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Remote Sensing for Heritage Conservation and Structural Monitoring: The case of Wolvesey Castle, Winchester

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***Abstract* – Heritage sites are vital cultural assets, preserving the history and achievements of societies. These sites face threats from urban expansion, environmental degradation, and climate change. This paper proposes a systematic, methodological, and multi-temporal monitoring approach for heritage sites, focusing on the historic Wolvesey Castle in Winchester, using medium-resolution satellite data. The approach aims to assess structural stability, quantify risks, and guide conservation interventions while respecting the sites' significance.**

The integration of remote sensing with traditional structural assessment methods provides a comprehensive framework for Heritage Conservation. While remote sensing offers significant advantages, it should be complemented by on-site inspections to ensure a detailed evaluation. The combined methodology supports the development of effective conservation strategies, ensuring the long-term preservation of heritage sites under changing environmental conditions.

Key Words - Heritage sites, Wolvesey Castle, Structural monitoring methods, Remote sensing Conservation

I. INTRODUCTION

Heritage sites serve as tangible sources of cultural memory, preserving the history and achievements of past societies. These heritage sites are impacted by urban expansion [1,2], environmental degradation [3], and climate change [4]. Addressing the impact of such factors is essential for safeguarding the heritage assets.

Remote sensing represents an indispensable, non-invasive tool that can monitor the conditions of heritage sites at a grand scale and quantify environmental parameters affecting their integrity. Satellite remote sensing can play a pivotal role in heritage asset management by revealing hidden archaeological features and guiding field investigations [5,6]. Early research also demonstrates the potential of techniques, such as image-based 3D modelling in heritage documentation [7]. The importance of using different sets of data is highlighted, such as key spectral and thermal indices derived from multispectral satellite imagery[8-12], offering a robust quantitative basis for evaluating environmental stressors that could affect the integrity of heritage structures [8,13,14]. These methods can significantly advance the field of Heritage structural health monitoring and conservation.

Multispectral satellite imagery and radar interferometry have become instrumental for monitoring cultural heritage sites [15-17]. Satellite observations such as Sentinel-1, Sentinel-2 and Landsat provide consistent temporal coverage, enabling long-term assessment of land use and environmental impacts on heritage assets[15,18,19].

This paper proposes a systematic, methodological, and multi-temporal monitoring approach for heritage sites, explicitly focusing on historical castles, using medium-resolution satellite data. The strategy aims to inform assessments of structural stability, quantify associated risks, and guide the development of compatible conservation and structural interventions in compliance with the sites' historical value and significance.

II. AIM AND OBJECTIVES

This paper aims to identify and quantify key environmental parameters in the study area of Wolvesey Castle, thereby showcasing a proactive framework that helps assess risks and guide conservation strategies.

III. THE CASE STUDY: WOLVESEY CASTLE

Wolvesey Castle (Fig. 1) is one of several medieval castles in England, located in Winchester, Southern England. This heritage site is currently exposed to multiple environmental stressors, including fluctuating moisture levels, vegetation encroachment, and temperature variations, all of which negatively affect the structural stability of its ruinous structures.

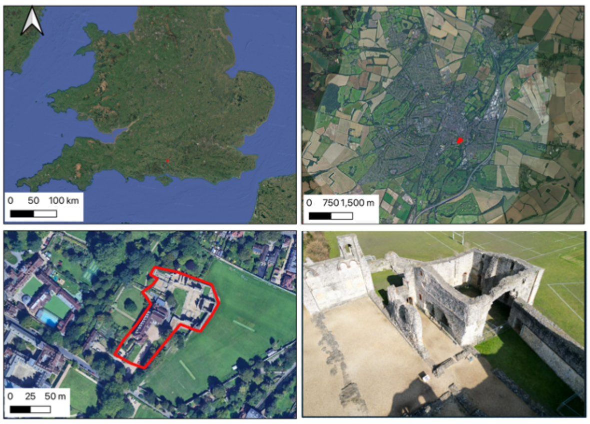

Fig. 1 Location map of Wolvesey Castle, Winchester, UK.

IV. DATA AND METHODS

Satellite imagery from Sentinel-2 and Landsat-8 was utilised to evaluate climate impacts on the historic castle site. Additionally, the Sentinel-1 radar interferometry product from the European Ground Motion Services (EGMS) was used to evaluate the site's stability[20].

