Monitoring the state of conservation of Paimogo Fort - digital survey

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Abstract. This article discusses and presents the methods and results of the digital survey carried out, in 2025, of Paimogo Fort, a military structure built in 1674 in the municipality of Lourinhã. The digital survey aims to safeguard and monitor the conservation state of this classified coastal heritage site. Paimogo Fort underwent a conservation intervention in 2024 to preserve and strengthen the values of its individual and collective memory, transforming it into a meeting point for the memories of local communities and as a source for recovering and bringing awareness of traditional knowledge within the region.

1 Introduction

Paimogo Fort (or Fort of Nossa Senhora dos Anjos de Paimogo), classified as a Property of Public Interest, is situated on the cliffs of Paimogo Beach, on the Atlantic coast about 76 km north of Lisbon (Figure 1). It was built in 1674 by order of António Luís de Menezes, Count of Cantanhede, also known as the Marquis of Marialva and hero of the Restoration Wars. Its main mission was the defence of Paimogo beach, to prevent enemy troops from landing in that otherwise easily accessible point. It is a small bastioned fort of baroque military architecture, with a quadrangular plan and cylindrical guardhouses with conical roofs (Figure 2). This fort was part of Lisbon's second fortified defensive line, which began at Praça Forte, in the town of Peniche and extended to the mouth of the Tagus River. It is an almost unique example of a post-Restoration fortification without architectural alterations. With the end of the Civil War, the mission of the Fort of Nossa Senhora dos Anjos de Paimogo as a maritime fortification also ended [1].

With a regular floor plan and surrounded by walled grounds (Figure 2), the Fort was made up of a single body, with a rectangular strong house, slabbed yard and terrace, and, inside, a main body made up of three large rooms, where the barracks would be, and two other rooms, which would be used as barracks or armouries [2,3].

The Fort, as mentioned, is in a cliff area subject to strong coastal erosion, putting the south-western corner and the western end of the southernmost wall at risk of collapse due to the retreat of the cliff crest and the consequent lack of support for the foundations of these structures [4]. Therefore, its preservation and maintenance are of utmost importance, and the use of information technologies and new tools presents an opportunity that should be explored to enhance the safeguarding of this rich heritage.

Fig. 1. Paimogo Fort general views, in 2021.

This paper presents the methods and results of a digital survey carried out at Paimogo Fort in 2025. The survey aimed at documenting its current state of conservation and providing geometric information for 3D, parametric, and information modelling. This information, along with updated technologies, should be used for a detailed description of Paimogo Fort according to a multidisciplinary approach and a comprehensive data model. This should facilitate sharing knowledge regarding the history of interventions, contexts and actions, materials properties, and techniques required for informed decision-making on Paimogo Fort management and conservation.

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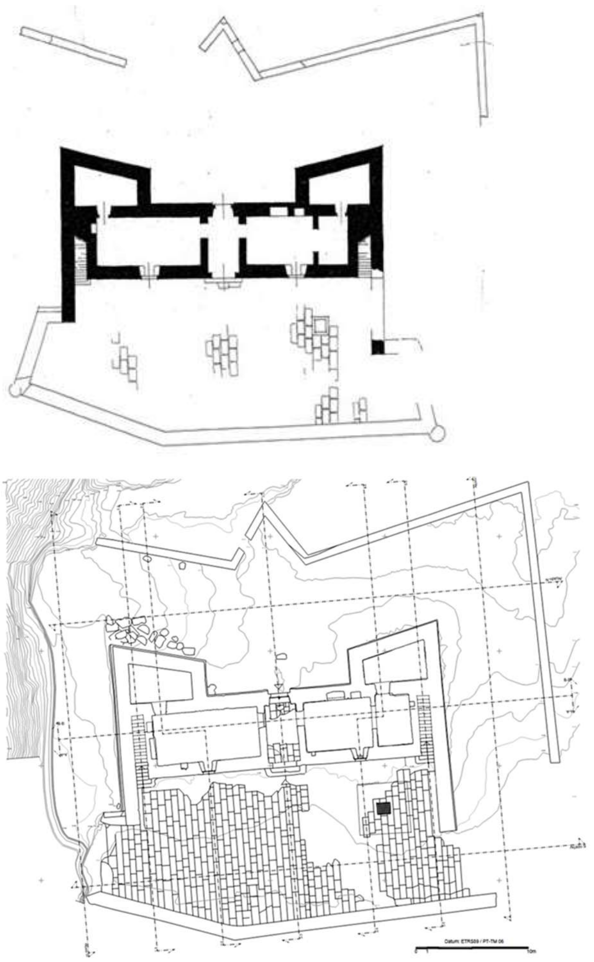

Fig. 2. Plans of Paimogo Fort: adapted from [2] (top) and from [3] (bottom).

