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Stone materials and construction technology in the Piscinnì tower (South-western Sardinia, Italy): archaeometric investigations and digital survey

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Abstract

The tower of Piscinnì (WGS84: 38°54′15″N 8°46′40″E) is located within a beautiful coastal enclave on the coast of *Teulada* (South-western Sardinia). The mighty building stands on a promontory dominating the wild and suggestive panorama of the beach surrounded by Mediterranean vegetation. It was built at the end of the XVI century and still stands out for its size and conservation state. It had a great strategic importance since it was meant to guard both the landing area towards the valley behind, and the homonymous pond, exploited in the XVI century by the merchant Pietro Porta as a fish reserve. In the Spanish period (between the XVI and XVII centuries), the tower was reinforced and guarded by an armed garrison. The area was previously frequented by the Punic and Roman people, who set up several sandstone and conglomerate quarries, used to build the villages and port structures of the various coastal settlements, e.g., Bithia (near to Chia village). The tower of Piscinnì is set in a very lively jagged coastline, characterized by rapid transitions from one landscape to another: from fine-grained, whitish sand beaches (as the not-so-far renowned Tuerredda and Capo Malfatano) to gravelly coves, from "rias" and ponds to high cliffs of intrusive magmatic (e.g. granitoids) and metamorphic rocks. The research involves several interdisciplinary work phases: 1) petrographic and physical-mechanical analysis of the building materials (stones and mortars) to understand their state of conservation, durability and their source in the surrounding area; 2) digital survey of the tower using photogrammetric techniques and 3d Laser Scanner technology to define the geometric-structural aspects; 3) stylistic-architectural analysis of the building and the load-bearing structures to understand the technologies and construction phases and any static-structural criticalities.

Keywords: fortifications, chemical-physical degradation, conservation, lasergrammetry.

1. Introduction

1.1 Environmental context

The tower of *Piscinnì* or *Pixinnì* (or *Pixini*, or *Pichini* or *Picinin*) is embedded in the beautiful coastal enclave of *Domus de Maria*, within the *Teulada* coastline at the south-western tip of Sardinia (Fig. 1). This area has been frequented since Punic and Roman times (Auriemma and Solinas, 2009). The tower stands on a promontory dominating the wild and evocative panorama of beaches and Mediterranean vegetation and can be reached by a path from the coastal road to the shore. In addition to the main path, there are other footpaths that lead to two beautiful and isolated smaller coves, called Porto and Torre Piscinnì (Fig. 1, on the left), which complete the enchanting bay. North of the stretch of coastline there is the homonymous Piscinnì beach. The shoreline is constituted by fine white sand that plunges into wonderful crystal-clear waters that take on

Fig. 1 - Panoramic view of Piscinnì Tower and the landscape (Columbu, 2022)

shades between green and turquoise. Behind the shoreline is the large pond of *Piscinnì*, which recedes in summer, is rich in plant diversity and has become a site of community interest. Being an area devoted to livestock farming, it is common, especially in the off-season, to encounter grazing cows or goats, which 'relax' between pond and beach.

This area is an enclave of the Municipality of *Domus de Maria* within the Municipality of *Teulada* thus is very close (southward) to the earthly paradise of *Tuerredda* and *Capo Malfatano*, two of the most resplendent and celebrated *Teulada*'s jewels. Northward, the two splendid gravelly-rocky beaches of *Campionna* (named after the islet that can be reached by sea in front of it), and *sa Canna* (fishing pole) which takes its name from the fishiness of its seabed made up of heterometric rocks, from gravel to boulders. The whole stretch of coast is characterized by abrupt transitions from one landscape to another. *Rias* (i.e. drowned river valleys), sometimes hosting salty ponds inland, alternates with high rocky cliffs interrupted by gravelly coves, and with fine-grained, very clear sandy beaches.

