Archaeological landscape of Thotlakonda and Bavikonda near Visakhapatnam, Andhra Pradesh: insights from remote sensing and GIS analysis

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India's rapid economic development, marked by industrial growth, expanding transportation networks and urbanization has brought many benefits but also poses a significant threat to the nation's cultural and natural heritage. A recent NIAS Policy Brief highlights the urgent need for clear regulatory boundaries and effective enforcement to protect cultural heritage sites from urban sprawl and degradation. Citing examples such as Nalanda, Halebeedu, Srirangapatna and Bodh Gaya, it emphasizes that unchecked development can erode the historical integrity of heritage landscapes. It advocates for a multi-tiered approach using modern technologies like geographic information system (GIS) and remote sensing, along with community engagement and stricter land-use controls, to ensure sustainable preservation. Thotlakonda and Bavikonda, two significant Buddhist heritage sites in Andhra Pradesh, were declared protected by the Government of Andhra Pradesh on 2nd May 1978. However, imprecise descriptions of the protected area have led to conflicting interpretations, fuelling litigation between parties aiming to preserve the sites and parties pushing for development. This study utilizes remote sensing and GIS to examine these sites and their surrounding landscapes, identifying potential archaeological features and assessing the impact of recent land-use changes in preserving these historically important areas.

Keywords: Bavikonda, crop mark, geographic information systems, landscape archaeology, remote sensing, Thotlakonda.

IN developing countries such as India, it is imperative to protect cultural heritage sites from potential damage due to rapidly growing cities, towns and villages as well as expanding transportation and industrial networks. Developmental activities often disrupt and obscure the spatial relationships and integrity of heritage sites, as seen in cases like Nalanda and Bodh Gaya in Bihar, Halebeedu and Srirangapatna in Karnataka, Sarnath and Agra in Uttar Pradesh[1,2]. Remote sensing analysis of these sites revealed many associated archaeological features lying outside the protected boundaries, leading to recommendations for extending those boundaries to encompass the nearby archaeological remains. Conferring such protection to a site can trigger fresh development activities up to the permitted edges of these boundaries. Hence, these boundaries must be selected with utmost care. The NIAS Policy Brief addresses the challenges of protecting cultural heritage sites in India[3]. It emphasizes the need for clear and enforceable regulation boundaries to safeguard these sites from encroachment, urbanization and other forms of degradation. It advocates for the use of modern technologies, such as remote sensing and geographic information system (GIS) to assess a site's integrity, delineate regulation boundaries and monitor these boundaries effectively.

Absence of clear and enforceable boundaries can lead to one or more undesirable consequences, including the whole or partial destruction of cultural heritage (e.g. Chikkajala near Bengaluru[4]), cost-overruns for development projects (e.g. the doubling of the railway line at the Srirangapatna railway station[5]) and litigation.

Thotlakonda and the nearby site Bavikonda were discovered during an aerial survey by the Indian Navy in the 1970s (ref. 6). Subsequently, the Government of Andhra Pradesh, through a notification dated 2 May 1978, declared Thotlakonda as a protected site under the Andhra Pradesh Ancient and Historical Monuments and Archaeological Sites and Remains Act, 1960 (https://tinyurl.com/y3sb27uu (accessed on 21 August 2024)). The notification describes the boundary as encompassing 'The ancient site Totlakonda situated in the revenue S. No. 314 at Mangamaripet (village) Hamlet of Kapuluppada in Bheemunipatnam Taluk of Visakhapatnam District, bounded by East: S. No. 295 and 296, West: Hill, North: Hill and South: Hill.' Bavikonda is also situated within the survey number 314 (Figure 1). This imprecise description of the protected area has led to multiple interpretations, fuelling litigation (https://indiankanoon.org/doc/125623085/ and https://indiankanoon.org/doc/143207319/ (accessed on 23 August 2024)). One party has argued that the entire survey number 314 (covering over 3000 acres) should be preserved and the other has interpreted the notification as referring only to a

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sub-region of this survey number (G.O. Rt. No. 131 dated 31 July 2021 issued by the Government of Andhra Pradesh).

The root cause of this conflicting interpretation lies in the lack of comprehensive data and mapping the archaeological features in this landscape. In this context, the present study aims to use remote sensing and GIS to first map all known archaeological features from legacy data and identify new features through geospatial analysis. Additionally, it investigates land-use and land-cover changes in the vicinity and assesses their impact on the archaeological landscape.

The archaeological sites of Thotlakonda and Bavikonda

The Buddhist monasteries of Thotlakonda and Bavikonda, located on low hills near Visakhapatnam, are closely connected, both geographically and historically. Bavikonda lies about 12 km northeast of Visakhapatnam, with Thotlakonda just 2.5 km further northeast. Separated by a narrow hill (Hill 2), both sites are visible to each other (Figure 1) (we use the terms Hill 2 and Hill 3 for the hills located south and west of Thotlakonda respectively, based on the nomenclature in Fogelin[7]. The two hills situated south of Hill 3 have been labelled, Hills 4 and 5). Discovered in the 1970s during an aerial survey by the Indian Navy, they were later explored by the Andhra Pradesh Department of Archaeology and Museums (APDAM). Excavations at Bavikonda (1982–1987) revealed a large stupa, viharas (monastic cells), chaitya grihas (prayer halls), wells, cisterns and relic caskets – used to enshrine the remains or belongings of revered monks or Buddha himself – indicating its religious importance[8]. Thotlakonda, excavated between 1987 and 1991 (ref. 6), revealed similar structures and artifacts, dating its occupation from the 2nd–3rd centuries BCE to the 2nd–3rd centuries CE. The material remains suggest that Bavikonda and Thotlakonda were contemporaneous and closely related[7].

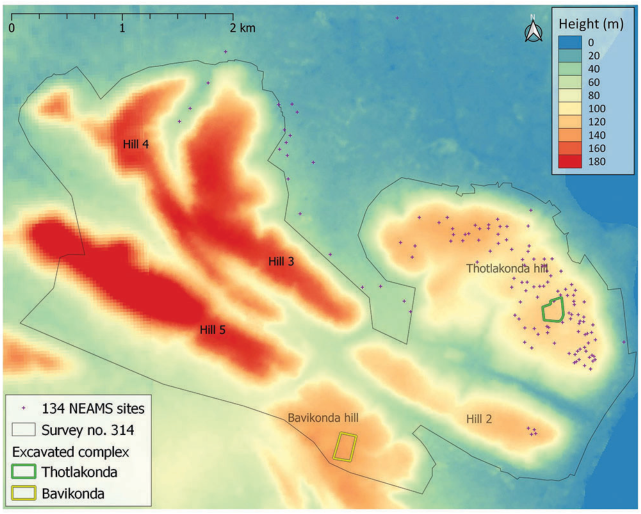

Figure 1. Digital elevations model (Cartosat 10 m) of hills around Thotlakonda.

From November 2000 to March 2001 and January to March 2002, Fogelin conducted the northeast Andhra monastic survey (NEAMS) surrounding Thotlakonda[7,9–12]. This archaeological surface survey spanned six months over two years, covering approximately 7.3 square kilometres and identifying 134 sites.

The survey by Fogelin[7] covered the entire Thotlakonda hill, Hill 2, Hill 3 (Figure 1), and parts of the region north and northeast of Thotlakonda. Among the 134 NEAMS sites, 105 are located on Thotlakonda hill, 22 to the northwest, 1 to the east and 4 on Hill 2. Fogelin provides the coordinates of these sites along with detailed descriptions and documentation of the observed features[7]. While exploring Hill 3, he noted approximately 75 cairns, all on the side facing the Thotlakonda site, with none on the opposite side, emphasizing the significance of sight lines and visibility between these hills. However, these cairns were not systematically documented. Due to time constraints and the inaccessibility of the areas covered by dense thorns, the survey did not extend to Bavikonda or other hills to the west (Hills 4 and 5).

Fogelin offers critical insights into the archaeological landscape, detailing the status of the remains on and around Thotlakonda hill, prior to land-use and land-cover changes observed in the last two decades. His work is supported by photographs and graphical illustrations of features such as tanks, cisterns, cairns, assemblages and structures[11,12]. Additionally, the spatial materials – maps and plans – help contextualize the previous work for the current geospatial analysis.

