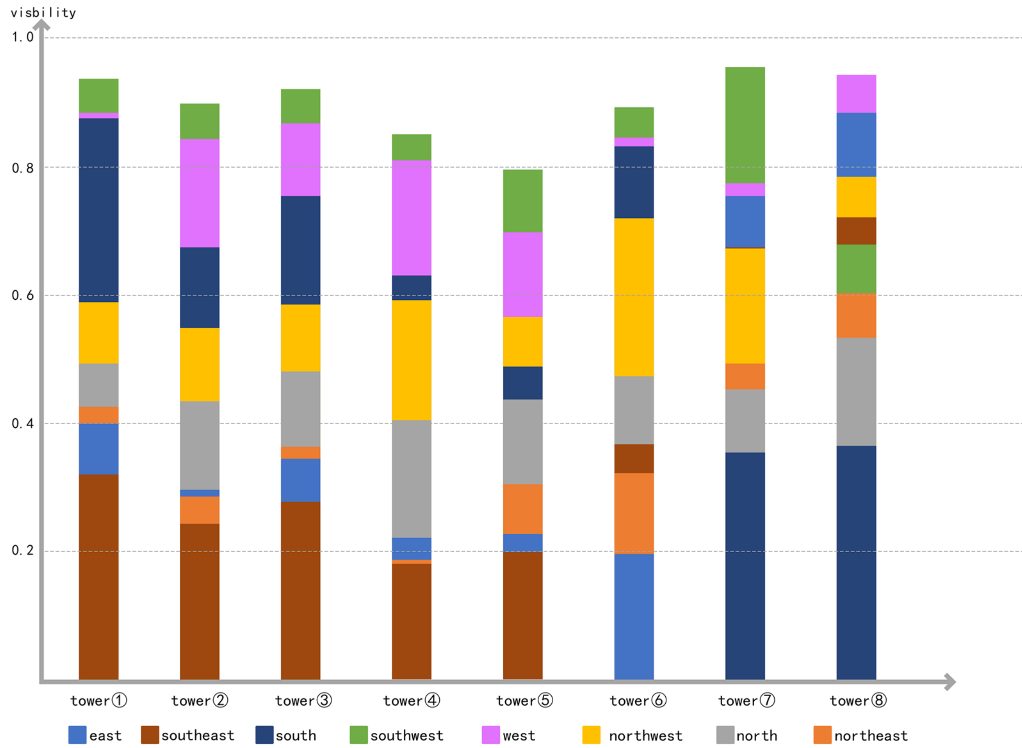


Fig. 7 Stacked bar chart of visibility accumulation for eight towers in different orientations

surrounding environment and surveillance area, and considering the visual ability of the human eye, three view distances were determined: 300 m, 300–600 m, and 600–1200 m (see Fig. 6). These ranges include village buildings, complete village spaces, rivers close to villages and traffic along rivers.

The results are presented in Table 3.

(1) Within the 300 m view distance range, it has been observed that the towers. The best visual observation and surveillance results have an average visibility of 0.888, with each tower having a visibility greater than 0.8. It is worth noting that the absolute height of the towers and the gentle terrain surrounding them provide optimal visual control. Traditional villages are often inhabited by multiple ethnic groups, with bloodlines and clan relationships serving as bonds. The distribution of towers within the villages reflects the characteristics of cluster defense, with the towers serving as the core of a specific group that radiates outward and cooperates with other buildings to achieve the goal of fortification.

(2) Within the 300–600 m view distance range, the visibility of the six towers is significantly reduced due to canyon topography, terrain changes, and other factors, with an average visibility of 0.628. It is worth noting that battle towers ⑦ and ⑧, which act as vanguards, guard the main road to the entrance of the village. When compared to the 300 m view distance results, visibility decreased by only 0.071 and 0.025, respectively, indicating their importance in the visual surveillance of the village and its surrounding environment. Towers can also use spears, rubble, and other means to defend against enemies within 500–1000 m [11]. Therefore, towers play an essential role in regulating the process and speed of a foreign enemy march.

(3) Within the 600–1200 m view distance range, they cover the surrounding rivers, external transportation roads, and adjacent villages. According to the comparison, towers ⑦ and ⑧ continue to have the highest visibility, providing the best visual advantage for observing the surroundings and having the ability to transmit information to nearby villages.

Analysis of visual orientation visibility

It is important to note that this analysis is based on the maximum scale of view distance visibility (radius 1200 m) within the scope of the study.