Key spectral indices from Sentinel-2 were derived to assess the vegetation on the site, the moisture content of the structures, and the presence of water bodies over time. The Normalised Difference Vegetation Index (NDVI) is used to assess vegetation on buildings, the Normalised Difference Moisture Index (NDMI) is used to detect moisture, and the Normalised Difference Water Index (NDWI) is used to detect water bodies in the site. The spatial resolution of these indices is 10m×10m. Additionally, Land Surface Temperature (LST) was estimated using Landsat-8 thermal band with 30m×30m spatial resolution to identify surface heat patterns [21]. Landsat-8 is often used to calculate Land Surface Temperature (LST) to study how heat affects different regions. Although its spatial resolution is coarser than Sentinel-2 (30 meters per pixel), Landsat-8's extensive temporal archive and 16-day revisit time make it invaluable for long-term environmental monitoring. The combined use of multispectral and thermal data enables effective monitoring of environmental changes and supports the conservation of heritage sites under varying climate conditions.

V. RESULTS

Results using multispectral and radar satellite data are presented. These are primarily used to assess conditions employing publicly available medium-resolution satellite observations.

A. Land Surface Temperatures (LST)

Land Surface Temperature (LST) has been used to identify thermal anomalies in the urban environment. Summertime data was used, when higher temperatures are usually expected in built-up/urban areas. Fig. 2 shows large-scale observations where low temperatures, below 15 °C, are aligned with parks, and high temperatures/anomalies > 25 °C are observed in built-up areas. At Wolvesey Castle, a temperature of below 15 ºC was observed within the castle walls and up to 25 ºC around the castle.

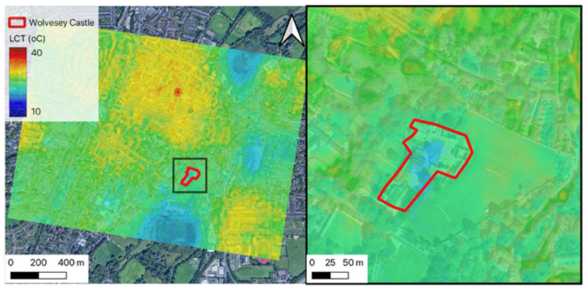

Fig. 2. Land Surface Temperature, Summer 2024. The red polygon shows the location of Wolvesey Castle.

The LST thermal maps can detect thermal anomalies at a large scale. However, they are not capable of detecting local variations around the ruin structure due to limitations in the spatial resolution of publicly available datasets. LST maps enable us to develop a holistic approach to tackle the heat wave in summer.

B. Spectral Indices

The common spectral analyses are demonstrated in Fig. 3. The NDVI is shown in Fig. 3a. It correlates well with green spaces and street trees. The castle walls show a relatively lower index value (< 0.2) that indicates low vegetation on the ruin structures. However, there is a higher value of NDVI in the middle of the castle that correlates well with the green spaces. The NDWI (Fig. 3 b) shows the patch of higher value (i.e. > 0.40). Similarly, NDBI (Fig. 3) shows a low value (< 0.5) inside the built-up area and a higher value (> 0.65). The NDMI serves as a proxy for the moisture in the ruined buildings. They show a lower value (<0.3) around the outside of the buildings.

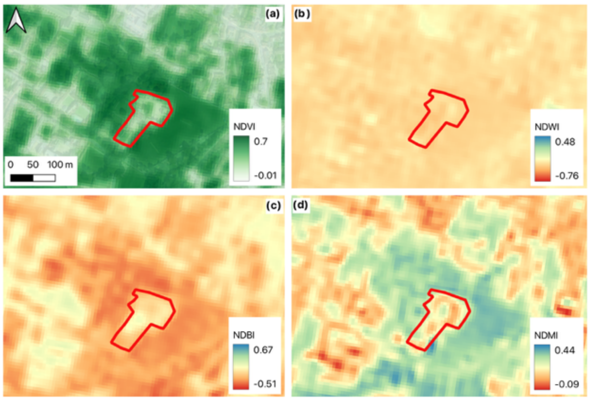

Fig.3. Spectral indices: (a) NDVI, (b) NDWI, (c) NDBI and (d) NDMI

Overall, the NDWI results demonstrate a complex water dynamic at the site. While outside the Castle walls, the environment remains arid, inside it exhibits pockets of elevated water presence that are further intensified during the warmer months. This seasonal fluctuation in free water—combined with the variation between vegetated and non-vegetated areas—serves as a reminder that even when vegetation retains moisture (as indicated by high NDVI and NDMI), it does not necessarily correspond to the presence of free, accessible water. Appreciating these nuances is crucial, as the accumulation of free water within the castle during spring and summer may heighten risks such as material degradation and potential land subsidence, ultimately affecting the long-term preservation of this historic site structure.

