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4D recording and analysis: The case study of Nuraghe Oes (Giave, Sardinia)

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ABSTRACT

The work is related with reality-based 3D modelling and monument analysis. In this project we stressed the importance to use 3D technologies as a tool to improve archaeological research and to increase the production of information from archaeological data to 4D analysis and interpretation. The object of our research is a "nuraghe", a typical megalithic monument built only in Sardinia during the Bronze Age. The building, called Nuraghe Oes, is composed of one main tower and a basement – similar to a bastion – with two smaller towers; it shows peculiar features both in the internal and the external shape and it is well preserved. This project is related with the first season of stratigraphic excavation: after this, we have performed a 3D survey of the entire monument using an integrated approach. We used a TOF laser scanner for a massive data collection of the external and some internal parts of the monument and, overcoming instrument and accessibility limits, we integrated the data using image-based modelling. All datasets have been aligned in a dedicated software in order to produce a complete mesh. After the mesh editing, the model has been textured using HDR images. The high resolution and accuracy of the 3D model allowed us to highlight interesting details in construction techniques and, together with a structural comparison with other nuraghi, to esteem the original height of the main tower. Furthermore, we performed volumetric analysis to esteem the capacity of the stones collapsed inside the main tower for making hypothesis about the ancient/original aspect. Lastly, using information collected during a visual survey of the walls and the 3D analysis, we have been able to map some structural issues of the monument, like cracks or disruptions in the stones and in the masonry. All these analysis are useful to plan further stratigraphic interventions both from time and costing points of view, and to monitor the health of the nuraghe over time.

Contents

1. Introduction

The case study is related to a "Nuraghe", a bronze-age megalithic building. A Nuraghe is a type of monument only built in Sardinia (Italy). It symbolises Sardinia and its distinctive culture,

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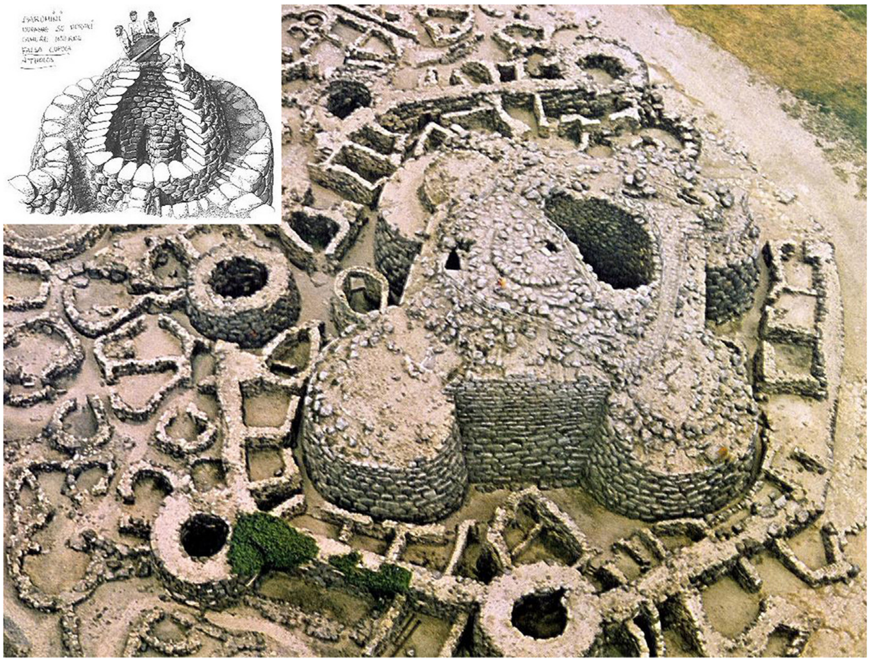

Fig. 1. Nuraghe Barumini and a drawing of Francesco Corni showing the corbel vault.

the Nuragic Civilisation, developed between XVII and VI BC.

As we can see in the Fig. 1, a nuraghe is a building made of huge stones and can have either one tower or multiple very complex towers, as does the most famous nuraghe in Sardinia, the Nuraghe of Barumini (an UNESCO World Heritage Site) which is composed by five towers and a nearby village of 50 circular huts.