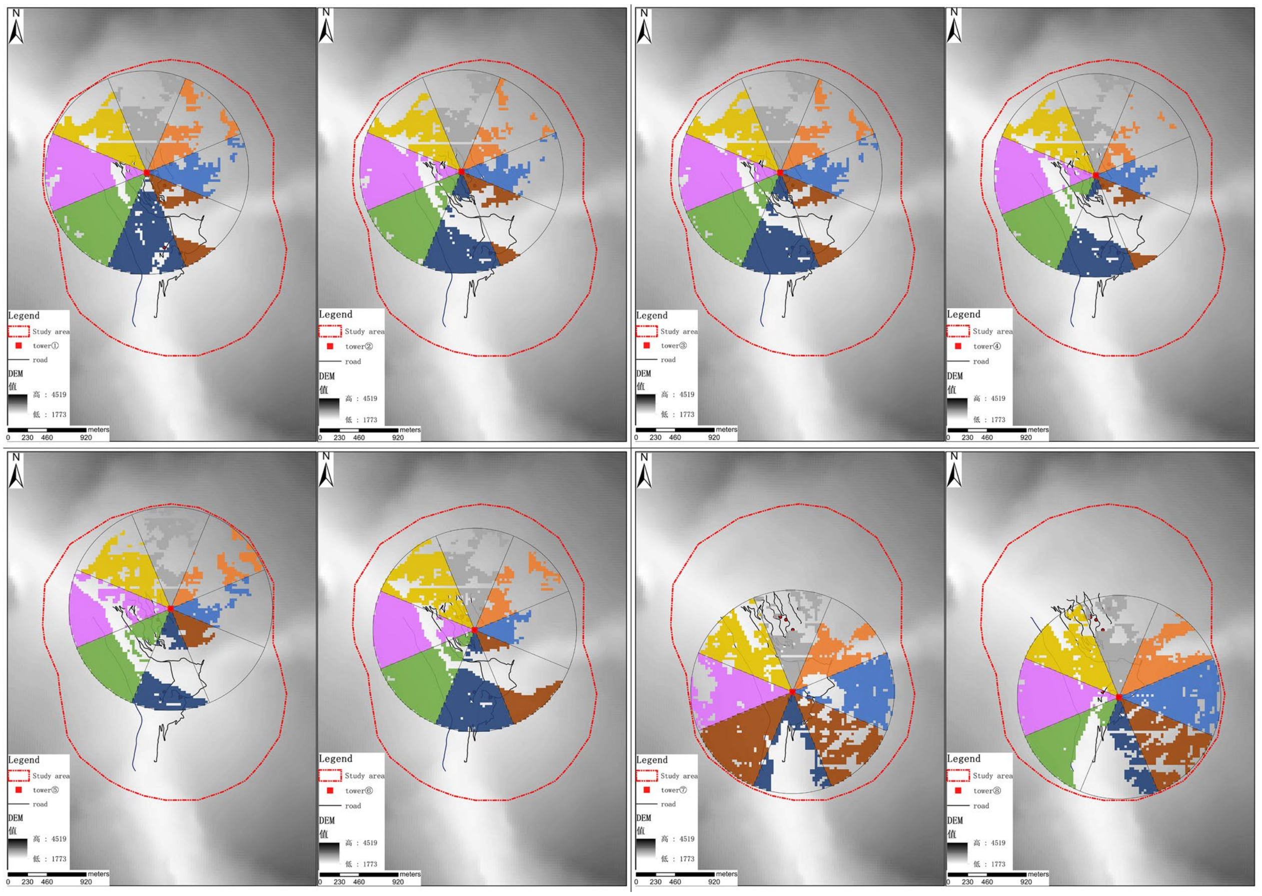


Fig. 8 Illustration of visibility for eight towers in different orientations

(1) The analysis of visual orientation visibility (see Figs. 7, 8) indicates that most towers in the southwest and west areas have the highest visibility. This result is closely related to the layout form of the southwest direction of Moluo village, which is consistent with the orientation of early village entrances and exits.
(2) Towers ⑦ and ⑧, located on the south side of the village, show a strategic visual advantage toward the east. On the other hand, the towers ① to ⑤ on the north side have their visual advantage facing the south. This suggests that each tower in the village had a specific strategic function and role. The towers complemented each other visually, controlled and oversaw the situation in all directions, and provided timely military defense and reinforcement.

The results indicate that the construction of the towers fully considered the harmonious relationship with geographical and environmental factors. The selection of tower locations based on surveillance, defense, and other requirements greatly expanded the visibility range, reducing the possibility of blind spots and facilitating functional synergy between the bunkers.

Analysis of riverside roads and river visibility

Rivers serve as excellent natural defense lines for villages (see Fig. 9). Deploying and conducting strike operations near the river in advance can weaken the enemy's marching speed and numbers. This approach can provide additional time for transmitting military information to the front and rear. It also allows the residents of rear villages to prepare for and respond to threats promptly. Therefore, the importance of monitoring rivers and along-river transportation routes, which are linear spaces, is self-evident.

The results indicate that each tower can overlook nearby rivers and along river transportation routes within a visual range of 1200 m (see Table 4). The strategic positioning of the towers at key locations provides absolute, effective visual control over the strategic lines, forming a visual defense barrier around the village perimeter. At the same time, by taking full advantage of

