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Restoration of the distribution of pit-type yaodong dwellings in the 1970s using US military reconnaissance satellite images in Luoyang Basin, China

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Abstract: This study used US military reconnaissance satellite images to identify the locations of lost pit-type yaodong in the Luoyang basin. A total of 7,668 data points were obtained by estimating the positions of the courtyards of pit-type yaodong. Pit-type yaodong were found in the west, north, and east but were rarely observed in the southern part of the basin. In the eastern and western parts of the basin their density tended to be high. I examined the factors that influence the distribution of pit-type yaodong by analyzing the relationship between the pit-type yaodong locations and the altitude and topography, using GIS. By estimating the number, distribution, range, and locations of pit-type yaodong, this study provides new geographical knowledge of architectural and cultural aspects of yaodong in the Loess Plateau.

Keywords: vernacular architecture, land use, spatial analysis, remote sensing, Loess Plateau

1. Introduction

Academic concerns regarding traditional vernacular architecture have been growing worldwide over the past ten years. This is a result of the need to respond to environmental problems (Nguyen *et al.*, 2019). Yaodong are traditional cave-type underground dwellings distributed on the rural Loess Plateau, China. They are commonly found in high altitude, semi-arid areas with deep underground water levels and thick loess deposits. In particular, the pit-type yaodong is a form in which a rectangular pit is dug on the surface of the plateau, which is used as a courtyard, and several holes are excavated horizontally on the side of the pit. It is mainly observed in western Henan, the southern tip of northern Shaanxi, and eastern Gansu provinces.

Yaodong has various advantages that are suitable for climate. For example, fluctuations in outside air temperature can be suppressed, creating an indoor environment that is "cool in summer and warm in winter." In addition, yaodong maintains a relatively steady indoor air temperature and, therefore, has an energy-saving effect (e.g., Liu *et al.*, 2011). Energy consumption and CO_2 emissions can be reduced by approximately 40% compared to those in modern houses constructed on the ground due to high solar gain and thick envelopes (Zhu *et al.*, 2014). Moreover, the construction cost is reduced to approximately one-tenth of that of constructing a building on the ground, which contributes to reducing the economic burden on residents and sustaining resource utilization in areas with few trees.

However, since the mid-1980s, as moving to a market-oriented economy progressed, the "New Rural Construction" movement aimed at modernization and reduction of poverty of rural areas, with many traditional yaodong being replaced by modern houses. In addition, flat land due to reforestation campaigns in mountainous areas and the demand for securing farmland on flatlands have led to the disappearance of most of the pit-type yaodong (Li and Sun 2011). Thus, it is difficult to predict the situation at during those times by considering the current landscape in many places.

Therefore, in this study, I attempted to recover the distribution of pit-type yaodong in the Luoyang Basin, Henan province in the 1970s by visually interpreting U.S. military satellite images and using previous field survey data as a teacher. Furthermore, I examined the factors of pit-type yaodong distribution by analyzing the relationship between the recovered pit-type yaodong locations and the altitude and topography on GIS. This study provides new knowledge from a geographical point of view on the architectural and

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cultural study of yaodong and the Loess Plateau by estimating in detail the number, distribution range, and distribution tendency of the pit-type yaodong, which is now lost and unknown. In addition, it provides the basic spatial information required for the evaluation of energy consumption and regional resource utilization associated with urbanization.

2. Study area

The study area is the Luoyang Basin, northern Henan Province, at the southeast end of the Loess Plateau (**Figure 1**). It includes the main region of Luoyang city including Yanshi county-level city, and Gongyi county-level city as the west side of Zhengzhou city. The annual mean precipitation is approximately 600 mm. The Luo and Yi rivers flow in the basin, and both rivers make two or three river terraces. The loess platform developed between the river terraces and mountains. This area has one of the longest human histories in China, over 5,500 years, and there are several remains of ancient capitals and cities on the river terraces. The basin is surrounded by eight passes that provided defense to the urban area (Fig. 1).