In the most common type of nuraghe, the towers have internal rooms, one above the other, built with a *corbel* vault, similar to the Greek *tholos*.

A nuraghe has the function to control the surrounding territory, but each nuraghe has a different architectonic structure (one tower or multiple and complex towers) depending on the context, the geographic position and the chronology.

1.1. State of the art

The 3D recording is characterized by several methods and techniques used in relation to specific needs, without a systematic use procedures. Nowadays the most common techniques used for 3D modelling are based on terrestrial laser scanner (range-based method) and photogrammetry (image-based method), in single or integrated use. During the past decade different research groups tested the advantages and disadvantages of both approaches[1]. Laser scanners have been tested within various archaeological projects and the possibility of recording excavations and buildings in three dimensions has attracted great interest amongst archaeologists. Today the use of laser scanning can be considered a proven technology whose precision in the process of data modelling has been widely declared and verified in the field. However, the use of this instrument for archaeological purposes it is still sporadic, due to high cost of instrumentation, along with the inherent complexity of the processing and management of data.

In recent years, however, the advent of photogrammetric software based on multi-image photogrammetry (Structure from Motion) has gradually made three-dimensional digital recording accessible and practical within the documentation process to archaeologists. New processing algorithms of image matching allow to obtain image-based surface models in automatic or semi-automated way with an accuracy and detail level that can be surely compatible with 3D scanner clouds in terms of point density and accuracy (Fassi et al., 2013). In the last years, the availability of commercial packages software that automate the restitution process of images is creating a sort of revolution in cultural heritage; it is making faster their use as well as more accessible to largest users, allowing archaeologist to directly manage the acquisition and processing tasks.

In several projects has been used the integration of sensors and data (multi-sensor data fusion): the combination of the methods is considered a good solution where each technique has attributes and elements that balance one another, in particular when surveying large and complex sites. (Gonizzi Barsanti et al., 2012; Fassi et al., 2013; Guidi et al., 2008; Remondino et al., 2009; Remondino, 2011b).

In Sardinia, the use of 3D recording in archaeological sites is quite rare. In fact, traditional "bi-dimensional" survey is still the most common approach to produce the documentation of archaeological sites or buildings, especially in a prehistoric contest.

When the Project of Nuraghe Oes started in 2012, the 3D recording methodology was one of the first applications in Sardinia that allows to obtain detailed graphic documentation of the state of the nuragic monument and make 3D/4D analyses increasing the knowledge process about the megalithic building. We optimised the 3D documentation process using both photogrammetric and laser scanning techniques. In fact, as previously said, the integration of various geomatic techniques is nowadays an important requirement to produce complete 3D models.

In 2012, the 3D metric survey of Nuraghe Tanca Manna (Nuoro) has been also developed during the archaeological excavation of the site (Fiorini, 2013). As in our research, Tanca Manna 3D survey follows the same idea to make a scientific and detailed documentation of the monument for its study and analysis. For the study of Nuraghe Tanca Manna, a photogrammetric approach has

[1] For recent researches e.g. Arrighetti and Cavalieri, 2012; Benedetti et al., 2010; Caldarelli et al., 2012; Callieri et al., 2011; Campana et al., 2008a; Campana and Remondino, 2008b; Campana et al., 2009; Campana et al., 2012; Campana et al., 2014; D'Andrea and Barbarino, 2012; Forte et al., 2012; Gonizzi Barsanti et. al., 2012; Neubauer and Doneus, 2008; Panella et al., 2011; Peripimeno, 2009; Remondino and Rizzi, 2010; Remondino, 2011a; Remondino, 2011b; Russo et al., 2011. For a *summa*: Campana and Remondino, 2014; Cowley and Opitz, 2013.

been applied by archaeologists.

In recent years other few cases of 3D recording are the TLS surveys of Nuraghe La Prisgiona (Arzachena) in 2013, Abini archaeological site (Teti) in 2013, and the nuragic village of Sant'Imbenia (Alghero) in 2014. All these 3D surveys are still unpublished. The three-dimensional approach is often a test during an excavation in which the archaeological documentation is mainly made by the use of a total station.

Other 3D surveys are related to case studies on historical buildings, especially from an architectonic point of view (Columbu and Verdiani, 2014), but recently also from an archaeological approach (Lai, 2015).