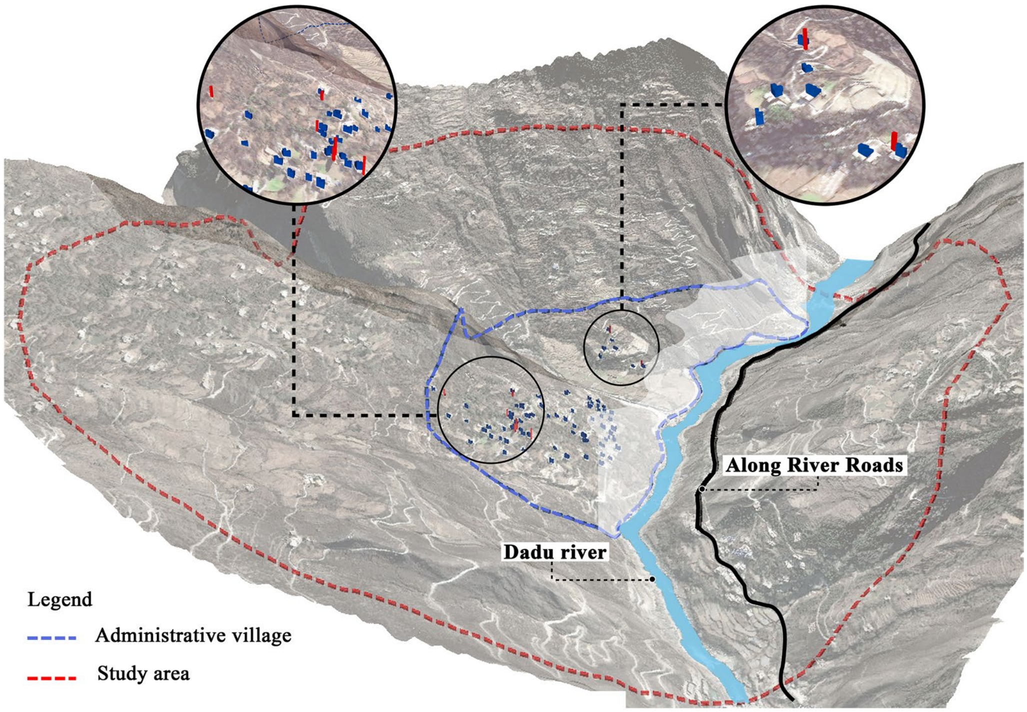


Fig. 9 The visibility range of towers on rivers and along river roads

Table 4 Visibility statistics for rivers and along-river roads

	Visibility of the river	Visibility along river roads
Tower ①	0.93	0.87
Tower ②	0.92	0.89
Tower ③	0.93	0.90
Tower ④	0.90	0.94
Tower ⑤	0.90	0.97
Tower ⑥	0.91	0.96
Tower ⑦	0.90	0.98
Tower ⑧	0.78	1.00

Table 5 Visibility of the single field of view of the towers

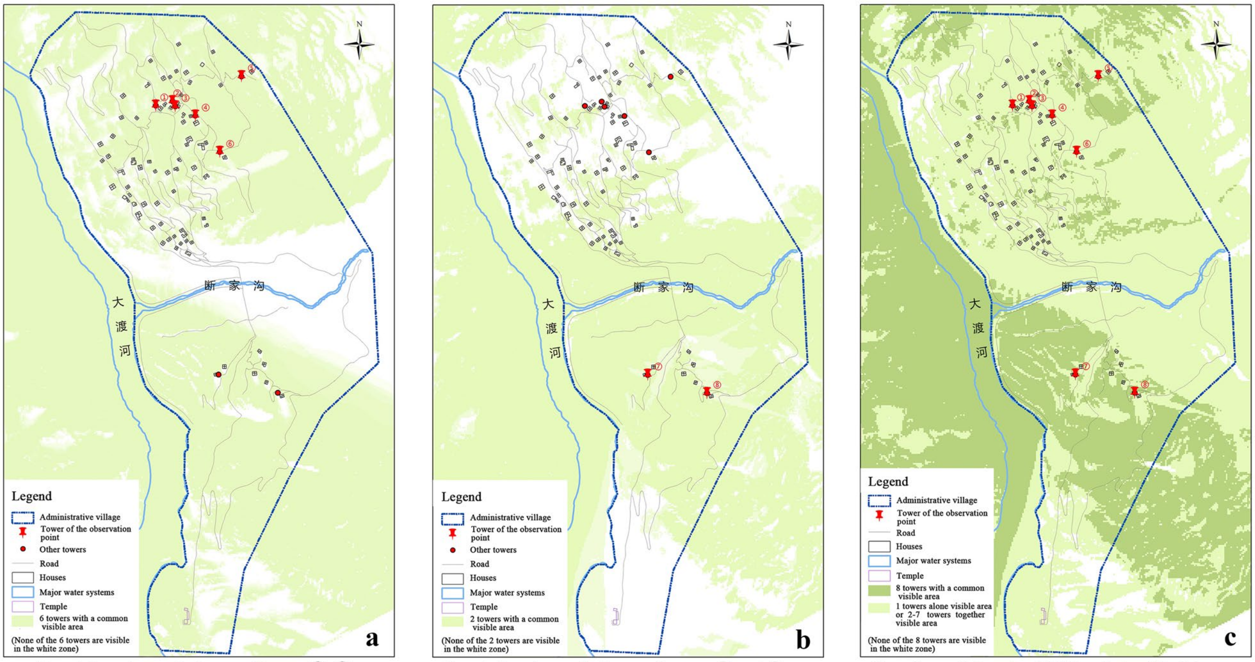
Tower No.	Visible grid	Invisible grid	Visibility (keep two decimal places)
Tower ①	34,958	15,346	0.69
Tower ②	31,961	18,343	0.64
Tower ③	33,455	16,849	0.67
Tower ④	30,090	20,214	0.60
Tower ⑤	27,968	22,336	0.56
Tower ⑥	32,024	18,280	0.64
Tower ⑦	28,283	22,021	0.56
Tower ⑧	28,449	21,855	0.57

the advantageous location of being backed by mountains and facing water, villages reduce the vulnerable areas to a minimum. Extending defense lines to river areas makes it possible to set traps along river roads and strategically create gaps. This allows for surrounding or counterattacking the enemy under more favorable conditions, thus defending against attacks at minimal cost.