The findings at Thotlakonda and Bavikonda are of great archaeological significance, providing a detailed view of the monastic and daily life of early Buddhists in southern India. The architectural remnants and artifacts offer insights into the religious practices, economic conditions and cultural exchanges of the time. The proximity of Thotlakonda and Bavikonda to the coast indicates their involvement in maritime trade routes, which likely facilitated the spread of Buddhism[8]. The similarities and differences between the two sites also contribute to our understanding of regional variations in Buddhist architecture and monastic organization[7].

Remote sensing and GIS: data and applications

Remote sensing involves collecting data about an object without direct physical contact, making it a non-intrusive method that maintains the integrity of the object. This study used data from space-based remote sensing, where satellites orbiting the Earth capture images of its surface. These images offer a comprehensive view of a location, enabling analysis in relation to its surrounding areas and facilitating the

Table 1. Remote sensing data used along with their dates

Declassified satellite images: analogue greyscale	Declass 1 (Stereo medium)	7 October 1965
	Declass 3 (2–4 feet)	9 December 1975 and 21 February 1981
Indian remote sensing satellite series sensor: LISS-IV 5.8 m spatial resolution. G, R and NIR bands	Resourcesat-1	9 February 2005, 31 May 2005, 19 June 2005, 25 August 2005, 3 September 2005, 24 November 2005, 13 September 2006, 1 January 2008, 24 May 2008, 19 January 2009, 12 February 2010, 20 April 2010
	Resourcesat-2	15 May 2012, 3 June 2013, 24 May 2015, 19 January 2016, 7 March 2016, 18 March 2024
	Resourcesat-2A	11 February 2024
Google Earth Pro: high resolution, natural colour, open source	Maxar Technologies and CNES/ Airbus	Total 84 images between 30 December 2010 to 17 March 2024 (available on Google Earth Pro in June–July 2024)

identification of connections and alignments among various surface features. High-resolution images, with approximately 1 m per pixel resolution, reveal intricate details of structures and roads, while lower resolution images (5.8 m or 30 m per pixel) display broader landscape elements such as drainage patterns and historic water bodies.

A geographic information system (GIS) is a software platform that provides a framework for collecting, integrating, managing and analysing spatial data. GIS software organizes information into layers based on geospatial location, enabling the integration of data from multiple images and other sources such as ground-truthing, field observations, old maps and historical spatial records. To integrate spatial data, it is crucial to ensure that all data is georeferenced, ensuring that features in one layer are accurately aligned with their corresponding footprints in other layers.

Satellite image data

A range of satellite sensors is available, each designed to capture data from different parts of the electromagnetic spectrum. The surface composition of the landscape of the study area determines the type of imagery that will be most informative. The book *Patterns in Past Settlements: Geospatial Analysis of Imprints of Cultural Heritage on Landscapes*[13] serves as an introduction to a branch of archaeology that focuses on analysing landscapes to uncover evidence of past human activities. Often, such evidence is difficult to detect at ground level, but may become visible through remote sensing imagery captured from aerial platforms and satellites. Figure 3.2 of the book categorizes sensors specifically for identifying archaeological features. Based on the guidelines provided in this book, we have used multispectral images from the Indian Remote Sensing (IRS) satellite series, declassified satellite images, Google Earth images and the digital elevation model (DEM) (Table 1).

Multispectral imagery: Multispectral satellite imagery captures images of the Earth surface in the optical and infrared spectral bands. This technology is valuable for identifying variations in the health of vegetation, land use and environmental changes.

Google Earth Pro (henceforth referred to as GE) developed by Google, is a popular and powerful geographic information tool. It offers users a virtual globe to explore the Earth's surface using satellite imagery of true colours (colours visible to the human eye) of various resolutions and dates (ranging from 30 m from the 1980s to 1 m or better from early 2011) and 3D terrain models.

Declassified satellite images were captured by American reconnaissance satellites during the Cold War, mainly between the 1960s and 1980s. These images capture land that remained relatively untouched by large-scale mechanized development, preserving information that contemporary satellite imageries no longer show (available as Declass-1, 2 and 3 at https://earthexplorer.usgs.gov/).

A Digital Elevation Model is a digital representation of the Earth's terrain, showing the elevation or height of the land surface at various points. This study uses a DEM with 10-m spatial resolution generated from stereo images taken by CARTOSAT-1, available at https://bhoonidhi.nrsc.gov.in/.

In this study, Google Earth Pro was used to analyse imagery and prepare some maps, while all other imageries were processed, enhanced, and mapped in QGIS.

Archaeological signatures visible on satellite imageries

Satellite images that cover large areas offer a comprehensive view of archaeological sites, shedding light on the interaction between cultural artifacts and their surrounding landscapes. Rajani[13] refers to the area around a site as its spatial context, emphasizing that it is subject to continuous, gradual change due to natural factors (such as weathering by wind and water, deposition of sand or silt, or encroachment by vegetation) and human factors, such as changes in land-use and land-cover, which also play a significant role. Some features are visible on the surface, while others are hidden beneath and can only be detected through their morphological expressions. These features, which vary in scale, are classified as direct or indirect indicators. Indirect indicators include palaeo drainages or dried channels and ancient mudflats or coastal strandlines, hinting at the possibility of past settlements. Direct indicators consist of remnants of structures and traces of buried settlements, appearing as unusual patterns in the landscape, such as crop marks, soil marks, field boundaries or urban land-use patterns[14].

The indicators that are most relevant to the feature identified in this study are crop marks, hence we have elaborated this below. Buried archaeological remains often impact crop health, creating positive or negative crop marks that appear as large patterns when viewed in satellite imageries[15]. Crop marks are not only among the most common signals for detecting archaeological remains, but also one of the oldest[16]. They were first noticed in aerial reconnaissance photographs taken during World War II and recognized for their archaeological significance[17]. Crop marks can reveal features such as disused moats, canals, tanks and pits. These buried and silted features often retain additional moisture, typically appearing as positive crop marks. Conversely, archaeological structures like brick or stone foundations, streets and solid floors inhibit vegetation growth by obstructing plant roots, resulting in negative crop marks. For more details on various forms of crop marks, see section 2.3.2 in ref. 18.

Corrections for geospatial data integration

The coordinates provided in the site description of NEAMS sites 1–134 by Fogelin[7] (appendix A, pp. 333–425) were used to create a point vector layer (pink points in Figure 2). These locations were determined using Garmin Etrex hand-held GPS unit. The accuracy reported for the unit was typically 7–8 m. However, when overlaid on the geoportal, it was found that these points were consistently (but for three exceptions) displaced by 218 m towards the

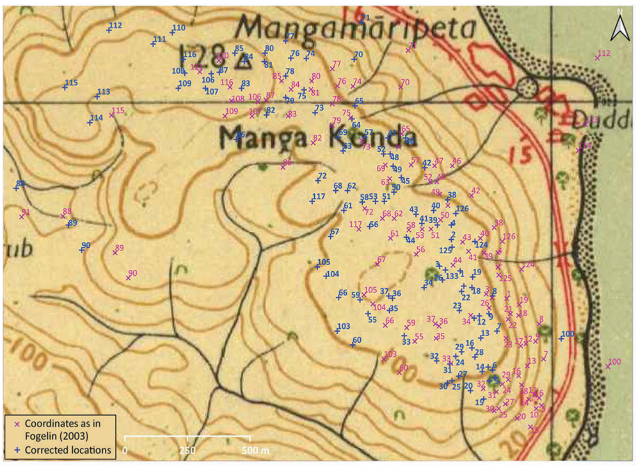

Figure 2. NEAMS site locations as in Fogelin[7] and corrected locations overlaid on Survey of India toposheet 65O5 (1977).

southeast. Here we first address the exceptions and then the corrections for the whole set of points.

NEAMS 112, 113 and 114 are three exceptions to the otherwise consistent displacement of all the other 131 NEAM sites. These three sites had to be corrected before addressing the 218 m displacement of the whole set of points. When plotted geospatially, these three sites appear further east towards the coastline (Figure 2). However, in the maps of NEAMS sites published in Fogelin[7,9,10], these three sites are shown close to the site 115, indicating that the displacement is only in longitude. Upon closely examining the printed longitude for the three erroneous plus site no. 115 (112: 83°24′59.6″; 113: 83°24′58.0″; 114: 83°24′57.1″; 115: 83°23′53.6″), we found that the three erroneous ones have one additional minute of an arc (24′ versus 23′, as in site 115), causing this exceptional displacement.

