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Digital survey for the structural analysis of the Verruca fortress

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Abstract

The paper deals with the documentation project of the Rocca della Verruca, a medieval fortress built on top of one of the peaks of the Pisan Mountains to control the valley of the Arno river; the fortress was fortified in modern times by the Florentines and was visited by important architects such as Giuliano da Sangallo and Leonardo da Vinci. The path of knowledge undertaken in the documentation of the structures, which are now in a state of ruin, are aimed at analyzing the superficial and structural conservative state of the fortress. The survey operations were carried out using the most recent digital instruments: laser scanner, aerial photogrammetry and ground photogrammetry. The resulting three-dimensional model, highly reliable, was useful for carrying out analyzes on the structure, from morphological to diagnostic and structural ones. A careful mapping of the cracking framework was performed and through the analysis of the real based models coming from the relief of the wall deformations; the cognitive overview has made it possible to clarify the state of structural conservation of the building.

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1. Introduction

The study that is going to be presented is part of a research project which purpose is to understand the heritage value of the Verruca fortress and its state of conservation. To better evaluate these aspects, it was necessary to undertake a cognitive path that, through historical, morphological, diagnostic and structural investigations, was able to provide a

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general picture of the architectural history of the building. The main results deriving from these analyzes will be addressed: they are all fundamental in order to correctly set up a conservation and enhancement project for the historic building. A knowledge process aimed at expanding the data on historical architectures is the only possible solution for the preparation of an enhancement project in line with the architectural characteristics and structural behavior of the artifacts. Knowledge thus becomes the main challenge: a knowledge that is transversal to academic disciplines, which requires the interaction of professionals specialized in the reconstruction of the historical, morphological, material and structural image of the artefact. Therefore, it is extremely important to carry out technical investigations, which return an image as accurate as possible of the analyzed building; in the case of the project for the enhancement of the fortress of the Verruca all these aspects have been investigated: a historical archival research has been conducted on the written sources, moreover, thanks to the intervention of specialized figures, precise archaeological investigations are planned aimed at identifying the stratigraphic wall units that are able to return the image of the building's evolution phases; the morphology of the fortress has been deepened down to the detailed scale thanks to modern technologies of digital survey, laser scanner and photogrammetry, integrating with high quality drone images; the diagnostic investigations have provided for an in-depth material analysis of the surfaces and their state of surface conservation, integrating the data with the investigations on structural conservation, reporting information on the presence of lesions and masonry deformations that allowed to obtain a picture of the mechanisms of the instability. From these main analyzes, of which the first results will be shown briefly, we can begin to envisage adequate measures aimed at the conservation and enhancement of historical architectures.



Fig. 1. General point cloud realized by laser scanner of the Verruca fortress.

2. Historical notes

The Rocca della Verruca rises on the summit of the homonymous mountain, which is the westernmost of the Pisan mountains: it is located in a strategic position which allowed to control the whole mouth of the Arno. Today's image from the top of the valley makes clear the great potential for control of the territory; however the current coast line, which is much more distant from the city of Pisa than in the past, does not express the importance of the fortress for the control of the pirate invasions, which in the early Middle Ages had caused serious damage to the Pisan economy and settlements [Dall'Antonia et al. 2001]; even the entire network of lakes and rivers, around the Bientina depression, which allowed the connection with Lucca, are no longer present today. In addition to the river traffic, the fortress was an excellent point of control for the main land routes that surrounded the Pisan mountains [Ceccarelli Lemut 2008].

In this historical-territorial context the first news of the Verruca fortress are found. In the Pisan mountain area most of the castles were built and remained in the possession of the imperial monastery of San Salvatore di Sesto, closely linked to the Marquis Ugo of Tuscany [Alberti, A. 2005]: thanks to his influence the monastery took the imperial diploma of Otto III in 996 [Kurze 1989]. On this occasion the possessions of the monastery are listed: among these the Verruca fortress, which had been donated to San Salvatore by Ugo di Toscana himself "pro rimedio animae suae", appears for the first time in a document: in the imperial diploma of Henry II of 1020 the ownership of the fortress is confirmed, while from the following one it no longer appears.