Analysis of the spatial visibility within the villages

In addition to providing visual coverage of the surrounding environment, the towers should also consider their ability to serve as observation points within the village, allowing for effective monitoring, enemy positioning, and corresponding actions to be taken. Hence, an analysis of both the single field of view of individual towers and the cumulative visibility of the towers is conducted (see Table 5 and Fig. 10), aiming to further understand the differences and synergies in visual coverage provided by the towers. This approach facilitates a more comprehensive understanding of the contribution of each tower to the defensive system.

(1) The ranking of the eight towers in terms of their single visibility field of the village's internal space is as follows: Tower ① > Tower ③ > Tower ② > Tower ⑥ > Tower ④ > Tower ⑧ > Tower ⑤ > Tower ⑦. The top 5 towers are concentrated in the village's



Cumulative view analysis map of towers ①–⑥ Cumulative view analysis map of towers ⑦ and ⑧ Overall cumulative visual field analysis of the 8 towers

Fig. 10 **a** Cumulative visibility of towers ①–⑥; **b** Cumulative visibility of towers ⑦ and ⑧; **c** Cumulative visibility of the eight towers

core area and are mainly used for internal observation.

(2) The visibility of the village-tower (②, ⑤, ⑦, ⑧) appears to be lower on average than that of the family-tower (①, ③, ④, ⑥). This once again confirms the close correlation between the functional positioning of village-towers for external and internal purposes and the emphasis on visual coverage in the village. In contrast, village-towers were set to face outward and provide visual coverage. Village-towers are often built at strategic locations along village roads or intersections to detect potential threats as early as possible and intercept them within the attack range if necessary. In addition, beacons are used to transmit information to the village's rear. Towers ⑦ and ⑧ serve as the first line of defense for the village and are strategically placed on steeper terrain along the ridgeline. Tower ⑤ is positioned along the main road leading to the higher-altitude Zuobi village, serving as a crucial sentry point for relaying messages. They all align with the role and positioning of the village-tower.

(3) Towers ①–⑥ supplement the blind spots in the field of view of towers ⑦ and ⑧ in the village entrance area, demonstrating that the synergistic role between the towers is far greater than their individual roles. (see Fig. 10a, b) The eight towers collectively provide visual coverage to more than 90% of the village area (see Fig. 10c). Additionally, the results show that the towers offer excellent visual continuity and place the entire village under tight visual surveillance. Despite hundreds of years of terrain and village layout changes, the existing towers effectively provide comprehensive visual coverage.

Further analysis of the visibility correlation within the village reveals that the height of the towers and their elevation play the major influencing factors. It is worth noting that the heights of the towers are highly correlated and play a decisive role (see Table 6). The most prominent example is tower ⑧, which is located at the village entrance and is the tallest. It strategically takes advantage

Table 6 Correlation analysis between the towers' height, the elevation at which they are located, and visibility

	Height of the towers	The elevation at which the tower is located	Visibility
Height of the towers	1		
The elevation at which the tower is located		1	
Visibility	R = 0.704	R = 0.121	1