The tower and aims of the research

The tower is rightfully part of the defensive system wanted in Sardinia by the Spanish kingdom and sanctioned by Philip II in 1587 (Pillosu, 1957; Montaldo, 1992). It was completed between the end of XVI and the beginning of the XVII century (Montaldo, 1992). Along with the tower of *Budello*, *Porto Escuro* and *Las Ganas*, it was built at the expense of the Cagliari merchant Pietro Porta to protect the staff of the tuna fisheries (see Pillosu, 1957: p. 16), and then ceded to the Administration that armed and garrisoned the towers. The tower of Piscinnì is thus distinguished not only by its size but also by its strategic importance since it was meant to guard both the landing place in the valley behind and the homonymous pond, exploited by Pietro Porta as a fish reserve (Columbu et al., 2020). In Spanish times the tower was reinforced and protected by an armed garrison. It has a truncated cone shape with a circular plan and a flat roof and, in its upper part hosts a single-domed, vaulted room with a central pillar. The only opening, at a height of about six metres, was accessible by a wooden ladder. A staircase obtained into the thickness of the masonry connects the inner room with the terrace. The tower is made up by stones with irregular shapes, consisting of sedimentary rocks (i.e., limestone, sandstone) and rocks of metamorphic origin. During the Punic period, and then in the Roman one, the low cliffs bordering the tower on both sides were sites of intense quarrying activity to produce sandstone ashlars, to be used for building's masonry, from the geological formation known as Tyrrhenian "Panchina". The coast still shows evident remains of this 2500 years-old exploitation, as squared surfaces, block-shaped recesses, and the original quarry floor. The main aims to reach are: I) petrographic characterization of the lithologies and mortars used in the construction of the tower, II) definition of the degradation processes and evaluation of the restoration interventions carried out in both historical and recent times, III) digital survey of the tower by 3d laser scanner technologies and photogrammetry to define the structural and architectural features of the tower that, being characterized by a stony central column and a conical structure (Figs. 2, 3), belongs to the 'sanzillas' category.

2. Geological setting

The Piscinnì area is characterized by the widespread occurrence of low-grade metamorphic rocks, belonging to the Variscan basement, locally overlaid by Quaternary sandstones. Metamorphic rocks are represented by the metasediments, intercalated with marbles and metavolcanics, of

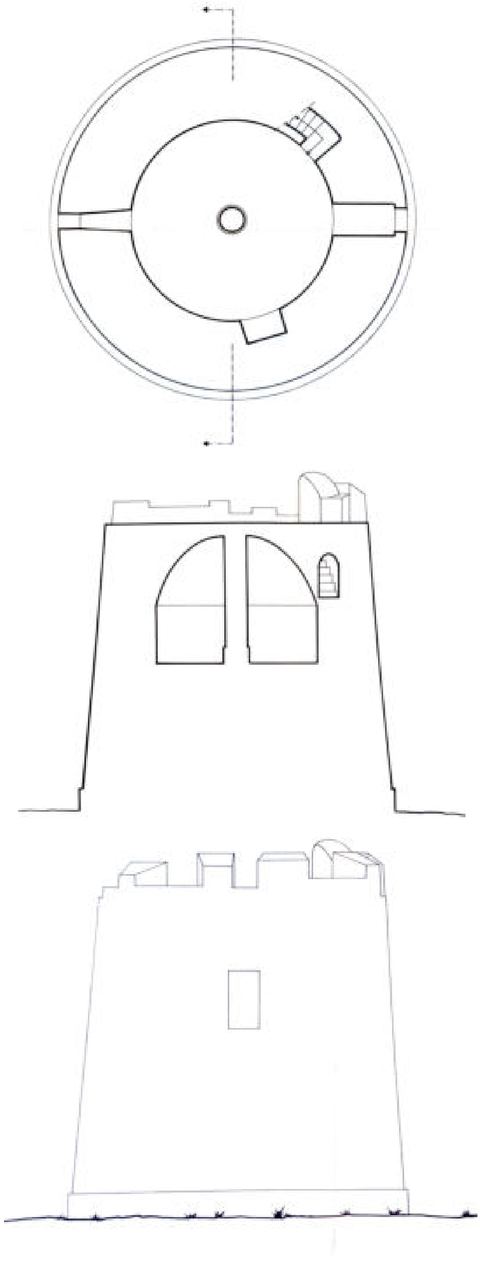

Fig. 2 - Plan, section and north elevation of the Piscinnì Tower (Montaldo, 1984)

the Bithia Tectonic Unit (BTU), an allochthonous unit of Upper Ordovician age (457.01 ± 0.17 Ma U/Pb dating on zircons from metavolcanic rocks; Pavanetto et al., 2012). About 1 km north from the tower, the BTU thrust over the para-autochthonous metasediments of the Nebida Formation (Early Cambrian) (Pavanetto et al., 2012).

Quaternary calcarenites, formed in offshore to backshore environments during the last MIS5 interglacial (Pleistocene), unconformably lie on the Variscan basement, marking a gap of more than 450 Ma. They are mainly made up of quartz, feldspars, lithic fragments and bioclasts with a carbonate cement. Calcarenite outcrops form a narrow (10 to 50 m in width from the coastline), discontinuous strip along several kilometres of coast. Its thickness varies from 1 to 5-6 m and, in vertical surfaces, and preserves sedimentary structures as cross-bedding and ripples. Calcarenites were exploited as building materials in Punic-Roman ages, as testified by several quarries, some of which in proximity to the tower of Piscinnì.