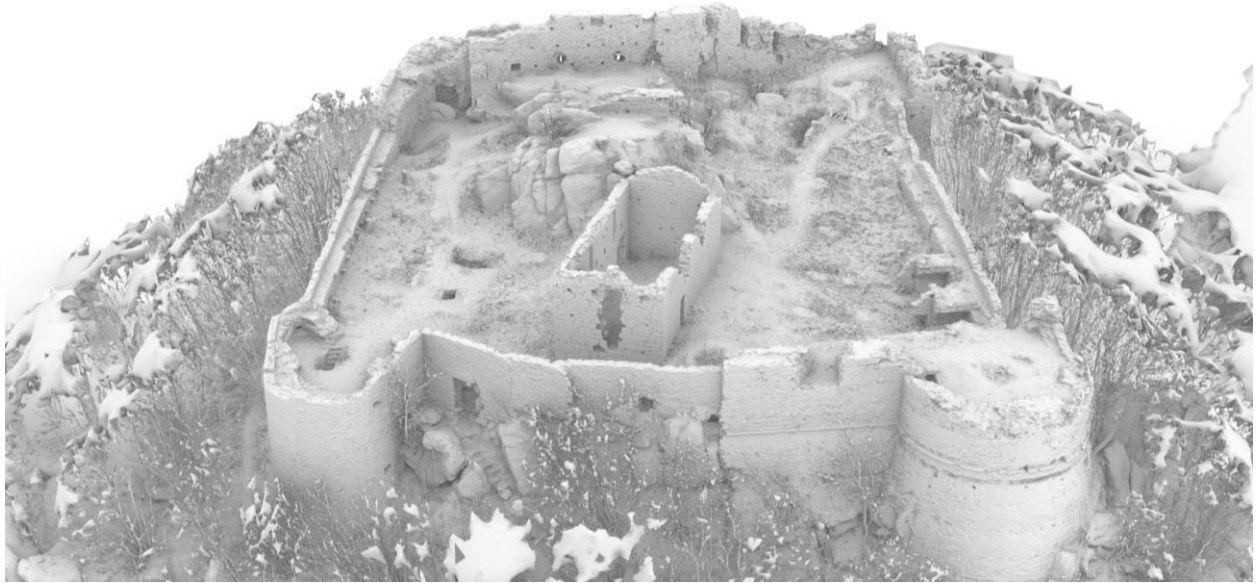


Fig. 2. 3D mesh model realized combining drone's pictures and laser scanner scan station.

The birth and development of the Verruca fortress are to be related to the events of the nearby monastery of San Michele, on which archaeological excavation campaigns have been conducted since 1996 which have discovered the entire site [Francovich, Gelichi 2003]: a first chapel linked to San Michele is attested from 861, owned by the Aldobrandeschi family, until the foundation of the monastery in 996. The fortress remained under the Pisan influence until the fifteenth century, when the Florentine rule began: the events of the siege of the Verruca fortress and the taking of the Pisan Mountains are narrated by Machiavelli in its "Frammenti Storici"; at the end of the fifteenth century, after the descent of Charles VIII into Italy, Pisa turned to the Florentines, causing a period of wars that ended with the definitive victory of Florence. During this period of conflict began the decline of the monastery of San Michele, which was used as a shelter for the troops who were alternately besieging the fortress.