C. PS-InSAR

The Persistent Scatterer Interferometry (PS-InSAR) technique is a multi-temporal SAR interferometry [22, 23] which uses a stack of co-registered SAR images to reduce the effect of temporal and geometric decorrelations [24]. Temporal decorrelation on InSAR images comes from physical changes in the surface over the period between observations [25]. The PSI technique selects only those scatters that are consistent over a long period of time so that temporal decorrelation is mitigated [22, 23]. The PS points over the castle are very sparse (Fig. 4).

PS-InSAR is increasingly being utilised to monitor coverage on scales ranging from cities to entire countries. Fig. 4 illustrates the Sentinel-1 PS-InSAR analysis conducted by the European Ground Motion Services (EGMS). The spatial resolution of the produced data is 100 meters, and the number of PS points near the castle is notably limited. The time-series plots indicate a gradual subsidence at an average rate of 1.4 mm per year. The results also demonstrate that seasonal variations are present alongside the linear trend. To obtain detailed coverage of the castle, higher resolution radar observations (1-3 meters) are necessary. Radar data from CosmoSky-Med (Italian Space Agency, ASI) and/or Terra-SARX (German Space Agency, DLR) satellite constellations could provide enhanced information regarding deformation detection at the scale of a castle.

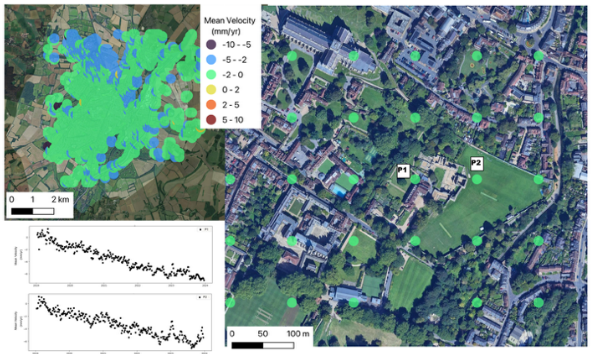

Fig. 4. PS-InSAR analysis using European Ground Motion Services (EGMS) data. The lower left panel shows the timeseries of P1 and P2 near Wolvesey Castle.

VI. INTEGRATION WITH STRUCTURAL CONSERVATION AND MONITORING

Roofless historic structures represent a critical challenge in heritage conservation, as their exposure to environmental factors accelerates deterioration and compromises structural stability. The case study of Wolvesey is used to showcase a comprehensive methodological framework for informing assessment, diagnosis, and mitigation of risks associated with these structures.

Remote sensing is undoubtedly a powerful tool for monitoring historic heritage sites; however, it has a drawback: remote sensing cannot detect every aspect of specific structural elements and does not replace traditional, on-site inspections as a stand-alone method. Indeed, the spatial resolution of satellite data may not capture very small features or subtle changes within the structure. This means that minor cracks or small-scale damage, which could still be significant, might go unnoticed.

A. Structural and Conservation Assessment

Based on the information gathered during the diagnosis, analytical assessment, such as limit state analysis and static equilibrium models, provides a rapid and straightforward method for evaluating structural stability. This approach is beneficial for predicting imminent collapse by assessing the critical points and overall integrity of the structure.

In addition to the analytical approach, a more detailed numerical analysis can be employed to examine the structural response under various conditions, including static loads and settlement or slope movement. This type of analysis focuses on both localised and global structural behaviour, offering a comprehensive understanding of how different factors affect the structure. To ensure accuracy, this approach requires a thorough understanding of the diagnosis and the assumptions made during this phase. These assumptions can be supported by established standards, relevant literature, and additional non-destructive testing (NDT) conducted in situ, if available.