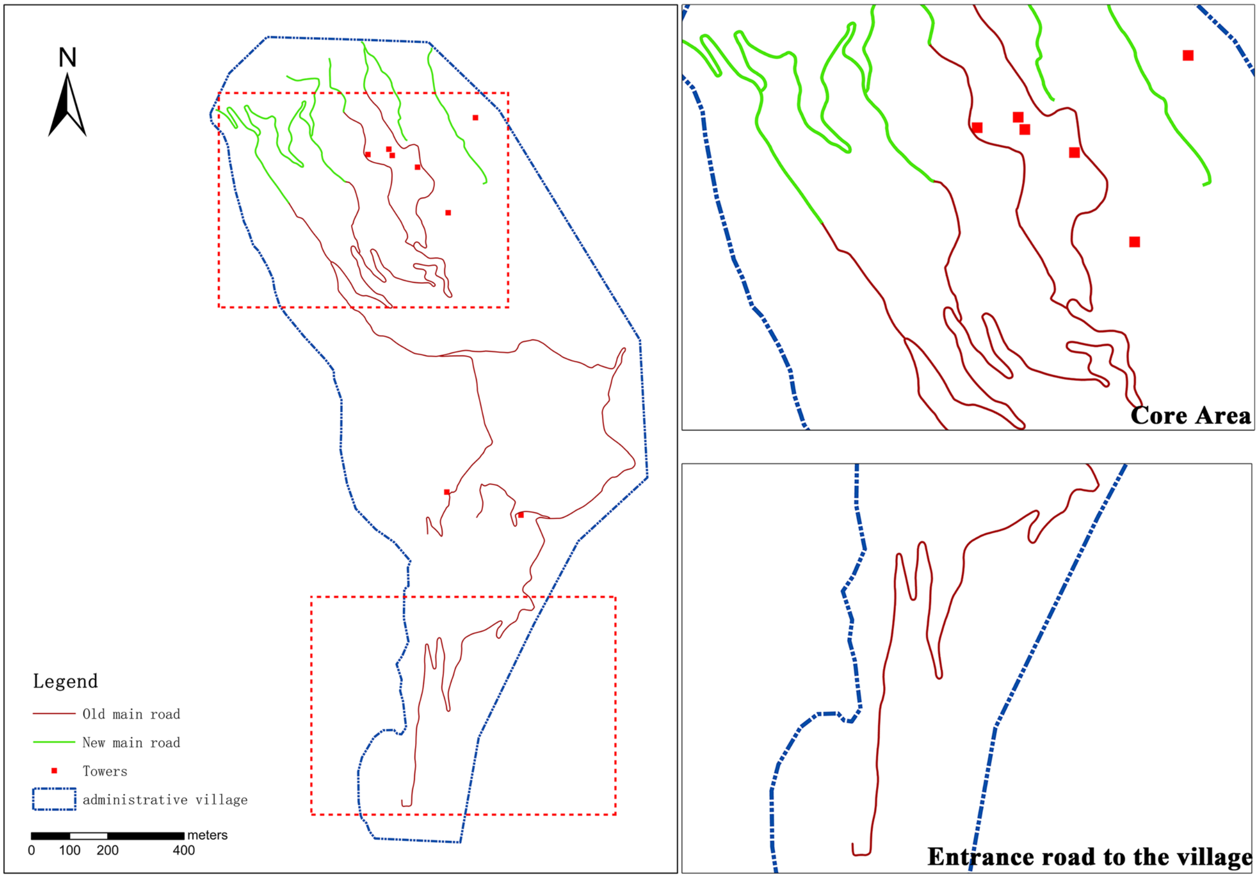


Fig. 11 Old and new main roads and core area, and village entrance road of the tower village

of its elevated position, forming a solid defensive point and creating a difficult-to-attack situation.

Analysis of visibility on main roads within the village

The village's main roads are classified as either old or new (see Fig. 11). Comparing these two types of roads helps to better understand the relationship between the towers and the village's road layout (see Fig. 12a, b).

(1) The visible range and visibility of the road are influenced by three main factors: the location of the tower, the positioning of the role, and the terrain. Notably, Towers ⑦ and ⑧, also known as battle towers, are responsible for observing the village environment but do not provide complete coverage of village roads. Meanwhile, Towers ①–⑥ are located in the core residential area of the village and provide similar visibility for both the entrance road and the road in the core area. However, it should be noted that the topography of the ravine limits visibility, and visual control over the roads on the southern and northern sides of Duanjia Gou (the stream in the village) has been lost.

(2) The average visibility difference between the new road and the old road is not significant. An analysis of individual tower visibility revealed that the visibility of towers ⑦ and ⑧ on the new road was significantly lower visibility than that on the old road (see Table 7). According to the analysis, it appears that the layout of the old road is more closely associated with the towers, and even if it is far from the village core area, it can still serve as a strategic buffer zone. Although the new road layout is commendable, with the disappearance of the original defensive function of the towers, the layout of the new road did not fully consider the visual correlation with the towers.

Analysis of the visible capabilities of towers toward ravuze

The construction of ravuze on the roofs of a residence indicates that individuals are aware of a homeland security crisis. Exploring the visual relationships between

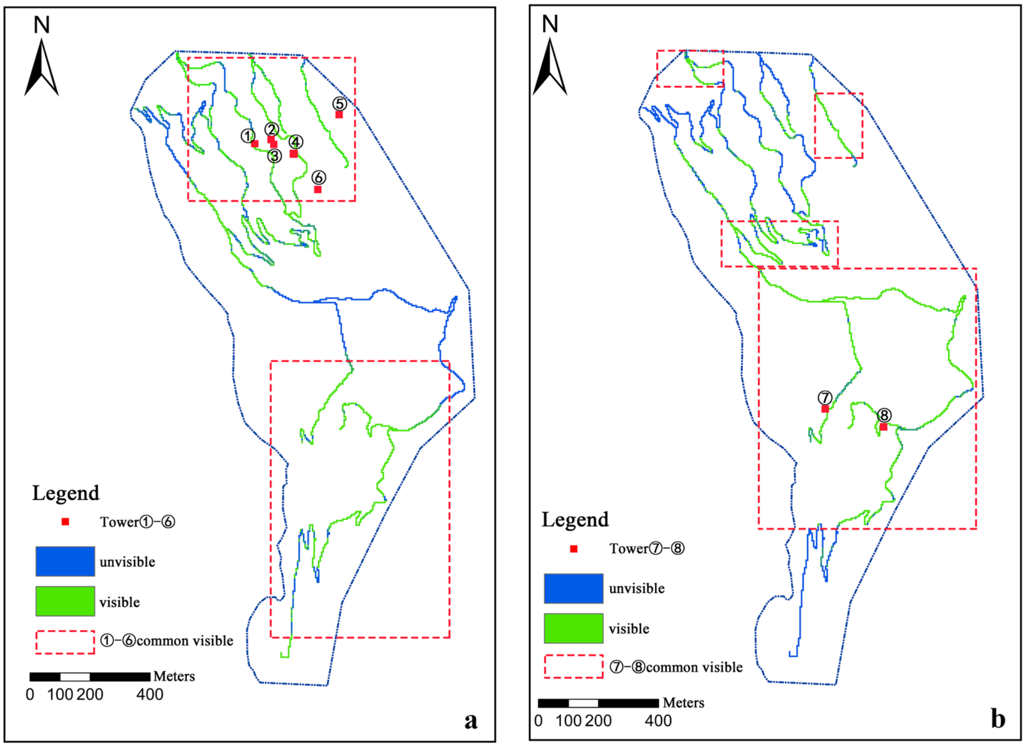


Fig.12 **a** Towers ①–⑥ are commonly visible to the internal roads of the village; **b** Towers ⑦ and ⑧ are commonly visible to the internal roads of the village