The consistent displacement

After considering various reasons for the consistent displacement of 218 m across all the site locations, we realized that it was due to differences in references (coordinate system and projections). We corrected the reference using the Survey of India toposheet map (65 O/5, 1977). Survey of India's geodetic marker on the hill (NEAMS site no. 84 in Figure 2), and site datums marked on various site maps in Fogelin[7]. NEAMS site numbers 1, 34, 38, 58, 66, 67 and 81 were identified on LISS-IV and GE imageries using features such as road, cisterns, terrace, modern terrace, dense shrubs, marked in the site maps in Fogelin[7].

For instance, Figure 3 *a* and *b* shows the main reservoirs (NEAMS 34). The curved shape of the wall is clearly visible (compare Figure 3 *a* and *b* with *c*). The site datum on the site map (Figure 3 *c*) is on the north end of the curved wall near the intersection of the roads, which can also be corroborated in LISS-IV (9 February 2005) and GE image (17 March 2024) (Figure 3 *a* and *b*).

However, NEAMS 1 is along a dirt road (Figure 3 *d*), with the site datum just to the north of the road. This can be corroborated with the road visible in the 2005 image (Figure 3 *a*), but not in the recent GE image (Figure 3 *b*). The route of the road changed between 13 September 2006 and 1 January 2008, and therefore, in the 2024 image (Figure 3 *b*), NEAMS 1 appears to be further north, away from the road.

The coordinates provided in the NEAMS site descriptions are expected to have an accuracy of 7–8 m (ref. 7). The LISS-IV imagery, with a spatial resolution of 5.8 m, has been georeferenced to an error of less than 1.3 pixels, resulting in an accuracy of 7.5 m. These two errors may overlap or may be exclusive. Therefore, the corrected vector layer consisting of all NEAMS 1–134 sites is expected to have an accuracy of up to 15 m. The corrected point layer with the NEAMS site is overlaid on LISS-IV image of 9 February 2005 in Figure 4.

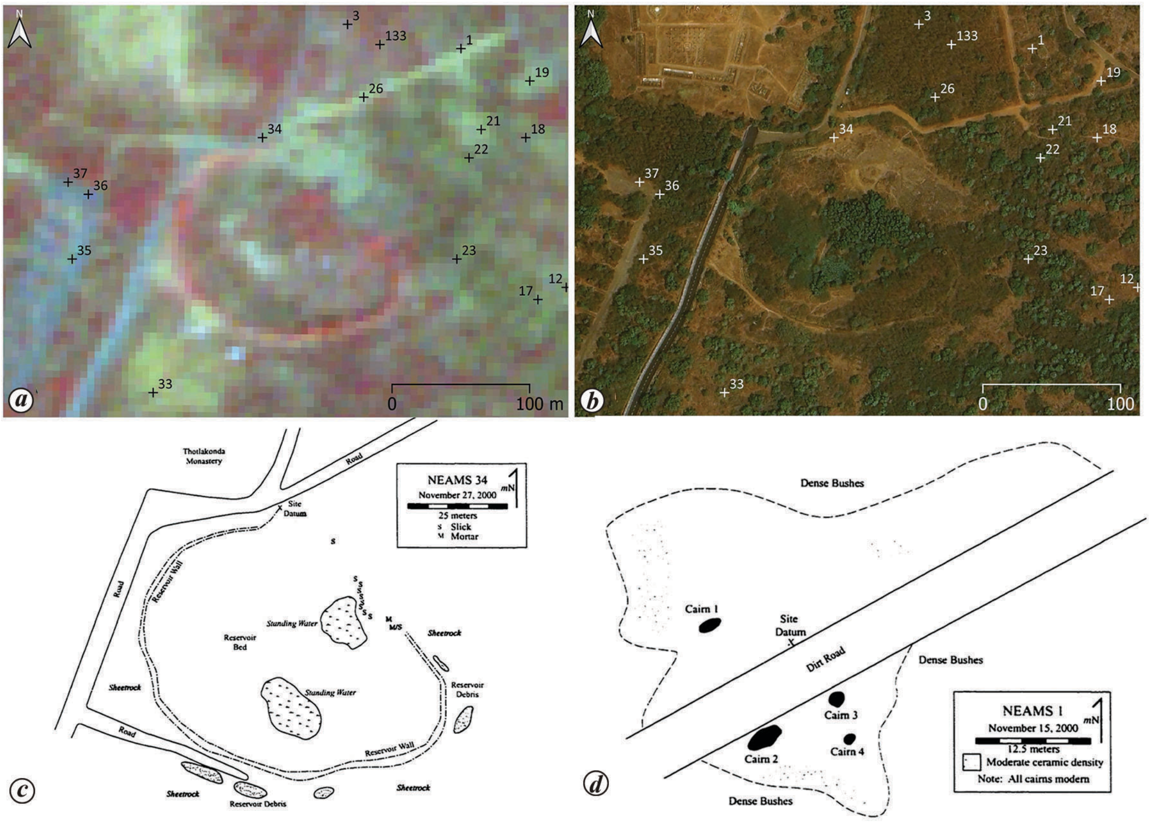

Figure 3. ***a***, IRSP6 LISS-IV image dated 9 February 2005; ***b***, Google Earth image of 17 March 2024; ***c*** and ***d*** are site maps of NEAMS 34 and 1 from Fogelin[7].

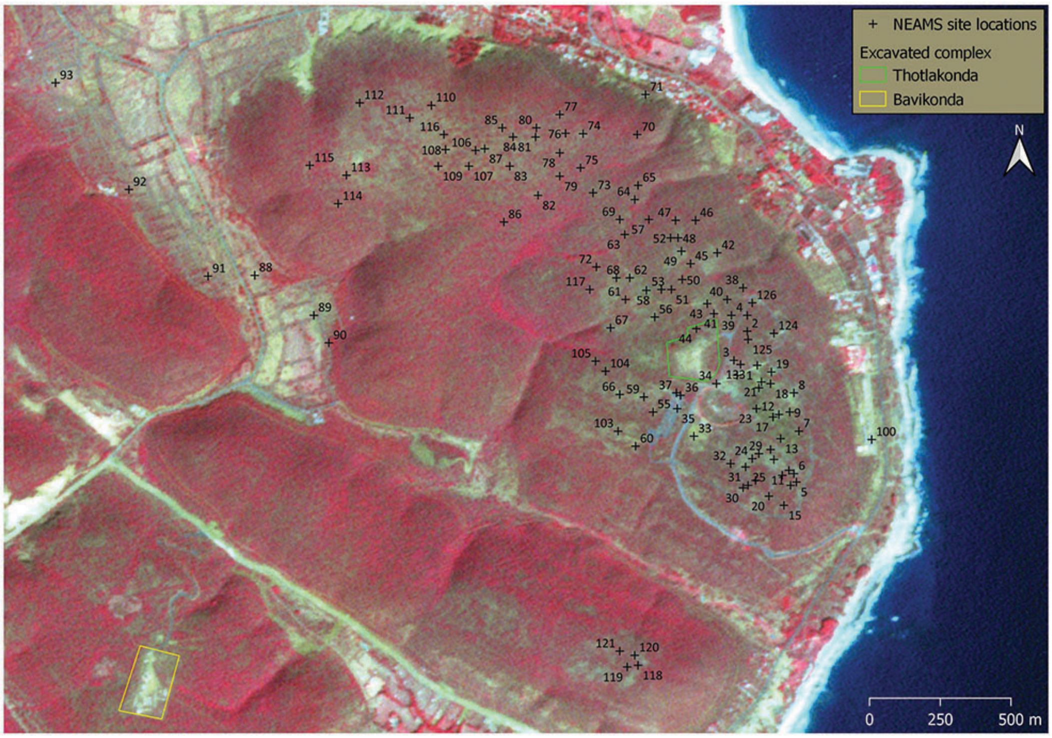

Figure 4. IRSP6 LISS-IV image dated 9 February 2005 showing the three hills: hill with Thotlakonda site on the north, hill with Bavikonda site on the south and the Hill 2 in between.