3. Methodological approach

The approach used in the study of construction materials and architectural aspects is based on different strategic intervention lines: evaluation of the formal and structural characteristics of the tower with dating the typological classification, analysis of the construction technique, lithological mapping, and analysis of the main petrographic and mineralogical features of stones and ancient mortars.

The lithoid materials (rocks, ancient mortars) used in the construction of the tower have been studied and analysed substantially on a macroscopic basis. In this first preliminary work, only the materials recognizable on the external surfaces of structure have been characterized. The macroscopic analysis of the entire external wall of the tower has also allowed the mapping and definition of the forms of degradation (e.g., exfoliation, flaking, alveolation, salt crystallisation, etc.) and to understand how the alteration processes of material evolve.

A digital survey by laserscanner and photogrammetry was carried out in June 2022 to obtain a digital model on which the sampling points, the results of the material analyses and the degradation forms can be placed. The digital survey establishes a link between the different approaches of this study. In addition, the survey has been extended to the surrounding landscape including the impressive cliffs on which the tower lays, the coastline and the remains of the

Fig. 3 - The tower rising over the ancient cliffs (Verdiani, 2022)

Punic/Roman quarries, in order to integrate the geological, architectural and historical investigation in their valuable natural scenario.

4. Results and discussion

4.1. Petrographic characterisation of stones and mortars

The Piscinnì tower is mainly built up with irregularly shaped, roughly squared ashlars, ranging in size from 10 up to 50 cm, bound together with a bedding mortar.

Discontinuous layers of more regular, flattened ashlars are placed at different heights, probably to set the horizontal plane during the building phase. The external wall was rendered with a lime-based plaster that was restored during the tower's history. The plaster is still preserved on the northward side (from NE to NW) hiding the underlying stones.

The nature of the ashlars can be seen in the SW to SE facing area where the plaster is almost totally ruined. They mostly consist of sandstone whose colour, grain size and sedimentary structures strongly resemble the nearby calcarenites outcropping around the coast.

Also, mineral phases, lithics and bioclasts, when recognizable at the naked eye or under a lens, match with those observed in the calcarenites from the quarries. Other rocks used in the wall are very rare irregular fragments of metasandstone and quartz pebbles from the Bithia Unit or from the basal conglomerate of the sandstone, consisting of reworked clasts of the same Bithia Unit. Finally, well-squared ashlars of a compact limestone form the jambs and threshold of the entrance door (architrave not visible) and the rest of the corbels that once supported the machicolation above the door. Fragments of the same limestone, probably belonging to the collapsed corbels, lies at the tower base; the macroscopic analysis suggests that they belong to the 'Pietra Forte', a Miocenic limestone outcropping in the Cagliari area that, thanks to its soundness, was commonly used to build valuable or fortified structures.

The study of mortars was carried out by subdividing them into: bedding mortar of stone ashlars (not always visible in situ), render mortars of walls, and plasters. The render mortars are used to close the centimetre-sized spaces between the stone ashlars and to prepare the substrate for the next finishing layer of plaster. From the macroscopic examination, it was not possible to understand whether they also act as a bedding mortars for the stone ashlars.

The bedding, as well as the render, mortars consist of a mainly silicate aggregate (almost totally quartz and feldspar), while the binder is lime-based (carbonates). The plaster mortars represent the external finishing that in the past completely covered the irregular truncated-conical wall of the tower. The presence of the original plasters is still observed in the north-facing part, but they have been likely reworked.

Fig. 4 - The 3D laser scanner unit at work in June 2022 (Verdiani, 2022)

4.2. Decay of materials

As above-mentioned, the decaying state of geomaterials strongly differs from one side of the tower to another. The northern area still preserves most of the plaster whereas, moving in both clockwise and anticlockwise directions, the plasters are gradually more disrupted, up to the southern side where it totally lacks. An exception to this general trend is represented by a vertical, metre-thick belt in the northern area, where the plaster is significantly less preserved. This is likely due to rainwater flowing along the walls from the entrance door, which is a preferred way for water flow, down to the ground level. The main degradation form of the plasters are exfoliation, cracking and detachment. The bedding mortars, where exposed, have low compactness, tending to grind into flour when touched by hands.

Stone ashlars, well visible in the southern area, are mainly affected by alveolation and locally flaking. The former is better displayed by the sandstone ashlars, while the latter effect is more evident in the metasandstone fragments where it is enhanced by the natural foliation of the material. Contrary to what is expected in a seaside environment, salt efflorescences are not well developed and can be locally observed at the base of the tower.