This research focused also in volumetric analyses. This type of approach is an innovative and significant aspect in Sardinian archaeology, but also in Archaeology in general. In fact, in this project we explore the "third dimension" as to help the archaeological interpretation of the original structure of the nuraghe.

1.2. Description of the monument

The nuraghe analysed in our research is called "Nuraghe Oes" and it is located in the municipality of Giave (Sardinia, Italy). The nuraghe is visually connected to a more known nuraghe, Santu Antine (municipality of Torralba), located about 1 km South-East. The structure had the function to control some passages into the Campo Giavesu valley.

Nuraghe Oes is a so-called "complex nuraghe" composed of a three-tower basement connected with a main tower on the North-West side (Fig. 2). The basement, defined as a *frontal addition*, consists of two bigger towers and a completely collapsed smaller tower. The basement also encloses a courtyard.

In July 2012, the Soprintendenza per i beni archeologici per le province di Sassari e Nuoro, which is the Sardinian agency of the Italian Ministry of Culture that preserves archaeological monuments, carried out a stratigraphic excavation.

The aim of this first season of archaeological investigation was to dig out the huge collapsed stones that covered the Southern tower of the basement and the courtyard in front of the main tower. In this tower archaeologists have discovered a well: the position in the centre of the tower is quite unusual, in fact, we usually find this type of structure in the courtyard, not in a secondary tower. The well is 1 m in diameter and about 3 m deep.

The pottery, especially some fragments found on the courtyard paving, allowed the archaeologists to confirm that the original monument was quite ancient. The monument was probably built during the late Middle Bronze Age and then it was reused during the Roman period. The results of the excavation are still unpublished.

The basement is not completely accessible: the ruins of the northern tower still have to be excavated, as well as the main tower of the nuraghe. In fact, the main tower is now accessible through a window located on the first floor level from where the remains of the internal spiral staircase can be climbed to reach the remains of the top level.

At the moment, the diameter of the main tower is 16 m and its height is 11 m. It is composed of three rooms, one above the other, connected with the spiral staircase.

The peculiarity of Nuraghe Oes is to be found all around the internal walls of the rooms, in the southern tower and in the main one, where an offset that had the function of supporting a wooden floor can be seen. This nuraghe does not have rooms with *corbel* vaults. It is quite unique in Sardinia.

2. 3D recording and 3D modelling

The geometry found in the architecture of Nuraghe Oes is extremely complex because of its circular structures formed by stone dry walls with a considerable space between them. The basement is problematic to record. It has many occlusions, a well for water, tunnels, and niches in very complex shapes. This kind of archaeological site required the use of multiple techniques in order to correctly detect the geometry (Fig. 3).

We chose a Time of Flight laser scanner for a massive data collection of the structures. The survey was performed using a variable resolution between 10 and 5 mm, depending on the type of element detected. Totally 24 scans were performed, recording about 44.5 million points. Some areas, like the well, the niches and the internal walls of the main tower are unreachable carrying the laser scanner (weight ca. 25 kg); to overcome this limit we used an image-based modelling technique. We used a calibrated Canon 50D with 15.1 Megapixel and CMOS sensor, equipped with 17 mm lenses kept at the widest setting. The distance between the camera and the object was variable, depending on both available space

Fig. 2. Frontal view and plan of the archaeological site Nuraghe Oes.