Table 2. List of newly identified features

Notation	Feature description	Remarks and current status	Ref. Fig.
F1	Circular soil mark	Undisturbed	5, 6
F2	Wall sections	Disturbed	8
F3	A large circular domical mound	Covered with vegetation overgrowth, overlaps with NEAMS[7] 61	9
F4	Ruins of enclosure wall	Undisturbed, overlaps with NEAMS[7] 58, 62, 67	9
F5	Circular soil mark	Undisturbed	9
F6	Circular soil mark	Undisturbed, overlaps with NEAMS[7] 56	9
F7	Enclosure (positive crop mark)	Northern half seem undisturbed but covered with vegetation, whereas southern half is replaced by a path/road	9
F8	Enclosure (positive crop mark)	Western part is disturbed due to land use changes. Small stretches of the northern and southern extremes seem undisturbed but overgrown.	9
F9	Circular positive crop mark, diameter 65–70 m	Undisturbed	11
F10	Double walls of a reservoir	Undisturbed	11
F11	Rectangular positive crop mark	Undisturbed, but not distinguishable on recent images	11
F12	Stepped-shaped positive crop mark indicating buried structure	Undisturbed	11
F13	Curve-shaped positive crop mark	Undisturbed	11
F14	Linear positive crop mark (900 m long)	NEAMS[7] 109 is along this feature	11, 12
F15	Wall	Originally 484 m, reduced to 335 m. Vegetation overgrown and northern portions have been built over	12
F16	Wall	Originally 300 m, currently not discernible	12
F17	Wall	Originally 275 m, currently not discernible	12
F18	Grove	Originally the north–south span was 145 m, currently reduced to 110 m	12

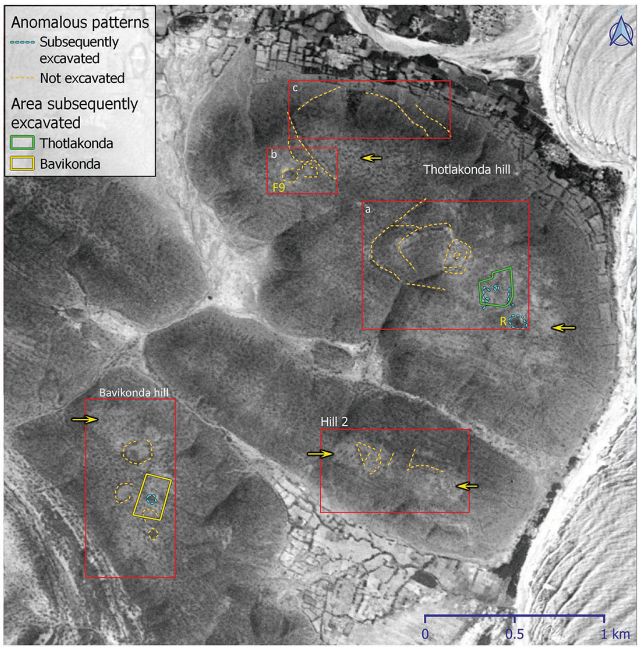

Figure 5. Image from Declass-1 series (dated 7 October 1965); yellow arrows point to large patches of lighter tone on the hilltops indicating negative crop marks.

Results

Remote sensing imageries (spanning the last 60 years) of the hills of Thotlakonda and Bavikonda environs were analysed to identify the archaeological landscape. The features identified in the present study have been numbered from F1 to F18 and listed in Table 2. The NEAMS sites have been overlaid on various maps to contextualize the features in F series with the series of sites identified in the NEAMS project. Our observations are discussed in the following.

Figure 5 shows a Declass-1 image dated 7 October 1965, depicting the landscape before the Indian Navy's aerial survey discovered the site. At that time, the archaeological site had undergone only natural deterioration and overgrowth. By carefully examining Thotlakonda, Bavikonda and Hill 2, we can see negative crop marks as large patches of lighter tone on the hilltops (yellow arrows in Figure 5). There are two such large patches on the Thotlakonda hill: one on the east (which includes the site of Thotlakonda that was subsequently excavated) and the other on the west. There is also one large patch on Bavikonda hill (which includes the excavated complex of Bavikonda) and two small patches on the Hill 2. These patches may indicate clusters of foundations or solid floors, especially as their texture is uneven and they all contain crop marks of various shapes (linear, curvilinear, circular) within and around these large patches. The crop marks that coincide with later excavated structures are distinguished in Figure 5. Within the region shown in Figure 5, five specific areas (marked with red boxes) have been identified for further discussion: one on Bavikonda Hill, one on the Hill 2 and three (a, b, c) on Thotlakonda Hill. These areas are also enlarged in the subsequent figures.

Bavikonda hill

Figure 6 highlights the Bavikonda site and its surroundings. The Declass-3 image of 9 December 1975 (Figure 6 *a*) reveals crop marks that indicate buried archaeological

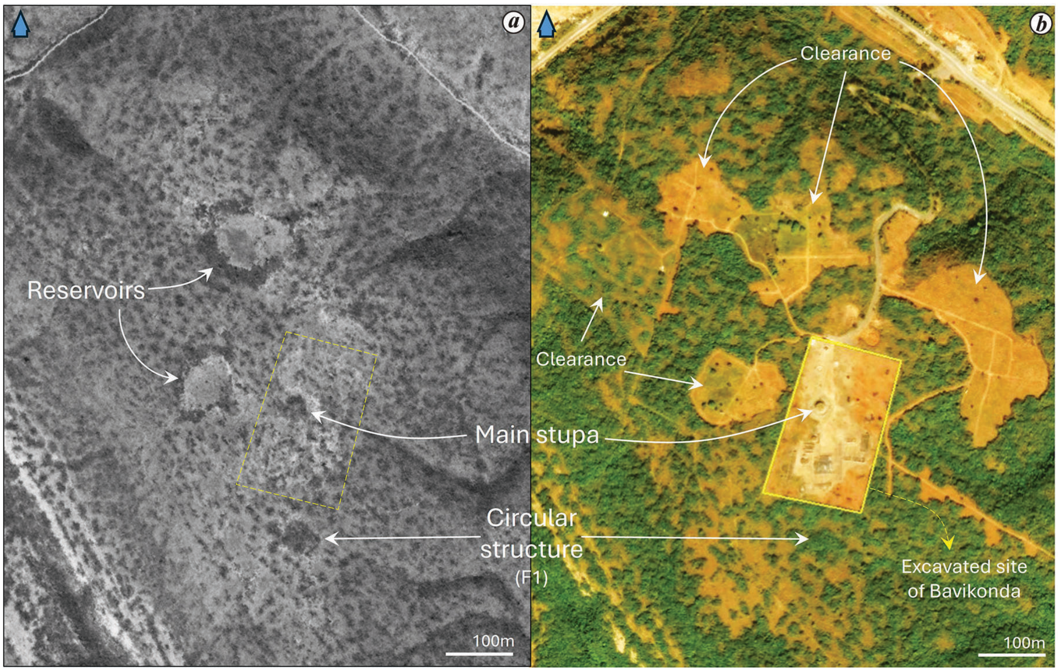

Figure 6. Bavikonda site and environs: (***a***) Declass-3 image of 9 December 1975; (***b***) Google Earth (Maxar Technologies) image of 14 March 2014.

Figure 7. View from the north of the main stupa at Bavikonda, in the foreground is Stupa 2. Photo taken by author on 30 December 2023.

features in the context of the site boundary that was later excavated. Notably, two large reservoirs or ponds northwest of the site boundary are visible as crop marks. Additionally, two circular crop marks aligned in a north–south direction are visible. The southern crop mark (F1) measures approximately 55 m in diameter and the northern one spans around 35 m in diameter. The smaller northern crop mark was later excavated, revealing the main stupa of Bavikonda (Figure 7). Drawing a line between the centres of the mound of the main stupa and the large mound of F1, one can see that they are along a north–south axis, indicating that the site of excavated boundary diverges from the original orientation of the historical site. Recent satellite imagery confirms that F1 remains unexcavated and is located outside the southern boundary of the current excavation.

The Hill 2

The Declass-3 image of 9 December 1975 (Figure 8 *a*), captures the region within the red box shown on the hill, clearly highlighting two light-toned patches observed in Figure 5. These patches likely represent areas of hard ground composed of a solid floor, inhibiting vegetation growth. A closer view (Figure 8 *b*) reveals a partially buried wall section (F2) that extends across both light-toned patches. This hill is also home to four NEAMS sites (118, 119, 120 and 121).