Table 7 Statistics of the visibility of the old main road and the new main road

	Old main road visibility	New main road visibility
Tower ①	0.70	0.91
Tower ②	0.64	0.76
Tower ③	0.67	0.79
Tower ④	0.61	0.61
Tower ⑤	0.54	0.58
Tower ⑥	0.68	0.56
Tower ⑦	0.64	0.30
Tower ⑧	0.66	0.37
Average	0.64	0.61

military buildings and military preparatory buildings is beneficial for a more comprehensive exploration and interpretation of the underlying network of relationships.

There are 74 existing ravuzes in Moluo village. Additionally, the visible capabilities of single towers to ravuze are all above 0.70 (see Table 8), and the visual capability of eight towers to the cumulative field of view of ravuze is 0.97 (see Fig. 13). The towers and ravuze have solid visual connections. As the number of towers involved in visible synergy increases, the overall visual control effect becomes more pronounced. Each ravuze can be seen by at least one tower, ensuring the stability of information transfer within the village and the integrity of the communication chain. Converting civilian structures into military buildings during wartime is particularly useful, as it allows for establishing a more systematic, precise, and complex defense network.

Analysis of the LOS relationships among towers

This paper utilizes ArcScene10.4 to reconstruct the line-of-sight relationship network of towers to reveal the information network dissemination between the remains of the towers. The LOS relationship is the analysis of 3D spatial structures within a visual field. The purpose is to reveal the smoothness of information dissemination and specific pathways within the network of tower remains.

(1) The eight towers in Moluo village have mutual LOS relationships with each other. (see Fig. 14a)The unobstructed LOS corridors intersect, establishing an effective information dissemination network. Towers serve not only as visual surveillance and defense structures but also as media for information

Table 8 Visibility statistics of 8 towers for ravuze

Tower No.	Number of fully visible ravuze	Number of partially visible ravuze	Number of entirely invisible ravuze	Visual capabilities (keep two decimal places)
Tower ①	59	11	3	0.88
Tower ②	61	10	2	0.9
Tower ③	63	8	2	0.92
Tower ④	62	10	1	0.92
Tower ⑤	60	6	7	0.86
Tower ⑥	63	7	3	0.91
Tower ⑦	44	13	16	0.7
Tower ⑧	47	17	9	0.76

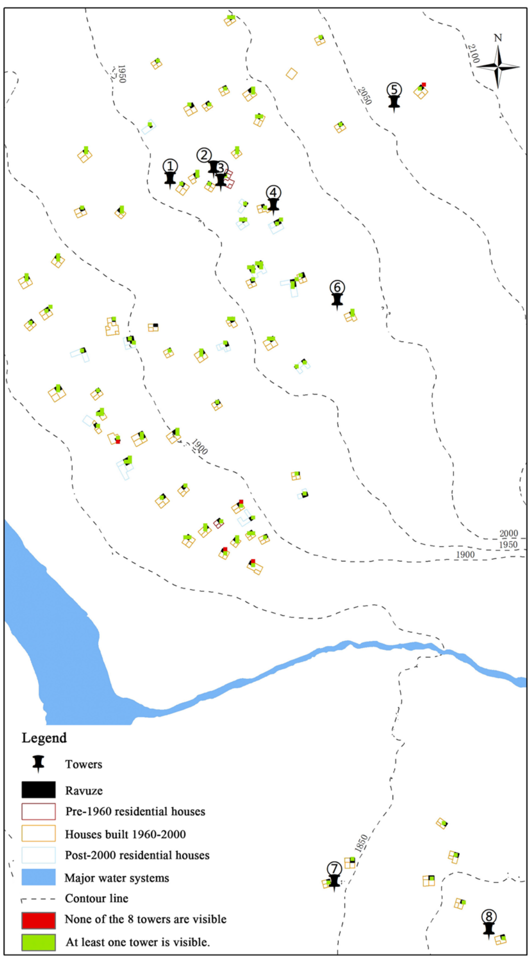


Fig. 13 Cumulative visibility analysis of 8 towers for ravuze

exchange. Depending on their position, the towers can collect, transmit, or execute commands, completing the entire closed loop from visual surveillance, transmission, and defense to guiding actions.

(2) Based on the analysis of the orientation of the towers, the relationship between LOS distances, and functional positioning, it was determined that the sources of information dissemination were towers ⑦ and ⑧ (see Fig. 14b). By following the principle of shortest distance, we can deduce the path of information dissemination among the remaining towers. This path toward the core area on the north side of the village is as follows: towers ⑦ and ⑧ → tower ⑥ → tower ③ → tower ② → tower ①. On the other hand, towers ⑦ and ⑧ → tower ⑥ → tower ⑤. This path provides the fastest message delivery to the village at a higher elevation. Among the above two internal and external information transfer paths, tower ⑥ serves as a connecting point that links the northern and southern areas of Moluo village and provides an information channel for neighboring villages in the east. It plays a role in information relay, forming a complete information dissemination architecture for Moluo Village.