2 Case study – Paimogo Fort and 2024 rehabilitation

2.1 Structure, state of conservation and original materials

The fort comprises a single-storey masonry structure, constructed from irregular limestone and sandstone, sourced from nearby quarries, bonded using traditional air lime mortar. Both the interior and exterior surfaces of these walls were originally finished with successive layers of air lime mortars, providing both protective and decorative functions. The vaulted ceilings in the interior were built using porous clay bricks, also coated with air lime plasters.

Investigations conducted by Veiga et al. [5] have revealed that the original mortars compositions (renders and plasters) were based on calcitic air lime combined with siliceous and limestone sands of coastal origin, including fragments of crustacean shells. Moreover, several lime lumps, measuring a few centimetres, were also found in the renders. These findings demonstrate the fort's reliance on locally available resources and construction techniques well-suited to its coastal environment.

Laboratory analyses of the original mortar samples [5] further demonstrated that the original mortars, rich in lime, exhibited favourable mechanical properties (mechanical strengths ranging between 2.5 and 5 MPa in compression), notable deformability, and a moderate capacity for water absorption by capillary action (capillary water absorption coefficient between 0.4 and 1.7 $kg/m^2 \cdot min^{1/2}$). However, during a 2006 conservation intervention, most of the original air lime renders were removed and replaced with mortars based on hydraulic lime. These newer materials have shown degradation phenomena, particularly erosion and loss of cohesion, detachment and hygroscopic salt efflorescence, as illustrated in Figure 3, largely due to prolonged exposure to harsh coastal climatic conditions, including salt-laden winds, humidity and high thermal amplitudes.

Fig. 3. Paimogo Fort, in 2021.

2.2 Recommended mortar solution for the rehabilitation

Given its cultural significance and vulnerability to environmental factors, the fort requires a comprehensive conservation strategy, which encompassed the diagnostic assessment of existing materials and structural conditions, followed by laboratory and in situ tests with the main objective of selecting an appropriate repair mortar composition to use.

The new mortar formulations should prioritise the use of compatible materials, employing lime-based mortars and plasters in accordance with the original compositions identified through laboratory tests. Furthermore, it is required that the new repair mortars should present good mechanical performance and durability to the aggressive environmental conditions to which the fort is subjected [6].

To choose the most feasible, compatible and durable repair mortars compositions, several lime-based mortars were developed, and their main physical and mechanical characteristics, in laboratory and in situ environment conditions, were analysed and compared [7-9]. Therefore, in this particular case study, a mix of slaked air lime with 30% of quicklime (by volume of lime) and 95% of siliceous sand added with 5% of fine limestone sand (d<1 mm), at volumetric ratio of (1:0.3):(2.5:0.1), lead to a balanced solution for the rehabilitation. This composition present relative high strengths, with moderate deformability, to accommodate stresses that might occur within the substrate without failing.

Moreover, it demonstrated a progressive improvement in performance during the carbonation process, which indicates a stable microstructural development with no significant cracking. Additionally, it is the closest to the original mortar composition, reinforcing its suitability for the rehabilitation intervention.

2.3 Rehabilitation features

The rehabilitation process began with structural consolidation by filling cracks with hydraulic lime grouts. Afterwards, the mortars applied in 2006 were carefully removed. After cleaning masonry surfaces, repairs of active water infiltrations were conducted, along with the construction of new water drainage channels and enhancements to the natural ventilation system. In addition, new windows were installed within the existing openings, preserving the original architectural configuration.

The new renders and plasters were applied in August 2024. Furthermore, for the exterior walls, in the finishing layer, an inorganic natural pigment, rich in Fe_2O, at 2% of lime weight, diluted in the mixing water, was added to the lime-based mortar selected [10]. This pigment gave to the render a pale rose tone (Figure 4).

Fig. 4. Paimogo Fort after the intervention work, in 2025.

3 Digital Survey

The main objectives of the digital survey of Paimogo Fort are: i) to document the current conservation state of the fort and cliffs in the first half of 2025, and ii) to provide the geometric data required for the 3D-HBIM modelling (HBIM-heritage building information modelling) of the fort.

The digital survey considers both the fort interior and exterior and is performed through two techniques: terrestrial laser scanner (TLS) and aerial photogrammetry with a drone. The TLS survey was already performed, while the aerial survey is currently awaiting authorization from the competent entities.