Thotlakonda hill

This hill is the largest, with a broad expanse at its summit, displaying patterns that indicate archaeological features in three distinct areas. Consequently, we focused on the three specific regions marked as boxes a, b and c in Figure 5. The details of the features within each of these areas are illustrated in Figures 9–11.

Box-a. Figure 9 presents the area within box-a revealing a substantial complex, beginning approximately 150 m northwest of the excavated Thotlakonda site and spanning 500 m. This complex comprises three main parts:

- *Part-1:* The part nearest to Thotlakonda is distinctly visible in the Declass-3 images (Figure 9 *a* and *c*). At its centre lies a prominent circular domical mound (F3), approximately 20 m in diameter. This mound surpasses in size the two mounds depicted in Figure 9 *d*, which were later excavated to uncover the main stupa and

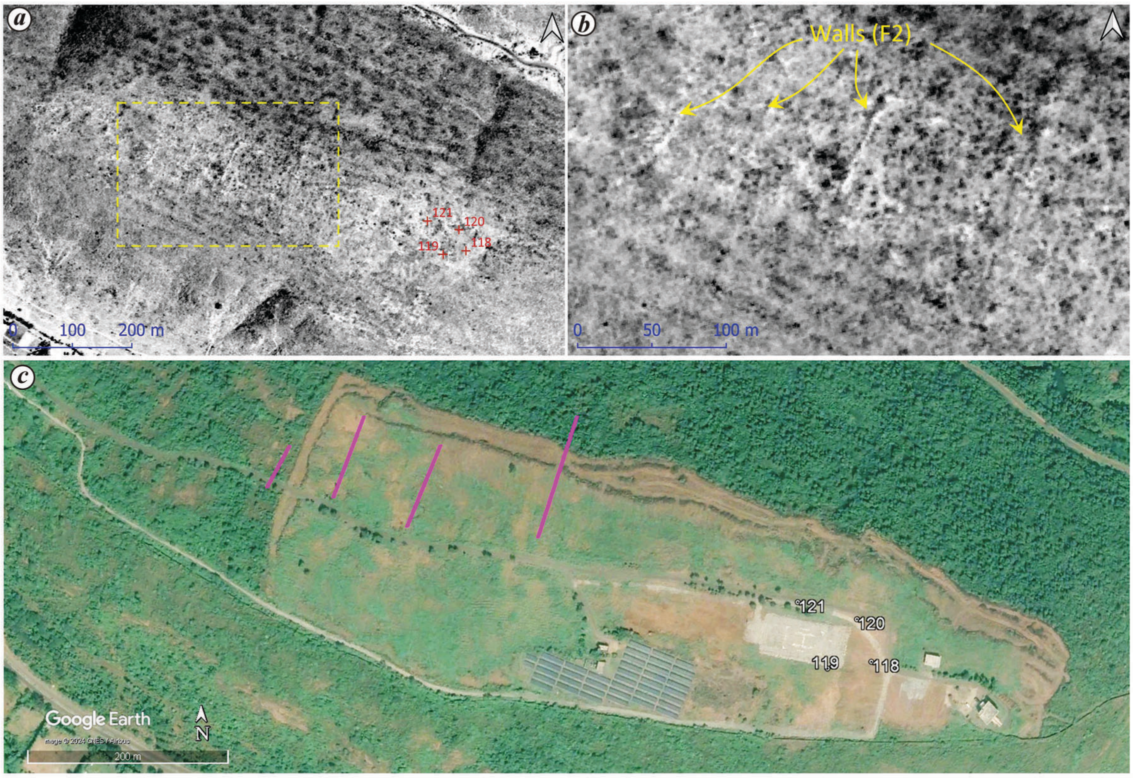

Figure 8. Hill 2. ***a***, Declass-3 image of 21 February 1981; ***b***, Closeup of the area marked in dotted yellow in ***a***; ***c***, Google Earth (CNES/airbus) image of 1 November 2020, showing the locations of four NEAMS sites and pink lines indicate locations of wall sections visible in ***b***.

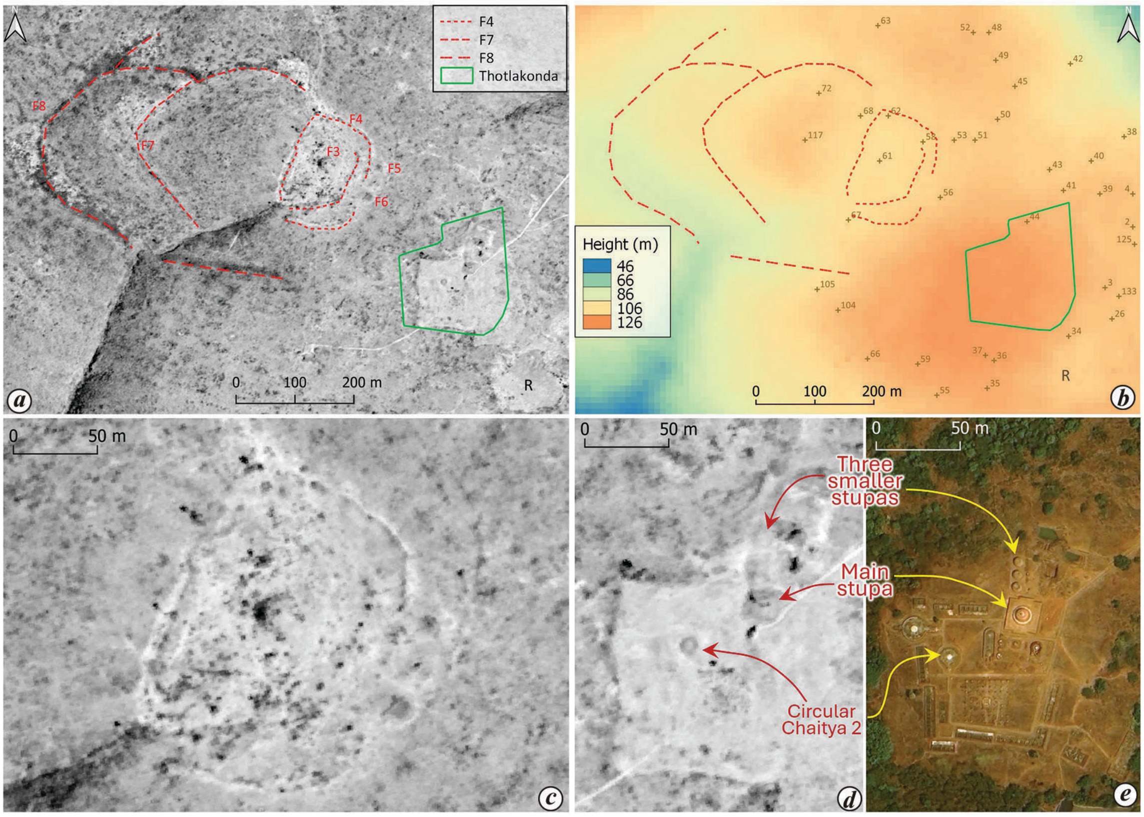

Figure 9. Thotlakonda hill: details of area within box-a: ***a***, Declass-3 image of 21 February 1981; ***b***, Google Earth (Airbus) image of 17 March 2024; ***c***, Close-up of F6–F9; ***d***, An enlarged portion in Declass-3, 21 February 1981; ***e***, Google Earth.

Figure 10. View from the north of the main stupa at Thotlakonda, three small stupa and a cistern are visible. Photo taken by author on 30 December 2023.