Combining the information derived from historical analysis and structural/environmental assessments, using both traditional and modern methods, it is possible to develop effective conservation strategies and plans. These strategies aim to preserve and enhance the significance and value of the heritage structure, ensuring its longevity and continued relevance.

B. Maintenance and Structural Health Monitoring

To ensure the long-term stability of any proposed solutions, the methodology incorporates Structural Health Monitoring (SHM), adopting both standard and modern techniques while balancing cost efficiency and accessibility. Traditional techniques primarily involve direct measurement methods, such as the use of crack meters, to monitor the development and progression of cracks and regular site visits to inspect the structure and assess its condition visually.

In contrast, modern techniques utilise remote sensing as a vital monitoring strategy at both urban and structural scales, swiftly addressing environmental and climate change factors with high precision. This technology allows the continuous observation of structures and their environments from a distance using tools such as satellite imagery, drones and ground-based sensors.

Through integrating traditional and modern SHM techniques, the methodology becomes more thorough, comprehensive and robust. This can lead to early detection of potential problems and can inform more accurate and effective conservation strategies. These lead to the ultimate goal, which is to maintain the structural integrity and heritage significance of the monitored structures, making sure that they are appropriately preserved for future generations.

I. CONCLUSION AND FUTURE DIRECTION

The preservation of heritage sites, such as Wolvesey Castle, is crucial for maintaining cultural memory and the achievements of societies. This study has demonstrated the effectiveness of using medium-resolution satellite data to monitor and assess the structural stability and environmental risks affecting these sites. By utilising remote sensing technologies, including multispectral and thermal imaging, as well as radar interferometry, valuable insights into the conditions and stressors impacting heritage structures can be obtained.

The integration of remote sensing data with traditional on-site inspections provides a comprehensive approach to heritage conservation. While remote sensing offers a broad-scale, non-invasive monitoring capability, it is essential to complement these observations with detailed, localized assessments to capture minor structural changes that may not be visible in satellite imagery.

Future research should focus on enhancing the spatial resolution of satellite data to improve the detection of small-scale structural features and anomalies. Additionally, the development of advanced image processing techniques and machine learning algorithms can further refine the analysis of environmental parameters and their impact on heritage sites.

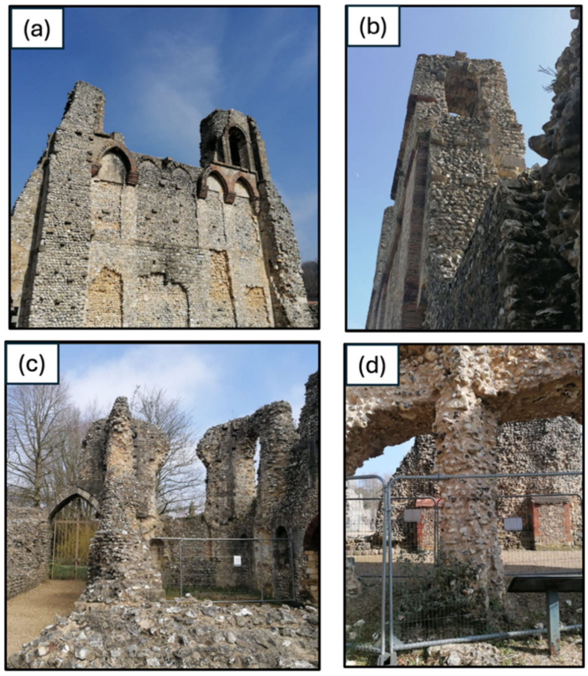

Fig.5. Wolvesey Castle Ruin Structures. (a) Free-standing wall with traces of ruined elements, (b) Rounded stones, low-quality material and no interlocking, (c) Slender structures with eccentric loads, and (d) Masonry degradation and stone falls.

Expanding the application of remote sensing to other types of heritage structures and diverse geographical regions will help establish a more robust framework for heritage conservation. Collaboration between remote sensing experts, conservationists, and structural engineers is vital to developing innovative solutions that address the unique challenges faced on heritage sites.

Finally, continuous monitoring and the implementation of Structural Health Monitoring (SHM) systems will ensure the long-term stability and preservation of heritage assets. By adopting both traditional and modern techniques, cost-effective and accessible conservation strategies can be created that safeguard the historical value and significance of these irreplaceable cultural assets.

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