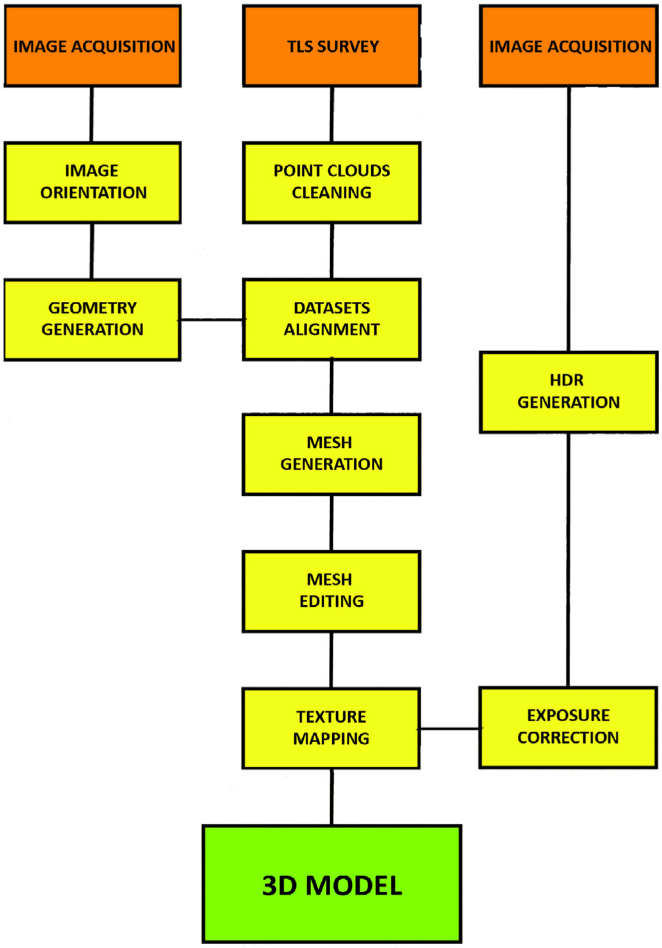

Fig. 3. Pipeline of the 3D recording and modelling.

and the shape of each surveyed element. The spiral stairs connecting the first floor with the top in the main tower were impossible to record since it was too narrow to capture nadir/convergent images. Finally, the same digital camera was used to record HDR images of the entire monument, in order to produce high-resolution textures.

Image-based datasets and range-based scans have been processed in order to produce a global mesh of the archaeological site.

The resulting mesh needed some editing tasks to correct defect and close holes. The shape of the collapsed stones of the towers and grass located between them requested a lot of editing in order to close holes and fix defects. Another time-consuming problem was the space between the stones of the drywalls, which in some case was more than half metre deep and in several cases needed a long manual reconstruction. The internal upper room of the main tower, partially obstructed by vegetation, as well as the top needed a manual reconstruction. The resulting mesh had about 16 million triangles. In order to proceed to the texture mapping, we reduced the mesh by 60%. Approximately, we produced and projected textures on 3D model 95 HDR to represent a photo-realistic high-resolution 3D model of Nuraghe Oes (Fig. 4).

3. 3D/4D analysis

If we compare the resulting 3D model to traditional archaeological documentation, we can appreciate that the 3D give us some advantages in archaeological analysis:

1. A very high level of precision and accurate documentation;
2. The possibility to edit sections, plans, and any other measurement at any moment and in any position;
3. An objective and standardized documentation, useful for improving the typological comparison of the same kind of structures;
4. A permanent link between object and research to develop interpretations using an open space very close to reality;
5. Very precise instruments allowing the personnel caring for monuments to easily check in detail the state of the building throughout time.

Through the high-resolution 3D model, we performed a very detailed architectural analysis of the monument and we produced detailed plans, sections and prospects (Fig. 5).

The masonry technique is particularly accurate, with well worked stone blocks. In the first three rows, blocks are considerably huge in size and irregular in shape; ascending to the top, the squaring of the sides of the blocks becomes more accurate and the size of the rows decreases to an average height of 30 cm from the mid to the top of the tower wall. The inclination of the wall at the base of the main tower is about 11–12 degrees. The first 3–4 rows are more flared while the rest of the wall shows a constant slope.

The building material is a local volcanic stone called *ignimbrite*.

We can appreciate that the main tower is mighty and wide in diameter, so we can hypothesise that it consisted of more than two rooms, one above the other. We propose some preliminary considerations and interpretations about the missing part of the principal tower of Nuraghe Oes.

If we want to make a comparison with some other well-preserved main towers of complex nuraghi, we have to take in consideration that the Nuraghe Oes main tower is one of the most architecturally impressive. The comparison is only structural, not typological nor exhaustive.

We observed five well-preserved nuraghi: Nuraghe Santu Antine, Nuraghe Santa Barbara, Nuraghe Orolo, Nuraghe Orolio, and Nuraghe Nuraddeo (Fig. 6).