3. Materials and methods

3.1. U.S. military satellite images

This study used U.S. military satellite images to identify the locations of lost pit-type yaodong. The first generation of U.S. photo intelligence satellites collected more than 860 thousand images of the earth's surface from 1960 to 1972. The classified military satellite systems code-named CORONA, ARGON, and LANYARD acquired photograp hic images of the former eastern bloc and the third world from space. The images were originally used for reconnaissance and to produce maps for U.S. intelligence agencies. These images were declassified by executive order in 1995. The images used in this study were No. DS1111-1063 AF-18, -19, -20, and -21 (Mission Designator: CORONA KH-4B), courtesy of the U.S. Geological Survey. They were taken on July 26, 1970. The best ground resolution is six feet, approximately 1.83 m.

3.2. Geometric correction

These images are distorted because they were originally taken using panoramic cameras and recorded on the film (Goossens *et al.*, 2006). This study ignores a quarter of the image from each side, which have the largest amounts of distortion. The used images were coregistered to the World Imagery layer of Esri (orthorectified high resolution WorldView-2 color images shooting in 2021) using road intersections and other stable ground features as ground control points (GCP). These GCPs (totaling over 50 points per image) were manually selected through careful inspection of the U.S. military satellite images and WorldView-2 images. The U.S. military satellite images were corrected using the third order polynomial on ArcGIS Pro.

3.3. Visual interpretation of satellite images and use of previous field survey data as ground-truth

This study attempts a visual interpretation of satellite

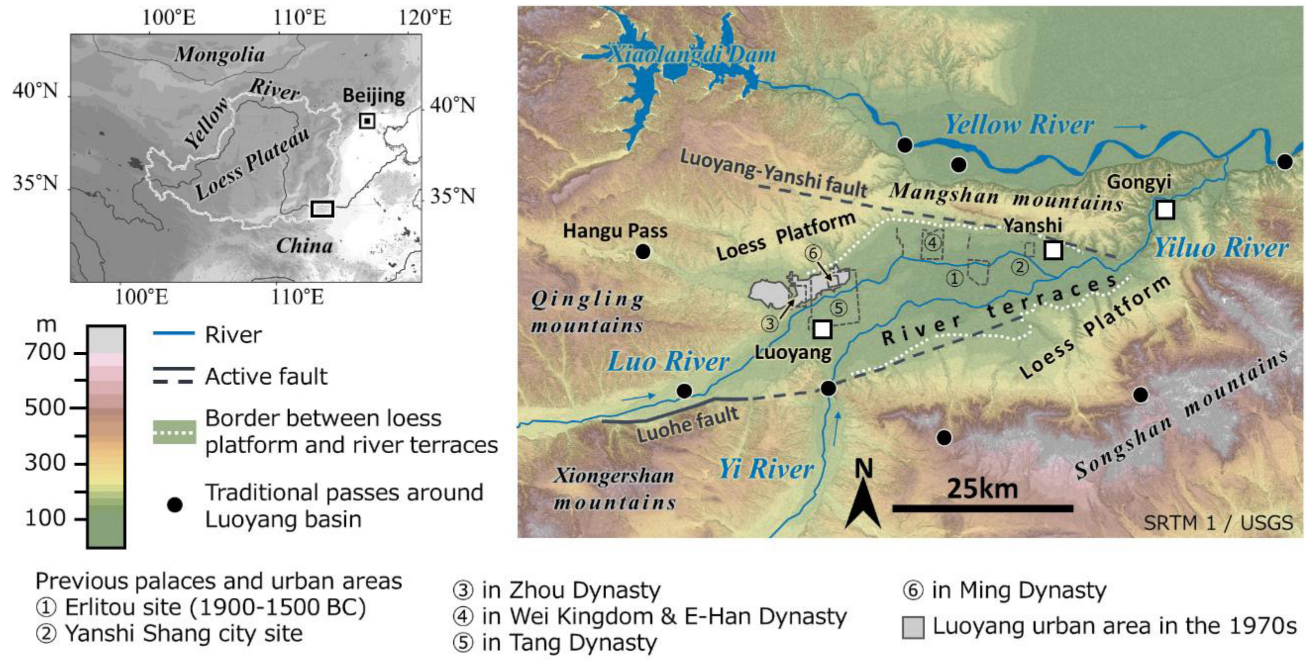

Fig. 1. Location of the Luoyang basin

images to distinguish pit-type yaodong. I propose that pit-type yaodong are detectable by satellite because they have a rectangular courtyard. In addition, field survey data are available from an architectural study of the geographical distribution of yaodong inside villages (Yaodong Research Group of Japan, 1993); therefore, we can make a comparison with satellite images in the same places, as shown in **Figure 2**. In Zhongtou village of Luoyang, 97.1% of yaodong had an accuracy of 34 per 35 (Fig. 2).