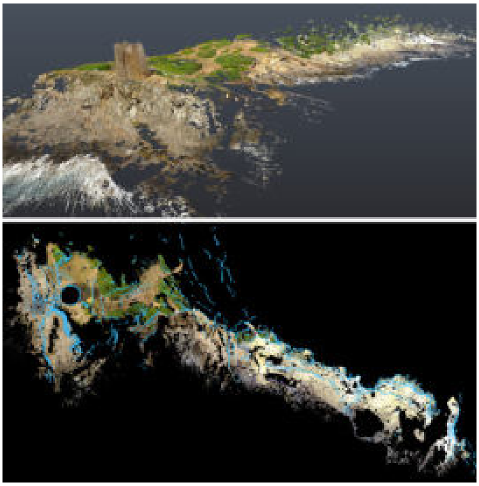

Fig. 5- The full point cloud with all the scans taken in the area aligned, perspective and top views (Verdiani, 2022)

Fig. 6- Front of the tower in orthographic projection, retouched point cloud with photographic colour mapping (Verdiani, 2022)

4.3. Digital survey

A very preliminary digital survey intervention took place in Spring 2022 and took care of the quarries area using a Cam/2 Faro Focus3D S120, a classic 3D laser scanner based on phase-shift technology and with an operative distance of up to 120 metres. This very first survey was operated in the quarry area with a total amount of just nine scans, taken in high resolution (1⁄4 setting, with up to 44.4 million points for each scan) and in medium resolution (1⁄5 setting, with up to 28.4 million points for each scan), all the scans from this session were taken using the photographic colours feature of this scanner.

The full dataset was then aligned using the software Cam/2 Faro Scene and later moved to Autodesk Recap. The second 3D laser scanner intervention took place in June 2022, with the full coverage of the external surface of the masonry of the tower and extended coverage of all the cliffs beneath the tower (Fig. 4) and along the paths until reaching the area of the first 3D laser scanner session. In this second session, a Cam/2 Faro Focus 3D 70s unit was used. This model has similar features to the previous one, it represents its evolution with higher accuracy in measurement and with an operative distance of up to 70 metres. The new dataset was based on 32 scans, taken once again with a resolution of 1⁄4 and 1⁄5 and using the photographic colour features. In this case, the files from each dataset were directly imported into Autodesk Recap and then aligned. Ending this phase, the two Recap projects were

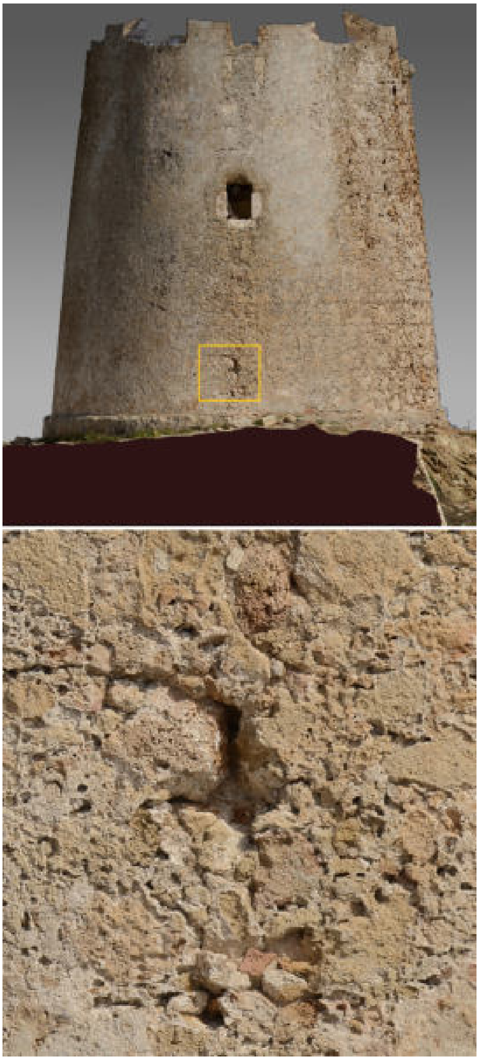

Fig. 7 - Main front of the tower, with the access to the upper room, from the terrestrial photogrammetry, general view and enlargement evidencing the quality of the details (Verdiani, 2022)

aligned together to form a complete description of the cliffs, the quarry, and the tower (Figs. 5-6). Even if integrated with the photographic feature, the overall point cloud was not fully satisfactory for the representation of the fronts in the scale of details. So, it was decided to integrate the 3D laser scanner intervention with a specific photogrammetry session, exploiting the best features of the active and passive procedures for capturing the reality (Rodriguez-Navarro, 2012). The session, operated from the ground using a Nikon D800e 36.3 Megapixel camera with FX (full frame sensor) mounting a Nikkor 24-120mm F4 zoom lens (used at 24mm), produced 309 shots covering the whole external surface of the tower with significant overlap.