1. *Nuraghe Santu Antine (Torralba).* It is a nuraghe situated nearby Nuraghe Oes in the Campu Giavesu valley. The main tower of this building has a diameter of 15.50 m and has a series of three rooms, one above the other. Today, it is 17 m high.
2. *Nuraghe Santa Barbara (Macomer).* The tower diameter is about 13 m. It has two remaining rooms.
3. *Nuraghe Orolo (Bortigali).* Its main tower diameter is 14.90 m

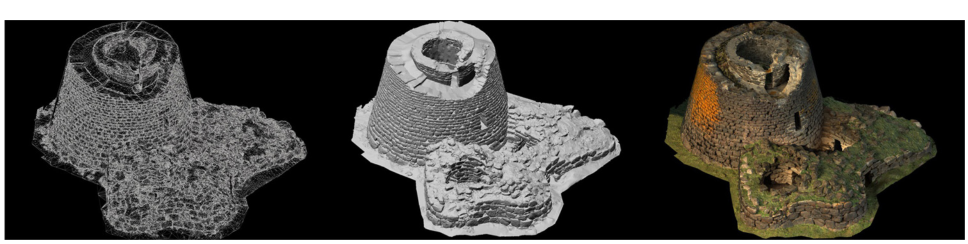

Fig. 4. 3D model of Nuraghe Oes.