After the Florentine takeover, the fortress was inspected by illustrious architects, such as Giuliano da Sangallo and Leonardo da Vinci [Pedretti 1972], who planned to improve its defensive structure: probably it was the moment when the medieval fortress began to be modernized with the insertion of circular towers and pentagonal bastions, in the same way as the other castles conquered during the wars: the modernization of the defenses was attributed to Luca del Caprina and Giuliano da Sangallo [Taddei 2007], despite the fact that no documents attesting to their work are reported. Interesting studies on comparative methods between designs, models and surveys of civil architectures made by Sangallo could also be adopted in the case of military architectures to verify the belonging of some of the Verruca structures to the master's design intentions [Frommel et al. 2018]. The end of the conflicts, the period of peace established by the Florentines and the increasingly less strategic importance of a defensive position, which was no longer on the border between two domains, quickly made the need for the garrison of the Verruca fortress vanish: it

was gradually abandoned starting from the 16th century, leaving the structures to deterioration caused by time and, in more recent times, by the strong fires that affected Mount Serra.

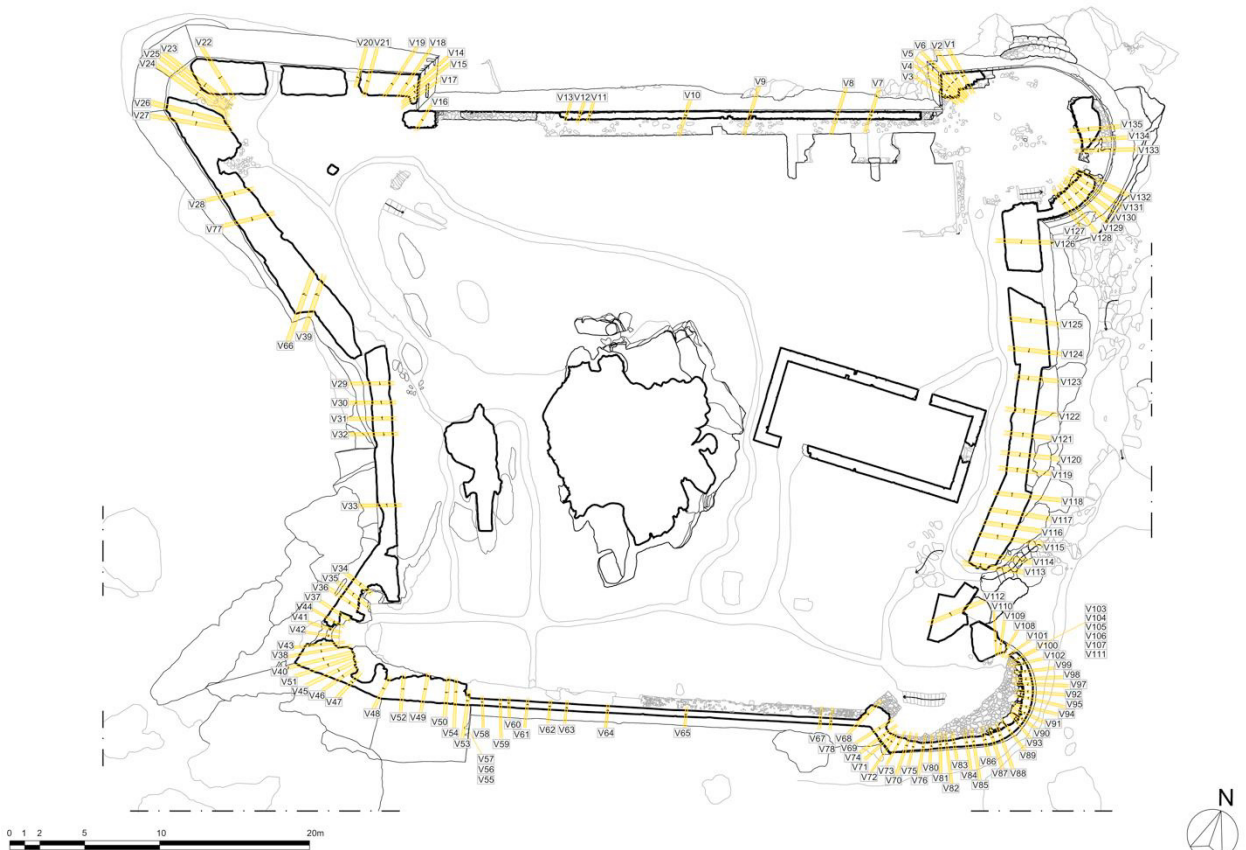


Fig. 3. Plan of the fortress with the drawing of the structural cracks on the walls.