All the pictures were processed using Epic Megagames Reality Capture SfM/IM software to produce one first complete 3D model of the external masonry using the classic process of alignment, polygonal surface creation, and texturing (Guidi et al. 2015). Following, a session of aerial photogrammetry was conducted using a Dji Mini 2, using the built-in camera at a resolution of 12 Megapixel. All the shots were taken according to programmed grids: two grids with the camera flipped at 90° (ortho-photogrammetry), one with a spacing of about three metres at 25 metres of height and another with about 1 metre spacing at 10 metres of height; a circular path around the tower targeting its central axis, at 15 metres of height and about 6 metres from the walls, taking a shot every 6°.

Another circular path at 10 metres of height was performed in manual flight mode to reach a further detail. This allowed to cover completely the top part of the tower and to have enhancement of the overall documentation of the landscape space around the fortification. Even in this case, the processing was operated using Reality Capture.

All the datasets coming from the 3D laser scanner, terrestrial and aerial photogrammetry were processed separately to check well their quality and possible weakness, and then the last processing was done by merging together the whole datasets into a single model with photographic quality. This last part was conducted using Reality Capture and exporting a final high-resolution model with full texturing.

The following steps in the data treatment provided the production of the classical orthographic representation of the four main fronts of the tower, the creation of a general top view in photographic and contour lines of the whole area, and a series of sections to put in evidence the relationship between the landscape and the tower.

Last but not least, the point cloud model defined in Autodesk RCP format was integrated with the information coming from the sampling, exploiting the annotation function available in Recap, using both the text comments, the links to online contents and the option for including images.

Fig. 8 - View from the inland of the tower and of the seafront it dominates (Verdiani, 2022)

5. Conclusions

Primarily, the research allowed to characterize the building materials (i.e., rocks, ancient mortars) used in the tower and to define their origin. Irregular stone ashlars of varying shape (only rarely they are pseudo-squared or appear in regular shapes) and size were used for construction: from under a decimetre up to about 50 centimetres.

The variable size, shape, and nature (from sedimentary to metamorphic) of the building rocks, suggest that the raw materials were derived from in situ reworked stones from the Punic-Roman quarries, mixed with newly quarried ashlars and with rocks taken from pre-existing ancient structures referable up to the mediaeval period.

The first hypothesis is supported by the fact that the most frequently used lithologies are sandstones and arenaceous conglomerates belonging to the Plio-Pleistocene formation (the so-called Tyrrhenian "Panchina"), widely exploited in the Punic-Roman period by massive quarrying activity, as can be seen in the vicinity of the tower by the numerous ancient original quarry fronts and plans still visible today. Subordinate local metamorphic rocks and occasional fragments of other rocks not belonging to the local outcrops were used as well. Regarding the degradation processes, it is possible to observe the presence of alterations, especially of the sedimentary facies (sandstones) and of the mortars, as they have a carbonate cement easily attacked by atmospheric agents, including the constant presence of marine aerosol (i.e., NaCl) and subordinately by the carbonic acid (formed by the interaction between meteoric water and CO2 present in the air) that dissolves the carbonate "cement" of sandstones and of the lime binder of mortars.

The degradation is concentrated especially in the south-facing part of the tower, also due to the increased incidence of solar radiation and wind that generally blows from the South, so in this case, coming from the sea. Adequate and statistically significant sampling and study of materials (currently not yet executed) could certainly resolve the constructive and stone-compositional aspects.

The complete and accurate survey of the area, missing just some 'impossible' parts, like those flooded by water pools, allows a clear description and measurement of all the morphology of the cliffs, quarry and of the tower itself. This creates a perfect base in which the information coming from the material studies can be placed, thus defining a perfect state of knowledge about the tower and its environment as it was in June 2022.

This work represents a valuable contribution, shareable with other scholars, and a perfect base for any kind of intervention, from the restoration to the accessibility enhancement and safety for the whole area. Such a documentation, already experimented in other contexts (Rodriguez-Navarro et al., 2015), should be a worthy base that, if performed following well-structured procedures, should represent a desirable tool appliable to any significant built heritage and for sure easily extendable to the fortification system along the Sardinian coasts.

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