(3) Under the 360° panoramic view from the tower, if any tower observes any anomalies, it can effectively communicate and coordinate actions promptly through means such as smoke signals or flag signals. The selection of tower sites during village construction is a deliberate process. The towers are designed to independently oversee a specific range while also being able to communicate with each other, forming an orderly and stable network for message transmission. This network plays a crucial role in the VDS of the tower (Diaolou) villages.

Conclusion

We utilize a multi-dimensional model for the quantitative analysis of landscape visuals, providing a scientific basis for the functionality and value of rural architectural heritage. Based on the perspective of the spatial

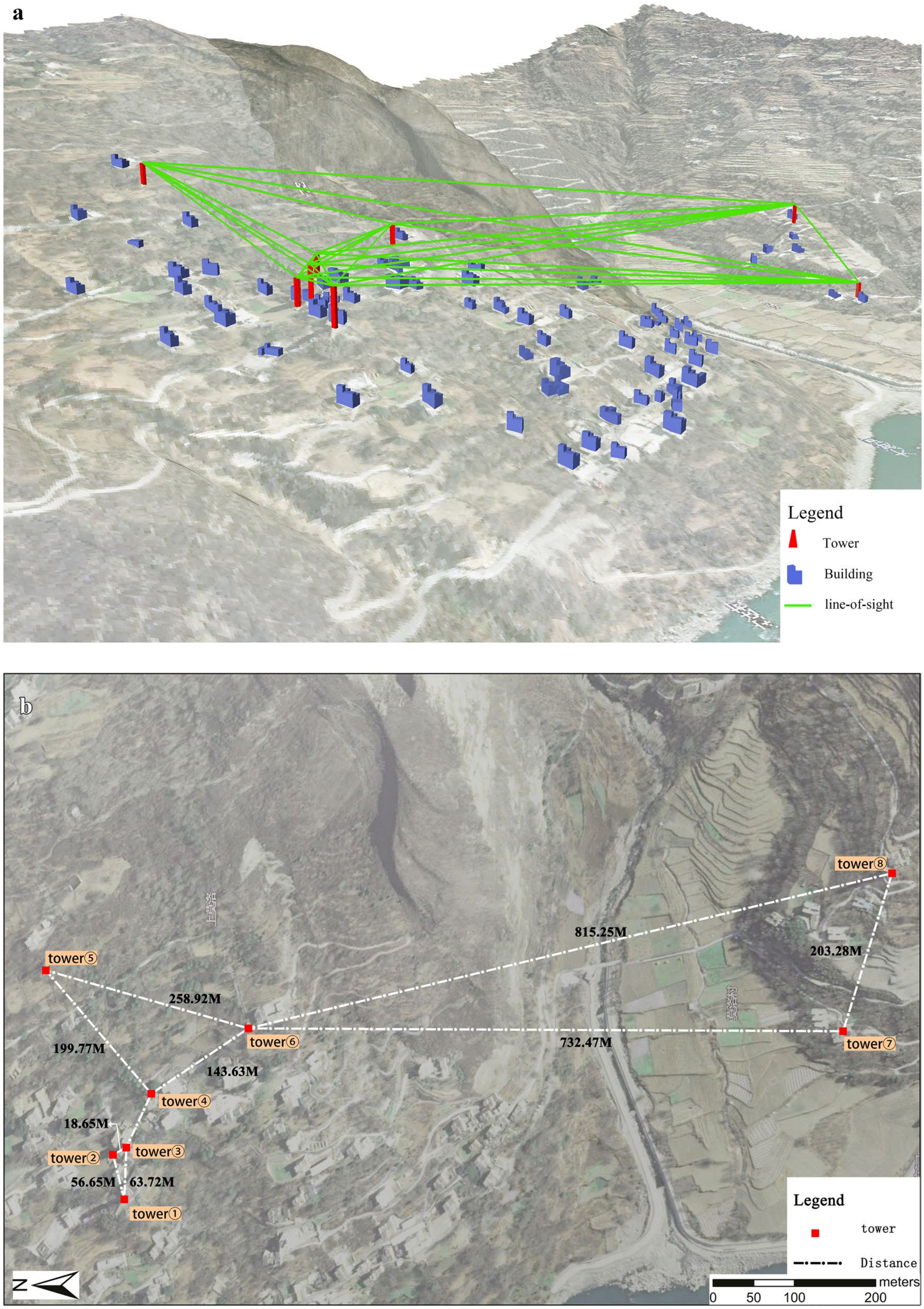


Fig.14 **a** Map of the intervisibility relationship between eight towers; **b** Map of the intervisibility distance between eight towers

’point-line-surface’ of village space, research on the visual perception of different landscape elements has confirmed that rural settlements establish a systematic, hierarchical, and effective VDS by utilizing natural ecological advantages combined with appropriate settlement selection and tower layouts. "Authenticity", which particularly emphasizes the form and design of heritage, use and role, tradition and technology, location and environment, spirit and feeling, is an important condition for the recognition of world heritage. In this paper, the use of the GIS spatial analysis method to restore the tower’s line of sight relationship for the authenticity of rural heritage research to provide a scientific basis, deeply aware of the residents in the construction of the human settlement environment contains the thought of safety and development of man-land symbiosis, which provides a reference for the research and protection of regional cultural landscape heritage. At the same time, it is important to support its application as a member of the World Heritage List.