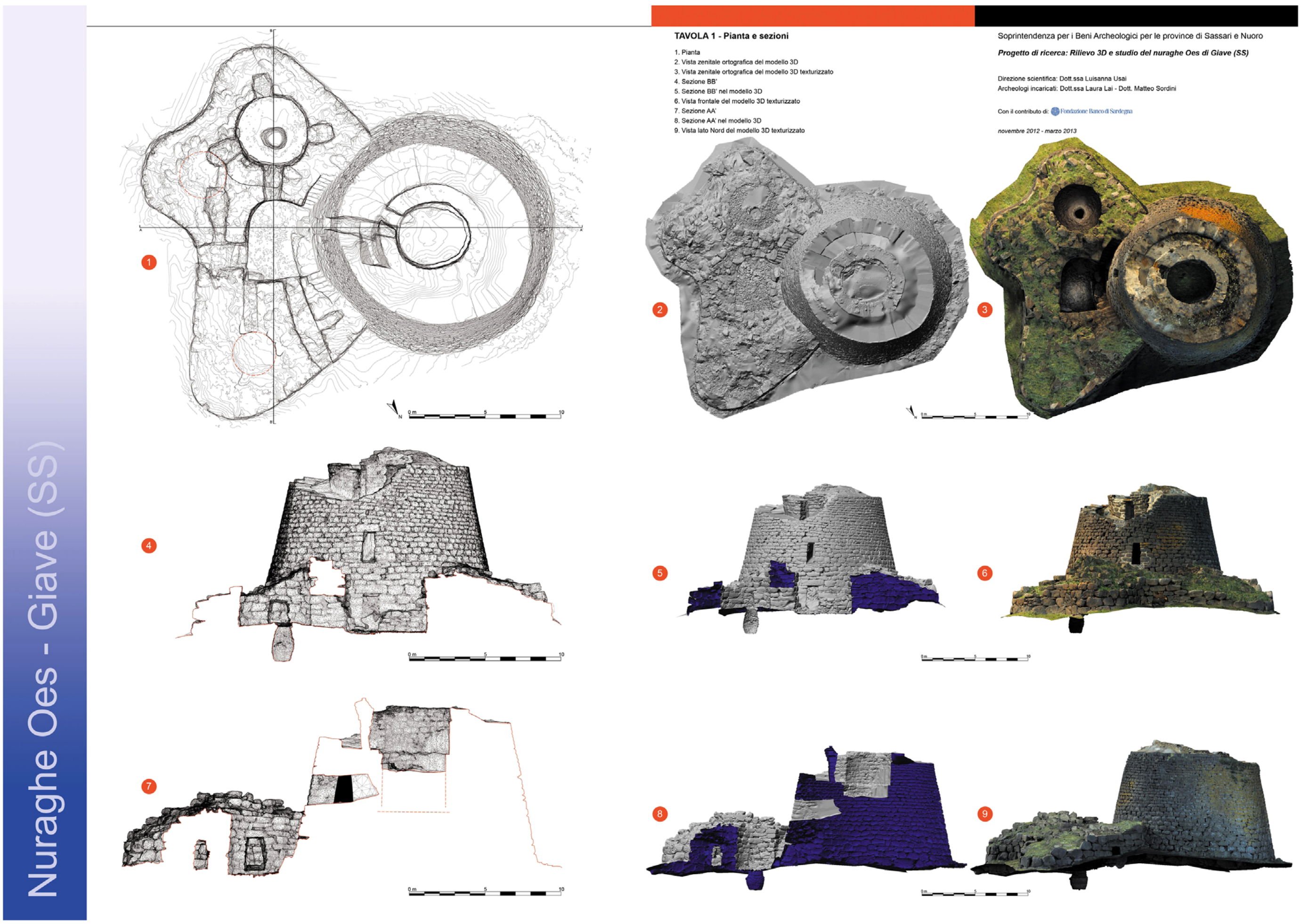

Fig. 5. Technical drawing in A1 format with plan and sections views in wireframe, non-textured, and textured mode.

and there are two rooms. Today, the tower is 14 m high.

4. *Nuraghe Nuraddeo (Suni).* The diameter is about 11 m, the remaining height is 12.35 m, and we can see two rooms, one above the other.
5. *Nuraghe Orolio (Silanus).* In this monument there are a 12.60-metre diameter and two rooms. The remaining maximum height is 11.50 m.

In this type of analysis we had an objective difficulty because we made a comparison of totally excavated main towers, whereas the main tower of Nuraghe Oes is still not excavated. Furthermore, it is important to take in consideration that these listed nuraghi are built using corbel vaults, so this type of structure can influence the architectonic development of the monument. There are few examples of nuraghi built with wooden floors and, unlike nuraghe Oes, they are badly preserved so they are not particularly significant to our analysis. However, we think it is interesting to compare two of these nuraghi: Nuraghe Funtana (Ittireddu) and Nuraghe Porcarzos (Borore).

In the first case, the main tower diameter is 18 m, and in the room at the ground floor, at a height of 5.10 m, we can see the offset for the hypothesised wooden floor. The second floor room is almost completely collapsed.

Nuraghe Porcarzos is a really interesting example. Today, the remaining maximum height is only 6.20 m, but this nuraghe has never been excavated, many collapsed stones are all around the monument and inside the structures. Certainly, there is much archaeological stratigraphy to be excavated. Archaeologists hypothesized that the main tower could reach more than 13 m in height and could have had at least three rooms with wooden floors, one above the other, because two offset are clearly visible from the internal walls of the second floor room (Moravetti, 1998).

We also analysed the monument from the point of view of the volume to build a more solid interpretation.

Using the 3D model, we approximately calculated the capacity of the stones collapsed inside the main tower. By assuming the absence of niches on the ground floor as well as including the volume of the access tunnel and hypothesising a sub-rectilinear shape of the internal non-visible walls, we calculated the presence of about 80 m^3 of stones. Consequently, any metre of the wall in the inner circumference of the upper room would require about 18 m^3 of stones.

These numbers lead us to think that the main tower could have been 4 m higher than what we see now (about 11 m), but through the typological comparison with other nuraghi, we can also propose different interpretations about the missing part of the structure:

1. The third room originally had a *corbel* vault similar to the most common rooms in the nuraghi, and the room was higher than the other two (about 5 m height, like Nuraghe Funtana);

2. There was a fourth smaller room above the third room;

3. There was an open-air structure built on the top of the tower above the third room, as we can see in numerous sculpted models of nuraghi found during archaeological excavations of nuragic contexts.

Only through a stratigraphic dig it will be possible to acquire more information for a better understanding of these aspects and to propose a more reliable interpretation. The measure of the

Fig. 6. Photos, plans, and sections of complex nuraghi: 1. Nuraghe Santu Antine, Torralba; 2. Nuraghe Santa Barbara, Macomer; 3. Nuraghe Orolo, Bortigali; 4. Nuraghe Nuraddeo, Suni; 5. Nuraghe Orolio, Silanus (Photos nr. 1, 4, 5 by G. Alvito from Moravetti-Alvito (2010); nr. 2, 3 by L. Lai; all plans and sections from Moravetti (1998), except nr. 1 from Moravetti-Alvito (2010)).

volumes can also help to plan further interventions in terms both of working time and cost.