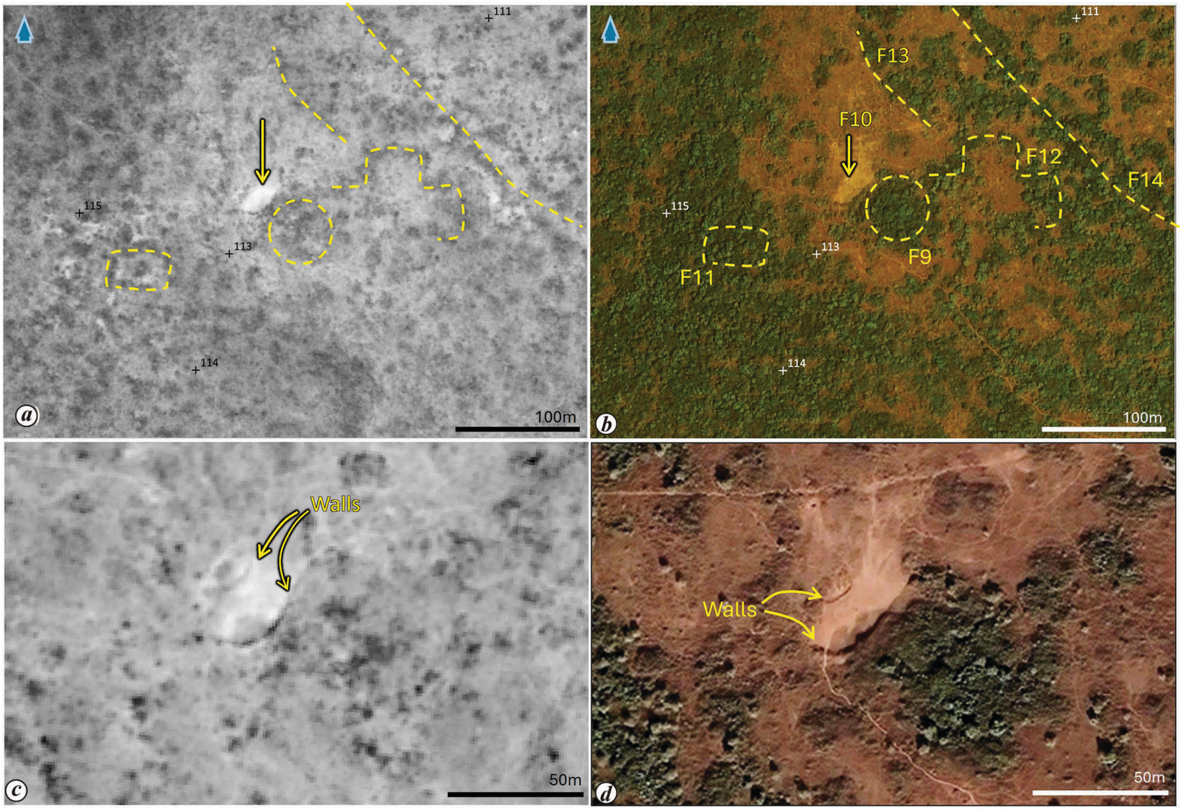

Figure 11. Thotlakonda hill: details of area within box-b: ***a***, Declass-3 image of 9 December 1975; ***b***, Google Earth (Airbus) image of 17 March 2024; ***c*** and ***d*** have an enlarged portion in Declass-3, 21 February 1981 and Google Earth.

Circular Chaitya 2 (Figure 9 *e*). Surrounding mound F3 is the remains of an enclosure wall (F4), creating a precinct measuring about 200 m north–south and 120 m east–west. Notably, this wall has an opening on the east side, facing directly toward the Thotlakonda site. Flanking this gap are two circular dark-toned features, each roughly 12 m in diameter, situated to the north (F5) and south (F6) (Figure 9 *a* and *c*). These features likely indicate buried structures, akin to a series of dark-toned features north of the main stupa, as seen in the 1981 Declass-3 image (Figure 9 *d*). These were later excavated to reveal three smaller circular stupa structures, now visible to the north of the main stupa in the 2024 GE image (Figure 9 *e*) and the photograph (Figure 10). It is plausible that F5 and F6 might similarly conceal circular structural remnants.

- *Parts 2 and 3:* To the west of F4 lies a second enclosure (F7), and further west, a third enclosure (F8). Both are discernible as positive crop marks. The shapes of these enclosures follow the shapes of topography. In the

DEM (Figure 9 *b*), a depression in the topography is visible, suggesting an occurrence of a valley or crevice to the south. It is possible that these enclosures functioned as some form of embankment for harvesting or channeling water, similar to the water channeling observed on the hilltops of Badami in Karnataka[19]. However, a thorough field investigation is necessary to validate this hypothesis.

The entire complex stretches 555 m east–west and 400 m north–south. While portions of F8, the westernmost enclosure, have experienced land use alterations, the rest of the complex remains largely undisturbed, but is heavily overgrown. The part-1 of this complex (F3–F6) is highly potential for archaeological exploration and excavation.

Box-b. The circular feature R in box-a mirrors the shape and size of the circular feature F9 in box-b, both appearing as positive crop marks (Figure 5). Feature R, identified as the main reservoir (Figure 3), is positioned just south of the excavated complex of Thotlakonda. This resemblance suggests that F9 might also be a reservoir. Moreover, the discovery of a large complex of structures near R raises the intriguing possibility of a similar hidden complex near F9. This observation opens up a compelling evidence for further exploration and potential discovery of significant archaeological finding(s).

Figure 11 shows the intricate details surrounding feature F9, a distinct circular patch of dense vegetation. Positioned to the northwest of F9 is a portion of a reservoir (F10), easily identifiable in the Declass-3 images from 1975 and 1981, where a double wall is vividly discernible upon close examination (Figure 11 *c*). Both F9 and F10 continue to be prominent in the latest images (Figure 11 *b*). Southwest of F10, a rectangular positive crop mark (F11) stands out in the Declass-3 images from 1975 and 1981, though it gets obscured by thick vegetation growth in the 17 March 2024 image (Figure 11 *b*). East of F9, a step-shaped feature (F12) is evident, with a curved feature (F13) to its north, potentially indicating buried structures of these shapes. Further east is F14, a linear positive crop mark stretching over 600 m in length in a northwest–southeast direction, which gives a hint to the occurrence of an extensive hidden structure.

Box-c. Figure 12 illustrates the landscape within box-c. The Declass-3 image of 9 December 1975 (Figure 12 *a*) showcases three distinct wall sections – F15, F16 and F17 – alongside a dense grove (F18). The curvilinear wall F15 extends 484 m, with its southern tip situated approximately 900 m northwest of the Thotlakonda site. Running almost parallel, 90 m to the east, lies F16, measuring about 300 m in length. To the west, another curvilinear wall section, F17, stretches 275 m and the northern ends of F15 and F17 are separated by about 250 m. All three walls are distinctly visible in the images of 1975. Between F15 and F17 is a significant patch of thick vegetation, F18, which spans 145 m north–south and 110 m east–west along the slope of the hill.

The area in box-c has undergone significant changes as seen in the recent satellite imagery (Figure 12 *b*). The three walls have become indistinct, largely due to overgrown vegetation. The urban sprawl has further altered the landscape, particularly in the northern section, erasing most signs of F16 and F17. However, traces of a portion of F15, about 335 m in length, remain visible as a positive crop mark. The north–south expanse of F18 has also diminished, now measuring only 100 m.

Change detection: recent land-use and land-cover changes impacting the archaeological landscape

Change detection in remote sensing analysis refers to identifying and measuring the spatial changes of any natural or man-made features using satellite images of different dates. In this study, changes are analysed by overlaying satellite images of various dates starting from 1965. We examine the changes on each of the three hills.

Bavikonda hill

Land-cover changes, such as surface clearance and levelling, are detectable on Bavikonda hill in the image dated 14 March 2014 (Figure 6 *b*), particularly along the two reservoirs northwest of the excavated archaeological complex. Although the area has since become overgrown with bushes, the contours of these features have been obscured due to anthropogenic surface modifications.

Hill 2

The land use on the Hill 2 has undergone several changes (Figure 8 *c*), diminishing the likelihood of any ruins surviving on the surface. As of 24 November 2005 (Figure 4), the hilltop remained undisturbed and the crop marks visible in the Declass-1 image (Figure 5), were still intact. However, by 13 September 2006, a road had been laid leading to the highest point, where four NEAMS sites – 118, 119, 120 and 121 – were located. Following this development, there was minimal change until early 2012. Subsequently, clearance activities began by 15 May 2012, levelling work had been carried out leading to the construction of a helipad (by 25 December 2013) directly over the area where the four NEAMS sites were situated. Figure 8 *c*, from 1 November 2020, shows the helipad still in use at that time along with a solar farm to its southwest. The levelling and landscaping thereof have obscured the wall sections (F2) which were visible in Declass-3 imagery (Figure 8 *a* and *b*). Later, the entire hilltop was levelled and by 17 March 2024, the area had become overgrown, leaving no visible traces of these changes.