Leica RTC 360 LT was used in the TLS survey. The survey was divided into four main areas, with a varying number of setups (individual scans) for each of them: i) the interior of the fort (17 setups); ii) the area surrounding the fort (10 setups); iii) the terrace of the fort (10 setups); and iv) the cliffs (7 setups), surveyed from a road located at their base as presented in Figure 5. Figure 6 shows the scanner locations, for all setups, seen from the top, on the point cloud achieved through the survey and coloured by the registered photographs to show a natural colour (RGB colour).

The surveyed data were georeferenced to the national reference frame, through four targets (control points) placed on top of tripods, outside of the fort, and coordinated by GNSS RTK. These targets were scanned during the survey of the exterior and terrace of the fort.

Fig. 5. Laser scanner scanning the west side of the cliff.

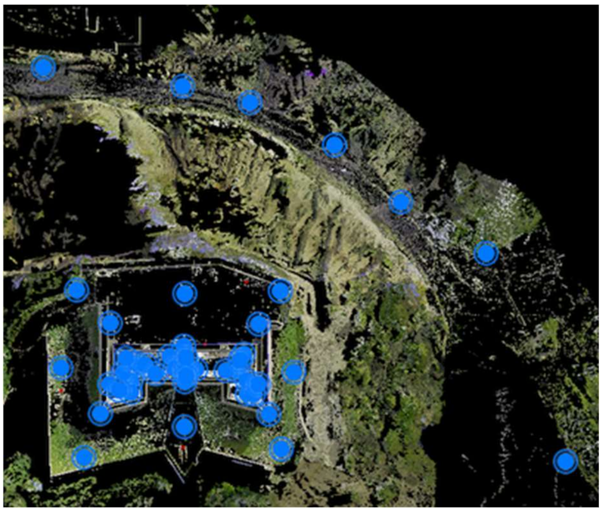

Fig. 6. Locations of the laser scanner.

The connection between the different setups and the control points was carried out in the software Leica Cyclone REGISTER 360. The point clouds were edited to eliminate unnecessary elements (the targets and tripods) and poorly located points due to the existence of water puddles.

During the survey, the intensity of the reflected signal is automatically recorded for each point. This information can be used to colour the cloud (instead of the usual RGB colour). This is also useful for highlighting certain anomalies on the surface of the construction elements. An example is provided, featuring a wall depicted in natural colour in Figure 7, and in Figure 8 coloured according to the intensity of the reflected signal.

Fig. 7. The interior of a room, natural colour.

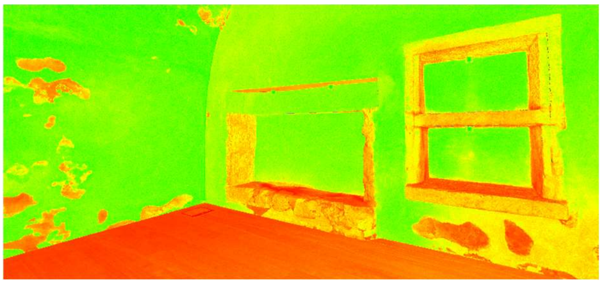

Fig. 8. The same area of Figure 7, with a colour pattern related to the intensity (from red, points with the lower intensity, to green, points with the highest intensity).

Several areas on the cliffs and top of the fort, not reached by the laser beams due to their position, will be covered by a photo survey with a drone DJI Matrice 300 RTK. The photos will be processed by Metashape Pro, and a second point cloud will be created. Control points materialized by canvas will be placed and coordinated by GNSS RTK. As the national reference frame will be considered again, the merging of the TLS and drone point clouds should be done without major difficulties.

A 3D model of the fort and the cliffs was already created, based only on the TLS data. As the final (merged) cloud is not created yet, the 3D model of the fort and the cliffs (Figure 9) was developed using a lighter cloud. On the other hand, as the interior of the fort has been fully surveyed, the final 3D model was already created as exemplified for one of the rooms in Figure 10.

Fig. 9. 3D model of Paimogo Fort and cliffs seen from SW.

Fig. 10. 3D model of one room of Paimogo Fort.

4 Conclusions and future developments

The results of mortar characterisation and the assessment of Paimogo Fort's conservation state were essential for providing recommendations for its rehabilitation. A new repair mortar composition was defined and applied in 2024.

Reality capture and 3D modelling, as exemplified in this paper, can accurately describe the geometric features, highlight unnoticed differences in materials, and aid in assessing and documenting the Fort's current state of conservation.

Additionally, to the 3D model, relevant data (e.g., historical, structural, materials, environmental) and monitoring, integrated within a comprehensive data model (spatial-temporal detailed), should facilitate knowledge sharing and enable collaborative efforts for the preventive management and conservation of Paimogo Fort.

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