3. The survey of the fortress and its geometry

The position of the Verruca fortress does not have optimal boundary conditions in order to carry out the measurement operations: the survey of the areas inside the enceinte is not as complex as the outside, which is arranged on a strong slope and with thick vegetation that does not facilitate the passage of operators and instruments. Some instrumental surveys have been carried out in the last decades, but the need for a detailed survey to interpret the state of conservation and the evolution of the building has led to the re-planning of a survey campaign.

The recent fires, which burned the top of Mount Verruca, have partly favored the creation of new measurement campaigns, using digital data acquisition systems: until now the fortress surveys have been carried out with older instruments such as total stations [Nicolosi 2012]. Three different acquisition campaigns were carried out: with laser scanner instruments to create a model that described the building's morphology, SfM photographic acquisitions from the ground to create three-dimensional models that describe the texture of the walls, and finally aerial photogrammetry with drone use, to create a mapped model of the whole complex [Volzone et al. 2018]. The data from different acquisition systems were used, integrating the information, to create the technical drawings according to the traditional system that provides for the extraction of geometries from the point clouds of the laser scanner, the materiality of the surfaces from the photographs and photogrammetric models: both databases were suitably subjected to data certification protocols, in order to verify the reliability of both the registration of the scans and the calibration of the

photographic orthoimages on the point cloud [Pancani 2017]. For each elevation, a 1:50 scale drawing was created in order to provide a useful technical tool for transferring diagnostic and stratigraphic analyzes.

From the drawings it was possible to understand the geometry of the building and the architectural spaces that compose it: the modern fortress is rectangular, with a single entrance facing east, towards the monastery of San Michele. There are no longer traces of roofing, whose structures should have been made of wood, leaving the walls completely uncovered. At the corners of the eastern side there are two circular towers - a typical corner solution of the military architecture of the late fifteenth century [Fiore 2019]- which house areas useful for the arrangement of light artillery for the flanking of the enceinte; from the north-east tower there is access to a gallery that leads to a further shooting position. The western corners instead present bastioned corner solutions, of different shape: the largest one is in the north-west, under which there are similarly low-level shooting environments which have been partially occluded and are therefore inaccessible; the minor one to the south-west does not have underground rooms, which have certainly been destroyed as evidenced by the gunboats on the sides of the bastion. The internal space of the fortress has a rectangular double-pitched building, and on the highest part, on a rocky outcrop, the remains of a medieval structure, probably the trace of the watchtower.