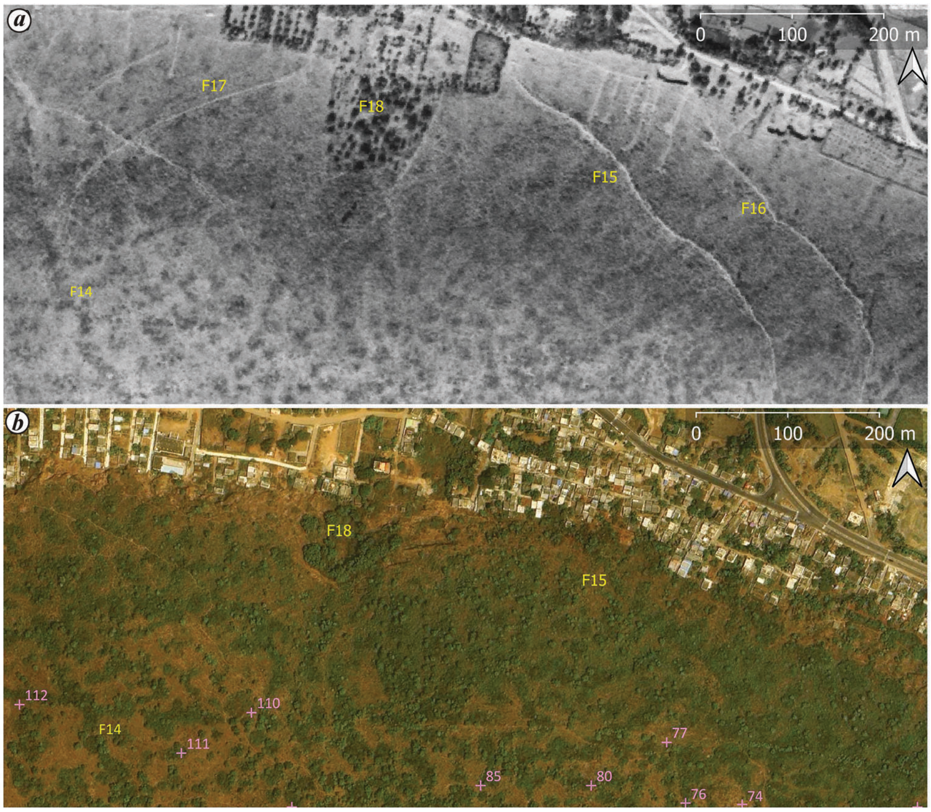

Figure 12. Thotlakonda hill: details of area within box-c: (***a***) Declass-3 image of 9 December 1975; (***b***) Google Earth (Airbus) image of 17 March 2024.

Figure 13. Land-cover changes on the hills of Thotlakonda, Bavikonda and environs (background image Google Earth Airbus 17 March 2024).

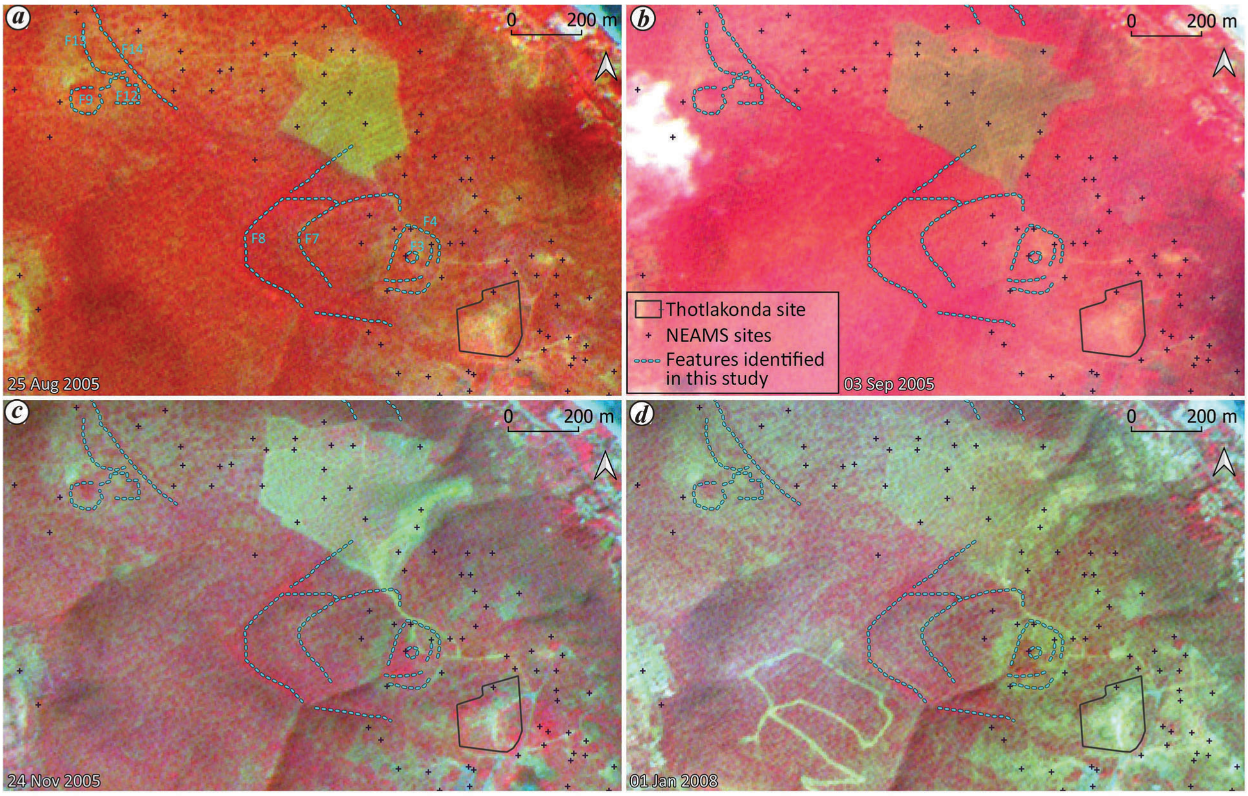

Figure 14. Land-cover changes on Thotlakonda hill observed in IRSP6 LISS-IV images on various dates: (***a***) 25 August 2005; (***b***) 3 September 2005; (***c***) 24 November 2005; (***d***) 1 January 2008.

Thotlakonda hill

Upon examining recent GE imagery of 17 March 2024 (Figure 13), the Thotlakonda hill appears to be predominantly covered by dense wild vegetation, suggesting that it has largely remained untouched by modern human activity. However, this impression is misleading. A detailed analysis of landscape changes over the past two decades, based on multidate satellite imagery, tells a different story. The acreage measurements mentioned in the following paragraphs are approximate, as they were derived from satellite imagery with 5.8 m resolution.

Crop marks visible in Figure 5 (image taken on 7 October 1965) are also present in Figure 4 (9 February 2005). Apart from the excavated areas of Thotlakonda and Bavikonda, and the access roads to these sites, the surface of these hills appeared relatively unchanged. However, subsequent imagery of 25 August 2005 shows significant changes. In Figure 14 *a* an area of 24.3 acres northwest of the excavated Thotlakonda complex has been cleared of surface vegetation, exposing the soil. The bright and uniform tone suggests high soil reflectance, indicating levelling by topsoil removal. This had been extended to 43 acres in just 8 days as visible in the image of 3 September 2005 (Figure 14 *b*) and then to 46 acres by 24 November 2005 (Figure 14 *c*). In the latter image, to the east of this clearance, we can see an even brighter patch (Figure 14 *c*), which may indicate excavation up to the bedrock, a typical signature in satellite imagery of mining sites. This whole area appeared overgrown in the image from 13 September 2006. However, by 1 January 2008 (Figure 14 *d*), the vegetation had been cleared again, extending to the east and north, totalling approximately 54 acres. By 2013, this area was overgrown completely, diminishing the contours of this clearance. In the image of 22 December 2015 (Figure 15 *a*), another 13.5 acres patch of clearance and levelling is visible north of the Thotlakonda site, only to be overgrown subsequently. Later, in the image of 10 March 2020 (Figure 15 *c*), a part of this has been cleared and levelled again. In the image of 8 May 2019 (Figure 15 *b*), a network of dirt roads of 5–7 m width is detectable, likely caused by the frequent movement of heavy vehicles. In an image of 10 March 2020 (Figure 15 *c*), we can see a layout with boundary markings. This area has been covered over by vegetation again with the feature being nearly untraceable in recent images. The Greyhounds Regional Training Centre is located in the valley between Thotlakonda hill and Hill 2. Initial features of this campus are detectible in the image of 13 September 2006 and this campus has gradually expanded.

