Journal of Archaeological Science: Reports 17 (2018) 195–211

Contents lists available at ScienceDirect

Journal of Archaeological Science: Reports

journal homepage: www.elsevier.com/locate/jasrep

Evidence for the breakdown of an Angkorian hydraulic system, and its historical implications for understanding the Khmer Empire

Terry Lustig[a,*,1], Sarah Klassen[b], Damian Evans[c], Robert French[d], Ian Moffat[e]

[a] Department of Archaeology, University of Sydney, NSW 2006, Australia
[b] School of Human Evolution and Social Change, Arizona State University, 900 S Cady Mall, Tempe, AZ 85281, United States
[c] École française d'Extrême-Orient, 22 Avenue du Président Wilson, Paris 75116, France
[d] Independent Scholar, 30 Woodlands Rd, Ashbury, NSW 2193, Australia
[e] Department of Archaeology, Flinders University, Bedford Park, SA 5042, Australia

ARTICLE INFO

Keywords:
Angkor
Archaeology
Engineering practice
Koh Ker
Lidar
Palaeohydrology
Trial and error
Water management

ABSTRACT

This paper examines the construction and design of a 7-km long embankment, probably built for King Jayavarman IV between 928 and 941 CE, as part of a new capital. We calculate that the capacities of the outlets were too small, and conclude that the embankment failed, probably within a decade of construction, so that the benefits of the reservoir stored by the embankment and the access road on top of it were lessened substantially. We explain how the design was sub-optimal for construction, and that while the layout had a high aesthetic impact, the processes for ensuring structural integrity were poor. Simple and inexpensive steps to secure the weir were not undertaken. We speculate that this early failure may have contributed to the decision to return the royal court and the capital of the Khmer Empire to the Angkor region, marking a critically important juncture in regional history.

1. Introduction

With the Angkorian state having lasted for more than six centuries (9th to 15th centuries CE), scholars have long sought to understand what contributed to its sustainability and what led to its eventual decline (Evans et al., 2007; Fletcher et al., 2008; Groslier, 1979; Groslier, 2007). We suggest that some insights might be gained from studying what happened at Koh Ker, another Khmer political centre about 80 km ENE of Angkor (Fig. 1). There is mounting evidence from archaeological excavation and survey for a long and complex history of occupation at Koh Ker (Evans, 2010–2011), but it is clear that the city was very short-lived as the centre of Khmer power, lasting only about 17 years as the capital, from 928 to 944 CE.

Jayavarman IV, the first recorded ruler at Koh Ker, was established there no later than 921 CE (Cœdès, 1931, 13; Cœdès, 1937, 50), while Harśovarman I (910–925 CE) and Iśanavarman I (925–928 CE), the sons of Yaśovarman I, his uncle by marriage, were still enthroned at Angkor (Cœdès, 1953, 98, 147). The first inscriptions to attest to Jayavarman's power over the Khmer realm do not appear until 928 CE (Cœdès, 1931, 13–16). Despite much debate on the topic (e.g., Cœdès, 1931, 16; Jacques, 1971, 169), it is now generally recognized that Jayavarman was likely a legitimate heir to the throne, not a usurper (Vickery, 1986, 108).[2] While it is yet to be agreed why the political center shifted to Koh Ker, for this paper, we are seeking factors that might help explain why its time there was so short.

It is clear from the inscriptions (Cœdès, 1937, 68) that Jayavarman constructed Prasat Thom during this period, its pyramid being the tallest in the Khmer world at the time (Cœdès, 1937, 70). As well, just to

Abbreviations: APHRODITE, Asian Precipitation – Highly Resolved Observational Data Integration Towards Evaluation (of Water Resources); ARI, annual recurrence interval; ASL, above sea level; DIAS, Data Integration and Analysis System; EFEO, École française d'Extrême-Orient; GPR, ground penetrating radar; HEC-GeoRAS, Hydrologic Engineering Center: GIS tools for support of HEC-RAS; HEC-RAS, Hydrologic Engineering Center: River Analysis System; HEC-HMS, Hydrologic Engineering Center: Hydrologic Modeling System; MCS, mesoscale convective system; RMSE, root mean square error; SRTM, NASA Shuttle Radar Topography Mission; TRMM, Tropical Rainfall Measuring Mission

* Corresponding author at: 15 Cottenham Ave, Kensington, NSW 2033, Australia.
E-mail address: terry@environmentalmanagement.com.au (T. Lustig).
1 Present address, 15 Cottenham Ave, Kensington, NSW 2033, Australia.

2 That Yaśovarman's two sons succeeded him may have been contrary to the rules of succession of the "conical clan", in which all members are ranked hierarchically in terms of nearness of descent from the common ancestor, in this case, Jayavarman II (Vickery, 1986, 108). Under that process, Jayavarman IV might have become king in 910 and not 18 years later.

https://doi.org/10.1016/j.jasrep.2017.11.014
Received 29 May 2017; Received in revised form 10 November 2017; Accepted 10 November 2017
2352-409X/