3.4. Probability density estimation in GIS

Data points were obtained by estimating the position of the courtyard of yaodong. To estimate the distribution of yaodong I used the kernel density estimation method, which is one of the methods in GIS for estimating the entire distribution from a finite number of samples. It has been used to delineate critical zones at the landscape level (e.g., Dong *et al.*, 2020). A function called a kernel is placed for each number of samples, and the probability density is defined as the sum of all kernel functions. The kernel density estimate is defined as follows:

$$f(x) = \frac{1}{nh}\sum_{i=1}^{n} k(s,h) \qquad (1)$$

where $f(x)$ is the estimated probability density, h is the bandwidth, s is the distance from the estimated point to the sample point, n is the number of sample points, and $k(s, h)$ is the kernel function. This study was used a quartic kernel function by Silverman (1986), implemented in ArcGIS Pro of Esri.

When spatial correction is performed using the kernel density estimation method, the results depend on the kernel function (that defines how the influence from each sample number spreads) and the bandwidth (that defines the spread width of the kernel function). If the bandwidth is large, it is possible to express a wide-area tendency, and if it is small, it is possible to express a local tendency. Kernel densities were calculated for village-to-basin scales of regional analysis, utilizing bandwidths of 1 and 5 km. The resultant estimates were hierarchically divided and depicted by GIS, so that the higher the density, the redder the color.

4. Results and Discussion

Maps of the estimated distribution of pit-type yaodong in 1970 are shown in **Figure 3**. A total of 7,668 data points were obtained by estimating the position of the courtyards of yaodong in the Luoyang Basin. The results prove that in terms of architectural culture, the basin was included in the Loess Plateau.

4.1. Prediction and mapping of the yaodong density

Comparing at the village level, the density of pit-type yaodong tended to be higher in limited areas of the eastern part of the basin when compared to the western part. On the other hand, behind the urban area of Luoyang in the western part of the basin, settlements with moderate yaodong density tended to be widely and continuously distributed.

Comparing at the basin level, pit-type yaodong were distributed in the west, north, and east to surround the basin and were most often found in the loess platform from the north to the west of Luoyang city, and around Gongyi city. However, pit-type yaodong were rarely observed in the southern part of the basin. Thus there is a marked bias in