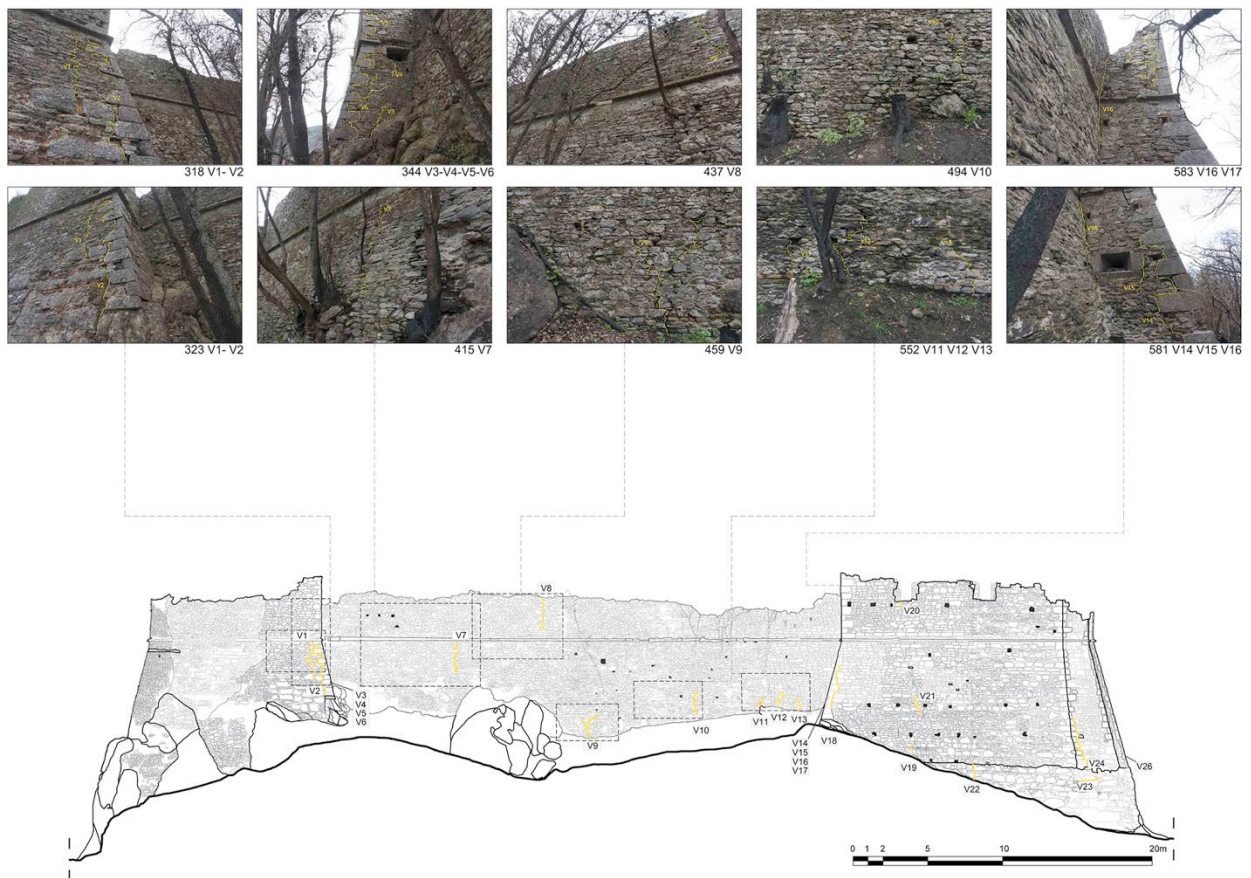


Fig. 4. West façade of the fortress with the drawings and the classification of the structural cracks

4. Diagnostic investigations

By an alteration of the original static model of a building disruptions can be triggered which alter its response to static stresses. The evidence of this process can be found precisely in the points of stratigraphic interface between two different phases, usually not completely well connected [Arrighetti 2019]. It is clear that today's structures are not all belonging to the same construction phase: there is no new unitary project, but as it is usual in the medieval period, the

buildings were only redesigned in part to be adapted to the new defensive needs. The Verruca was a watchtower, in visual relationship with a system of surrounding towers, and was fortified with the intention of resisting the typical assaults of the Middle Ages, with high walls and crenellations, where the shooting units were positioned; the building itself, located inside the fortress, which has at least three construction phases, all from the medieval period, has openings on the second floor (from the inside it is visible the arrangement of accommodation for beams that suggest the presence of a floor wooden) made to hide inside an archer and his weapon: the windows are instead embrasures. It is likely that the medieval castle had several entrances positioned on several levels: the tower, located on the top of the mountain, founded directly on the rock, is accessed by climbing through the spurs through boulders which, although ruined and eroded by time, reveal the presence of a staircase through a narrow passage: a transition to the final level of defense as can be found in many of the Tuscan castles [Francovich 1991][Arrighetti 2018].