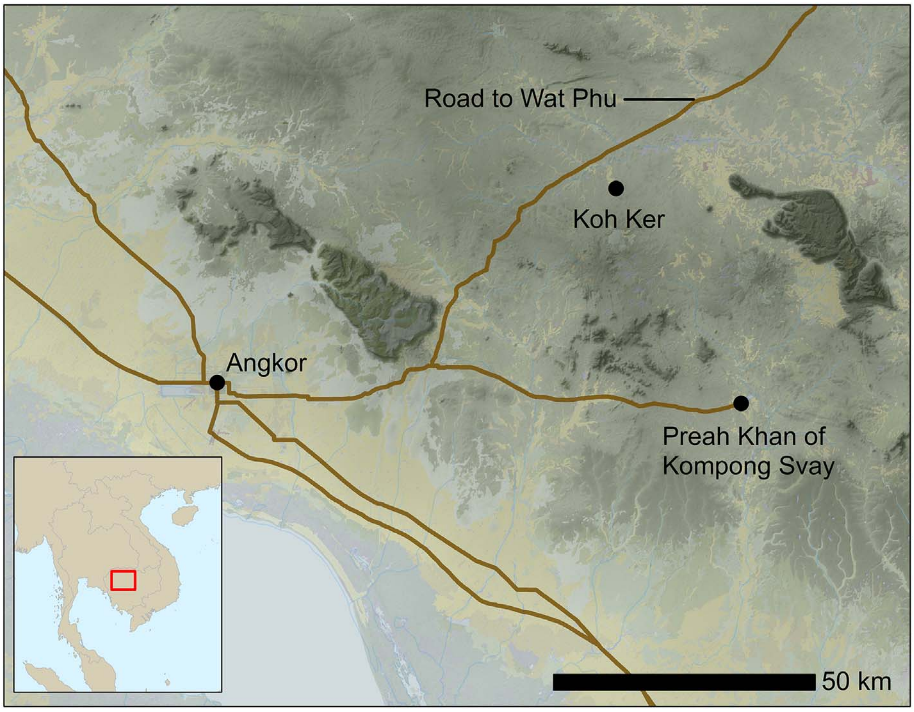

Fig. 1. Koh Ker on the road between Angkor in present-day Cambodia and Wat Phu in southern Laos. Road alignments from Hendrickson (2007).

the north of Prasat Thom, he built a 7-km long weir across the original Rongea River valley (Evans, 2010–2011), the longest water-management structure across a river valley in Khmer history (Fig. 2).[3] The embankment evidently provided both a level link to the Angkorian highway to Wat Phu in today's southern Laos and created the largest known Angkorian-era artificial lake (Fig. 3).

Just south of the main spillway are the remains of a small temple, now known as Prasat Boeng Voeng. Its western portal has an inscription, K. 823, dated 863 śaka or 941 CE (Jacques, 2014, 350).[4] The temple has a causeway linking it to the embankment. Our investigations were limited because the area is known to have landmines. However, we could see from the lidar that the level of the crest of the middle of the causeway is lower than the level of the crest of the embankment. This lower level probably results from continual erosion by water draining through it to the north (Fig. 4), and it is reasonable to suppose that it was originally at the same level as the main embankment. The main embankment would not have been built to match the level of the temple causeway, but the other way around. On the assumption that the temple was built at the same time as its causeway, this implies that the main embankment was constructed no later than 941 CE. While it is probable that the work to build the main embankment could have only been undertaken by a king, further archaeological investigation of the causeway is required to help verify that the northern reservoir and access road were built before 941 CE, presumably by Jayavarman IV.

But this infrastructure was not to last. Whereas the Rongea River originally ran eastwards past Point A in Fig. 2, we see that it now runs northwards, having overtopped and broken through the embankment at Point B. Once this happened, the large lake, the unimpeded access road, and any economic benefits from the reservoir would have been lost. Did this happen before the political centre moved back to Angkor, and were the two events linked?

[3] There were indeed longer Angkorian structures across rivers, such as an embankment about 30 km long at Angkor, but these were built on the Puok-Siem Reap Delta, where the flows were distributed into many channels, the slopes were shallower, and the water flowed more slowly, making it much easier to control.

[4] The date in the inscription in the eastern portal had been erased by the time it was recorded (Cœdès, 1954, 113), so all we know is that the temple was built no later than 941 CE.

2. Site investigations

It is necessary to understand how the embankment was designed, to understand how soon it overtopped. We will first examine deficiencies in the design of the embankment and the two outlets, and then assess the risk of overtopping by evaluating the flow of water into and out of the reservoir.

2.1. Methods

The bare-earth digital terrain model (DTM) we used was generated from airborne laser scanning (lidar) data acquired in a 2012 aerial campaign. The process used to generate the DTM is described in Evans et al. (2013). The elevations given as "above sea level" (ASL) in this paper are recorded or inferred from the lidar-derived DTM or from the processed lidar point cloud. According to the data specifications for the lidar, absolute vertical accuracy is ± 0.15 m RMSE (root mean square error) although data quality achieved was far superior to this specification in most cases, and relative accuracy of points nearby is in the order of cm-level.

We investigated the spillway (Section 2.5.1) on site by clearing it of grass and shrubs, and surveying the laterite surface with a total station to mm-accuracy. Where we suspected blocks were covered with soil, we located them with 1.5 cm diameter steel rods hammered into the ground to see if they encountered laterite over an informal grid pattern, and positioned with the total station, noting the depth to refusal. The probes could reach to about 1.8 m below ground. Laterite blocks that were washed downstream were located with a handheld GPS unit to ~10 m accuracy. Where the blocks were in piles, only the boundaries of the piles were surveyed using the GPS unit.

The chute was cleared of grass and shrubs from 10 m upstream of the within-chute structures located on the lidar (Section 2.5.2) down to the downstream end of the sloping ground, taken to be the toe of the chute's spillway. Where only a thin layer of soil covered laterite blocks, this was removed, particularly in the area around the pavement and the upstream end of the chute's spillway. Four trenches were excavated at the chute to elicit the extent and form of the structures and the type of damage they had suffered. As this was a water management feature,