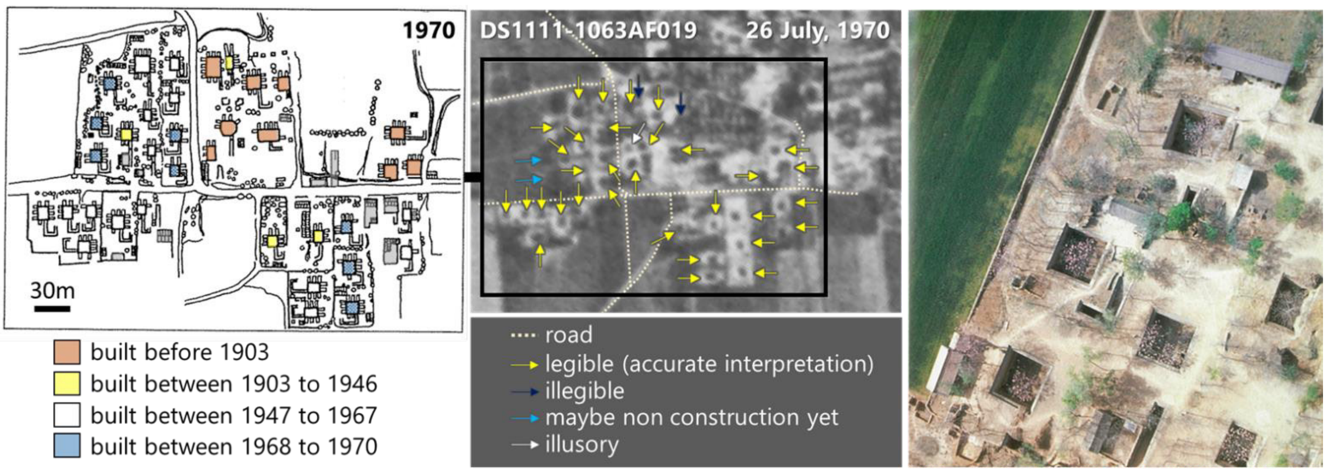

Fig. 2. Example of the previous field data (left) (Yaodong Research Group of Japan, 1993: 183) and U.S. military reconnaissance satellite image around the same year (in 1970) and same place (Zhongtou village, Luoyang) (center), as well as the kite photography of same village in 1985 (right) (Yaodong Research Group of Japan, 1993: 10)

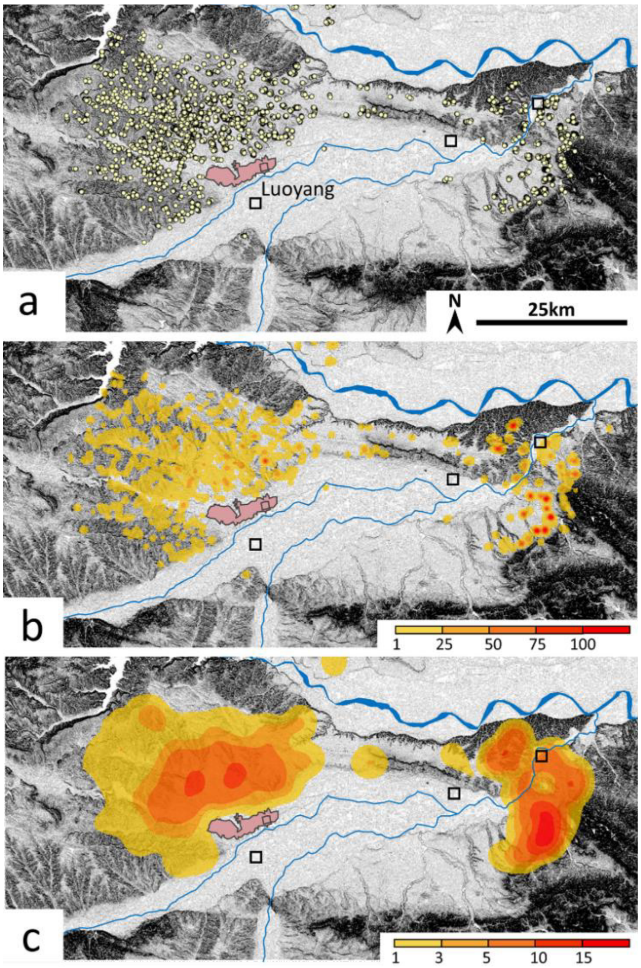

Fig. 3. Distribution of pit-type yaodong (a) and the number of yaodong per unit area by kernel density estimation (b: bandwidth is 1 km, c: bandwidth is 5 km) on the slope angle map

the geographical distribution of yaodong at the basin level, which is an important discovery in studies of architecture, culture, and rural society of the Loess Plateau.

With respect to geomorphological factors, pit-type yaodong were found on the loess platform and were not on the mountains, floodplains, nor river terraces. This is considered a good indication that pit-type yaodong are difficult to establish in places with high groundwater levels or steep slopes. The altitude and slope where the point data are located were revealed by the SRTM1 Arc-Second Global DEM to be gentle slopes, and most of the points (79.4%) were approximately 180 to 310 m above sea level (**Figure 4**). Considering regions in the basin, the location of yaodong in the eastern area (on the right side of the Yi River) tended to have lower elevations than the locations in the west (behind the urban area of Luoyang). I suggest that this is because the eastern area is located downstream, and the groundwater level is also deeper than in the west.

4.2. Necessity of referring to images taken during the 1970s for landscape restoration

The results from the distribution of pit-type yaodong in 1970 (Fig. 3) clearly shows the necessity for referring to high resolution images taken during the 1970s, especially for understanding landscape restoration in Luoyang basin.