Figure 13 attempts to capture all the land-cover changes in this landscape as observed through multidate satellite imageries. The earliest detected changes have been mapped. Some of these changes remain visible in most recent satellite images, while others have been concealed by vegetation regrowth.

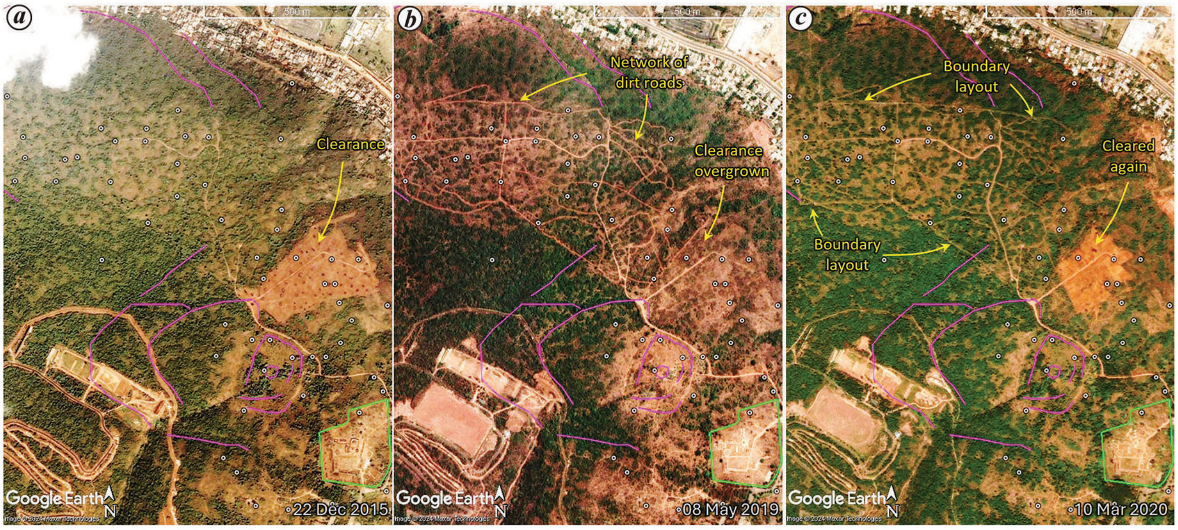

Figure 15. Land-cover changes on the Thotlakonda hill. Pink lines are features identified in this study.

Conclusions

The present study integrates spatial information from various sources, including archaeological excavations conducted by APDAM and site locations identified through the NEAMS surface survey, into a unified geospatial framework. This involved digitizing site coordinates listed in Fogelin[7], identifying discrepancies in the data and normalizing the location information with other geospatial datasets.

The present study has used multispectral satellite images of the optical spectral bands (blue, green, red and near-infrared) and declassified satellite images. By examining satellite imageries from the past 60 years, the study analyses the archaeological landscapes of Thotlakonda, Bavikonda and the Hill 2. Newly identified features include a circular crop mark of 55 m in diameter (F1), south of Bavikonda excavated complex that aligns with the main stupa, which indicates potential site extension. On Thotlakonda hill, three clusters of archaeological features have been identified: a large central complex with enclosures and circular features (F3–F8), a complex with a reservoir and structures to the east (F9–F13) and wall sections (F15–F17) along with a grove (F18) to the north. Additionally, previously unrecorded wall sections (F2) have been identified on Hill 2. The present study has highlighted the archaeological potential of the Thotlakonda and Bavikonda areas beyond the boundaries of the excavated complexes. Further analysis, including images of longer wavelength bands or active sensing technologies like microwave or LiDAR, could potentially reveal additional archaeological features on these hills. Therefore, the full potential of what remote sensing can reveal about the archaeological remains on the hills of Thotlakonda, Bavikonda and Hill 2 is yet to be fully explored.

Of the 18 features identified in the present study, some overlap with large features recorded in the NEAMS field surveys by Fogelin[7] (Table 2). These shared features help align the data within a common geospatial framework, while many other features remain as distinct findings by the two methods. This highlights how satellite image analysis and surface surveys complement each other, providing essential, yet non-redundant data for archaeological research. For example, F1–F18 are features that suggest the presence of buried structures larger than the cairns and assemblages recorded by Fogelin[7]. On the other hand, features like cairns and assemblages are often concealed in multispectral satellite imageries due to vegetation cover or material blending with the landscape.

To the west of Thotlakonda and Bavikonda hills are three additional hills (Hills 3, 4 and 5) which are higher in elevation than the three eastern hills (Figure 1). Hill 3 was explored by Fogelin[7], but Hills 4 and 5 remain unexplored. Given the intervisibility among Thotlakonda, Bavikonda and sites in surrounding hilltops documented by Fogelin[7], it would be surprising if these higher hills did not contain archaeological remains. Although this study did not identify significant features on the tops of Hills 4 and 5 through multispectral satellite image analysis, radar and LiDAR imagery may reveal important findings in these areas. Geospatial analysis, combined with systematic ground exploration, is recommended before any land-use changes are encouraged on these hills. Though Hill 3 has already been disturbed by road construction (Figure 13), Hills 4 and 5 remain untouched by modern development.

This study also documents substantial land-use and land-cover changes over the past 20 years, particularly on the Thotlakonda hill. A large area to the northwest of the excavated site (extending 1 km east–west and 500 m north–south) has been repeatedly disturbed by clearing and levelling during this period. This area overlaps with one of the large patches of lighter tone identified in Figure 5, which may indicate clusters of foundations or solid floors. Although these changes are concealed by vegetation regrowth, NEAMS sites within these clearances (Figure 13) may have been heavily impacted. However, several other noteworthy archaeological remains are still intact on both Thotlakonda and Bavikonda hills. Thus, in the light of this study, it is recommended to perform a non-invasive subsurface survey through ground penetrating radar (GPR), followed by excavation in areas identified as F1, F3–F7 and F9–F13, where features suggest substantial archaeological remains.

Until such investigations are complete, strict regulation of land-use changes can prevent further damage and protect the site's integrity, which is one of the two criteria (the other being authenticity) for a site to be recommended for protection according to the Ancient Monuments and Archaeological Sites and Remains (AMASR) Act (1952, amended in 2010). The NIAS Policy Brief[3] demonstrates that while field surveys can verify a site's authenticity, they often overlook or fail to fully assess the site's integrity (due to changing land-cover). The Policy Brief[3] posits that remote sensing, GIS and associated geospatial technologies should be used to delineate regulation boundaries that better preserve site integrity. It stresses the importance of clear, enforceable regulatory boundaries that protect the integrity of heritage sites from encroachment, urbanization and degradation. It highlights how existing legal framework often lacks precise boundaries and effective enforcement, leading to the deterioration of heritage landscapes. The Policy Brief[3] advocates for the use of modern technologies like GIS and remote sensing to more effectively delineate and monitor these boundaries. Without such measures, many heritage sites may suffer deterioration or become embroiled in legal disputes, as seen in the case of Thotlakonda's archaeological landscape.

With the growing demand for land, preserving cultural heritage can only be achieved through the establishment of well-defined regulatory boundaries. Protection boundaries are like a double-edged sword: while they safeguard the archaeological remains within, they also increase the risk to the remains that lie outside. Hence boundaries for protecting archaeological sites should be defined based on the extent of archaeological remains. Boundary delineation through careful analysis has the potential to both protect archaeological remains as well as free up the land for development. These boundaries can be effectively created using remote sensing data and geospatial analysis in addition to traditional archaeological surveys. Well-preserved sites not only attract visitors, but also become a sustainable resource that contributes to the regional economy. Stakeholders impacted by the creation of well-delineated and well-regulated boundaries that include cultural heritage remains have a strong incentive to participate in the preservation efforts, sharing in the collective economic benefits that follow.

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