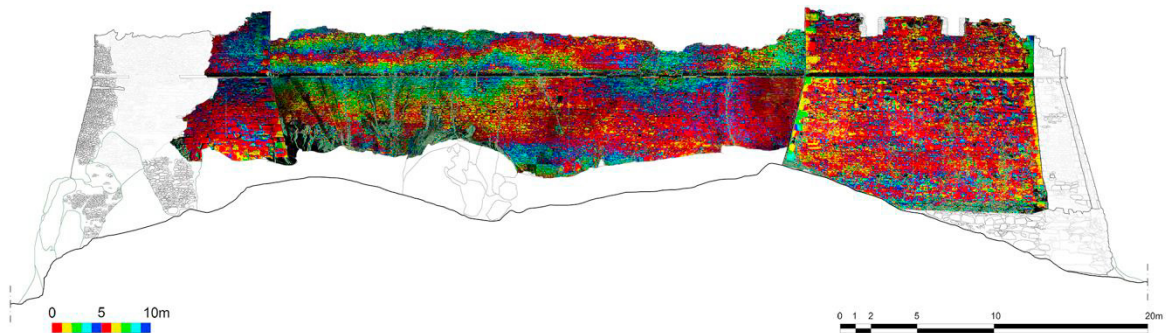


Fig. 5. Elevation map of the West façade, useful to understand the wall's deformation

The medieval fortress had walls surrounding the tower as quickly schematized in a Leonardo sketch: during the process of modernizing the defenses, the walls of the fortress were rebuilt and probably enlarged by adapting the wall sections to the resistance necessary to deflect the blows of the artillery; only the portions of masonry around the access door and the crenellation to the west are attributable to typical characteristics of the medieval period and can be considered part of the original walls. The rest of the walls is the result of an enlargement obtained with the construction of embankments. As is customary to expect from the enceinte of the fifteenth-century defenses, against them there was a system of barrel-vaulted galleries, orthogonal to the direction of any artillery shots, as in part is still visible in the northern sector. Understanding the evolutionary historical development of the walls of the fortress is important for analyzing its conservative-structural problems: the lack of roofing structures, or vaulted systems, with the exception of the rooms inside the towers and bastions still accessible, clearly reduces the possibility of encountering some types of damage as a result of static problems. The construction techniques of the fortress walls are of very different types: in general, they can be divided into two macro sets, the first typical of the medieval period and a second of the modern expansion. The oldest structures have a greater attention to the processing of regular and homogeneous construction elements, while the portions of modern architecture have very irregular elements and the almost total absence of horizontal texture. From a constructive point of view, therefore, the medieval walls in general as they were built should present fewer structural problems. The stone used for the construction of the walls is for the most part "Verrucana": a resistant metamorphic rock of sedimentary origin that was created in the whole southern part of the Apuan Alps. It must be considered that the regularity of the medieval textures, visible in the fortress, is distinctly different between the buildings, such as the portion of the wall of the tower still visible or the gabled building, and the enceinte, as can be seen around the door entrance or the crenellation: it is possible to see the composition of the core of these walls in the graft with the south-west bastion. The presence of the corner walls of the tower suggests the arrangement of its plant on the top rock. The construction phases of the internal building suggest a seismic problem, since following the stratigraphic interface lines it seems that a reversal action of the side façade has entered into a condition following the push of the roof pitches. Such hypotheses could be verified through calculation methods of the kinematic mechanisms of the now "archaeological" structures of the site [Galassi et al. 2018]. The masonry portions of the enceinte of the modern period have a very irregular wall texture, with stones of different material and size, which do not respect the

horizontal courses and with a large use of mortars to tie the masonry together. Only the advanced sides of the towers, which allow lateral flanking, and the angles of the pentagonal bastion reveal the use of square and regular Verrucana stone. The realization of the enceinte with construction materials of low constructive value is typical of construction of modern defensive architecture, which was not carried out by skilled workers and took place in very short times; defensive needs have always entailed the sudden fortification of the defensive perimeters, regardless of the construction of valuable architecture, as can also be seen in the corner walls of the small pentagonal bastion which has unworked corner stones along the side of the southern side.