Figure 5 shows a comparison between the satellite images taken in 1970 and 2021 (WorldView-2). In addition, the estimated locations of the pit-type yaodong in 1970 have been identified in both images. In some cases, such as the area in southern and eastern part of Fig. 5, yaodong were not only abandoned or reclaimed, their traces were also eradicated from the landscape due to construction of modern housing, high-rise buildings, factories, and roads after the yaodong were refilled. In addition, erosional valleys seem to have been drastically transformed by human activity in the area. This case study shows that the previous study's claim that "building construction is difficult on the site of pit-type yaodong because the landfill of pit-type yaodong is soft ground" (Yaodong Research Group of Japan 1993) does not necessarily reflect the various experiences of all yaodong sites. Moreover, it has been proven that there are cases where it is difficult to estimate the landscape and landforms prior to 1970 using images taken in recent years. The evidence presented here, have important impact for studies not only on architecture and cultural landscapes, but also for geomorphology, urban and rural planning, and disaster management.

4.3. Study limitations and future work

It is possible that pit-type yaodong were rarely located on the loess platform in the southern part of the basin due to the hydrological and geological local differences, or to some socioeconomic factors such as the proximity to cities. However, this has yet to be determined.

In the village shown in Fig. 3, although there were already several yaodong in the early 20th century, it can be seen that most of them were newly constructed after 1947. In particular, construction has been increasing rapidly since

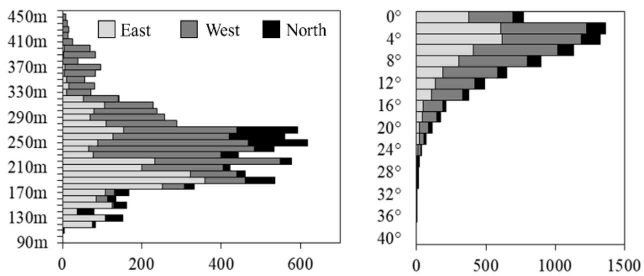

Fig. 4. Relationship between the location of pit-type yaodong and landform in each region

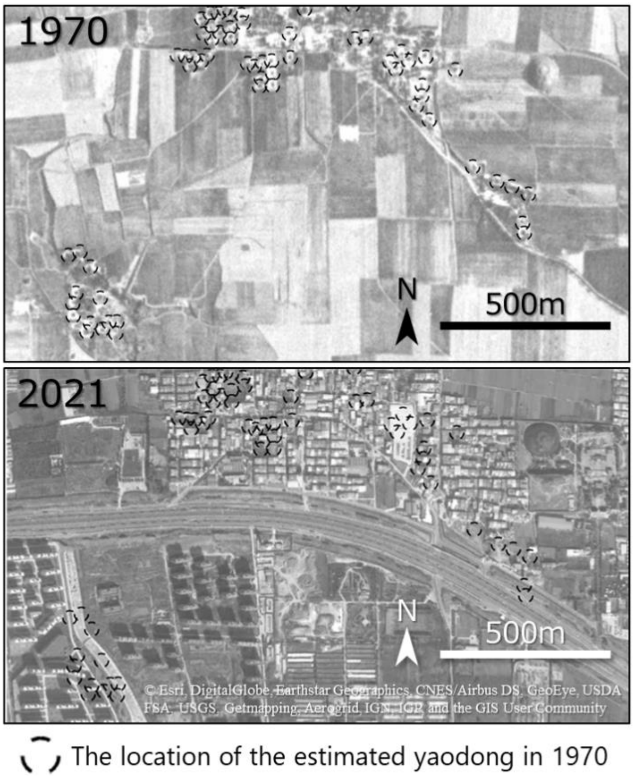

Fig. 5. Example of the disappearance of yaodong due to urban development in Luoyang city

the 1960s. The reason for this is that the population is increasing, and it seems that new constructions were to house the second and third sons, while migration to the city was restricted during the planned economy period. In China, the population increased significantly in rural areas until planned childbirth became national policy in 1979.

It is highly possible that a similar phenomenon occurred in high-density areas, but future verification is awaited for constructions of yaodong in the southern part of the basin. The 1970s was an era when the People's Commune system was still in full swing, and the dual structure of urban-rural areas was firmly maintained in China. Thus, it seems inappropriate to apply the models of suburban development that pertain in a free economy system. In future, the hypothesized historical factors that influenced the construction of pit-type yaodong in each region may be verified by collecting field-based information, and analyzing statistical data such as the population and livelihood of each town.

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