Overlapping, complementary, and synergistic visual relationships

Moluo village towers use 3D spatial vision to control the critical physical space inside and outside the village, and these three relationships mutually reinforce each other. The visual coverage and complementary orientations of the towers ensure a seamless defensive network for the village, improving the detection of potential threats and the probability of enemy incursions. The mutual visibility between towers improves the network response effectiveness and processing speed and enables collaborative observation and information sharing. It serves as a crucial foundation for the settlement of VDS.

Multi-level and well-organized VDS

By leveraging the advantages of the terrain, the defensive layout of Moluo village was built with front-rear depth and internal–external extension. The functional positioning and layout of the towers form a “dual” VDS that provides external monitoring and early warning, as well as internal coverage and defense. It also establishes an instant communication and response network. At the same time, there is a potential connection with military preparedness structures to expand into a more complex and precise defense network if necessary.

Dual mechanism of public and private collaboration

The village forms a radial architectural layout with tall towers as focal points, extending along the main visual corridors to create a two-armed circular pattern. The positioning, height, and functions of the towers align with the defense needs of public spaces. At the same time, the defensive structures in individual households, such as ravuze, represent private space defense requirements. This achieves collaboration between public and private defense.

A typical military defensive settlement

The rivers and steep terrain serve as tangible defense lines for the village fortress, while the visual coverage and coordination of the towers form an intangible defense line. The large number of ravuze in the village is an extension of the defensive capabilities of the towers. During war, village living spaces can quickly transform into defensive architectural complexes with shooting holes for close-range combat. Therefore, the towers, ravuzes, residential buildings, and roads collectively create a tightly organized and comprehensive military-style settlement space.

Discussion

Survival in rural settlements is essentially adaptation, which is also the ecological concept of coexistence between humans and nature contained in traditional Chinese cultural thought. The Tibetan ancestors here formed clan alliances through the medium of genealogy. Due to challenging natural conditions and complex ethnic relationships throughout history, a security-oriented settlement concept was formed. Both the selection of a settlement site and the form and positioning of tower construction, reflected the survival strategy of peace and security. To meet the needs of future population settlement, towers, and residential buildings are often built on rocky slopes, avoiding the occupation of fertile land. The surrounding farmland has also become a buffer to ensure village safety. At the same time, the height of the towers and broad view make it an ideal military lookout and defensive stronghold. Throughout the past few centuries, the village has been able to adapt, develop, and survive. Our research provides more scientific evidence to respond to rural heritage’s important functional value and historical significance.

Herein, we developed a practical quantitative method to analyze the defense level, scale, and spatial relationships between different landscape elements of towers to accurately judge the authenticity of the cultural heritage of rural settlements. The main finding of this study is that by constructing a rational multi-dimensional model and applying planar and spatial visual analysis methods, it was able to provide more effective and scientific evidence that tower (Diaolou) villages have formed a complete VDS. This approach overcomes the limitations of previous qualitative research on the heritage value assessment of rural settlements, which has mainly relied on historical records, field investigations, or questionnaire surveys.

To the best of our knowledge, this is the first empirical study on the defensive systems of tower (Diaolou) villages in western Sichuan. All analyses in the study were based on the assumption of ideal conditions during the summer months of June when the sun is high, visibility is high between 9 and 11 am, the observer's ability to perceive correctly, and the height of the remaining towers. At the same time, we also realize that they are inevitably imperfect due to the age of construction of these villages, as well as the impact of wars and geological disasters; analyzing the defensive systems solely based on the existing towers may have specific limitations and may not provide a comprehensive understanding. To better explain this phenomenon, further research should involve gathering historical data on the village layout and the towers, and exploring whether the tower defense system changed during the evolutionary process of the settlements. In the western Sichuan region, there are still a considerable number of Tibetan-Qiang Tower (Diaolou) villages. It would be valuable to explore whether there are differences in the construction approaches and defensive systems of rural settlements based on the cultural backgrounds of different ethnic groups and their geographical locations. Simultaneously, exploring human visual preferences, defensive visual trajectories, and other dynamic factors within a multi-dimensional spatial model further refines visual research methods on landscape heritage. According to our empirical research, this method can be applied to study the spatial visual relationship of village heritage, to provide evidence for the authenticity of the heritage function, and to support the application of the tower (Diaolou) village for World Cultural Heritage.

Abbreviations

VDS	Visual defensive system
DOM	Digital orthophoto map
DEM	Digital elevation model
UAV	Unmanned aerial vehicle
3D	Three-dimensional
LOS	Line of sight
Ravuze	The name of a specific building, which is an English expression derived from its Chinese phonetic translation

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Author contributions
W.X.: (1) Project Leadership and Conceptualization; (2) Acquisition of Funding and Resources; (3) Research Design; (4) Writing and Revision; Q.L.: Review and Editing; L.W.: (1) Methodology; (2) Data Processing and Analysis; (3) Visualization and Writing; M.T: (1) Research Design; (2) Writing the initial draft; X.L and S.J.: Data Curation. All the authors have read and approved the final manuscript.

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Availability of data and materials
All data sources have been listed in the manuscript. The datasets used and analyzed during the current study are available from the corresponding author upon reasonable request.

Declarations

Competing interests
The authors declare that they have no competing interests.

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