Fig. 6. Structural restoration, made using bricks, of the defensive walls of the fortress

The irregularity of the walls and the high usage of mortar is also due to the awareness of the purpose for which the enceinte were intended, or to the resistance to the bullets of the enemies: in case of a attack or siege these architectures, if they had been hit, would have required restoration interventions. From the point of view of the defensive system, the highlights of the defense would have been concentrated in the bastions and towers that have precisely more regular and elusive walls. The characteristic inclined scarp, which allowed the architectures to resist the blows of the firearms, appears regularly on the northern side and in the pentagonal bastions; there is no trace of it on the southern side, where the wall rises vertically, a rather strange shape considering the different development of the fortification which could suggest an intermediate phase in the construction. The signs of subsequent restorations are evident, with strong presence of brick elements that testify to the restoration of the enceinte and the circular tower; these interventions could explain the presence of the sign of a previous cordon. The presence of numerous signs of intervention shows that in a specific period the fortress has undergone an important renewal or consolidation. The use of brick elements, to fill the lack of the walls, indicates a construction phase that is incompatible with the late fifteenth century, since in the walls, even if mixed and unworked stones, there are no traces of brick elements, except in the consolidations. It is conceivable that the restoration interventions are directly linked to defensive needs following the continuous struggles to conquer the fortification. To understand the structural behavior of the fortress it was necessary to perform an accurate mapping of the damages: the structural lesions have been reported, distinguishing their direction and their vector. It was useless to differentiate between passing and non-passing lesions since the majority of the structures visible from the outside are not reflected on the internal face, because they are buried and placed against the ground on the filling performed in the modern age: the analysis of the fortification lesions provides in this case information on the construction phases, since the walls are oversized compared to those of civil construction and, unless there are problems of subsidence of the ground, they do not risk static problems. The same problems have already been addressed in the structural study of Porta Nuova in Verona, where the structural problems were the trace of the gradual dismantling of the walls [Parrinello 2018]. In the specific case of the Verruca, deformations hardly have been caused by subsidence of the foundations since the walls of the fortress rest directly on Verrucana rock, which is very resistant. The foundations may only have had some problems of cohesion between the rocky layer and the walls right at the ground attack, where in fact fillings with mortar and bricks are recurrent. Finally, the loss of most of the roofing structures has canceled the thrust on the structures, even in the event of seismic events, one of the main causes of

deformation problems. The only movements that the structure can have are to be found precisely in its particular topographical and constructive condition, therefore in the strong presence of embankments, arranged on top of a mountain, where the wall structures, in case of movement of the mass of soil, can behave as retaining walls, risking to undergo strong deformations: excessive rainfall and the natural filling of the drains, which took place over centuries of neglect, prompted us to analyze this problem. To highlight the presence of any deformations due to the thrusts of the ground, the point cloud obtained by laser scanner was used directly, checking the displacement of coplanar points by drawing contour lines, (also known as elevation map) [Bertocci et al 2015]. The complexity of obtaining a deformation analysis from real based models of these structures is congenial in the morphology of the structures. The use of alternative systems for the study of complex geometries [Bigongiari 2017] does not allow the analysis of too detailed models such as that of the Verruca. No important deformations have been highlighted except in some cases for the parapets of the fortress, which are completely free from thrusts and more subject to natural actions which allowed to more quickly erode the binders.

5. Conclusions

This first review of the results of historical, diagnostic and structural morphological analyzes confirmed the strong need to be able to base conservative considerations on the certainty of a reliable and detailed architectural survey when dealing with the conservation problems of historical architecture. The creation of a high-definition morphological and photographic database made it possible to collect the information necessary for understanding the evolutionary history of the building and to understand even more in detail the conservation problems of the masonry over time, and therefore to be able to assume the main interventions necessary to make accessible and enhance the fortress of Verruca, whose historical and artistic value is indisputable. Aware of the need to deepen the static and structural considerations of the building, it is equally clear how important the information collection phase was for the purposes of static and conservative considerations; the project will have its conclusions deepening these aspects.

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