Lastly, through a visual survey of the walls on the field and the high resolution 3D mesh we have been able to map some critical structural problems.

The main tower has three zones of instability in the external wall; one of these is around the window of the first floor (Fig. 7). Many cracks have been highlighted in the main entrance architrave, the courtyard architrave, the north tower access corridor, the room placed on the left of the basement entrance, and one of the niches in the south tower.

Mapping structural factors can give us quantitative information

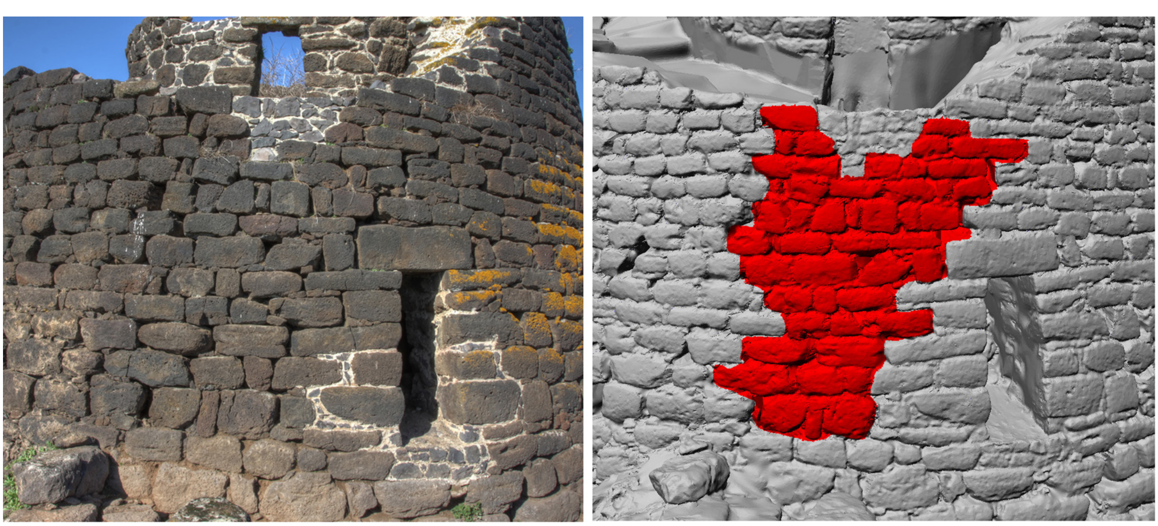

Fig. 7. Mapping of critical structural problems.

starting with qualitative information based on the visual survey, which is useful to plan intervention and to monitor the health of the monument over time.

4. Conclusions and next developments

The project illustrated in these pages is the starting point of a new approach in trying to carry on archaeological research, protection and evaluation of Sardinia's nuraghi.

The integration of various geomatic techniques allowed us to record a very complex building in all different measurable condition. The project showed, at the same time, the need of an UAV (Unmanned aerial vehicle) in order to improve data collection by saving time during recording step and improving the efficiency of image-based modelling. The "3D thinking" supported the interpretation process inside a virtual environment where we have been able to develop our theories on the basis of both quantitative and qualitative archaeological data.

The state of the art in the field of 3D recording shows a lack of applications in Sardinia. We think the first and main limitation is that the potentiality of the 3D documentation in archaeology is still unknown or not so known that it substitutes the traditional way to document a site/monument.

Therefore, in our opinion this project can be repeated in other nuraghi and archaeological sites in general, and it also illustrates an approach that reaches the fourth dimension using 3D models for analyses and archaeological interpretations.

The objective nature of 3D recording and modelling showed the need to start the production of standardized documentation, which is essential to improve and to make more objective the typological comparison of nuraghi. Detailed and standardized documentation is also a "key" (main) component for people working on monument conservation in order to best know how to monitor and protect historical architecture.

The 3D thinking played a role in improving the efficiency of archaeological work-flow too, in terms of cost and work time.

The next research steps will be focused on:

1. Improving 3D recording with UAV.
2. Managing 3D data with Geographic Information System (GIS) in order to integrate different kinds of information and monitoring the status of the monument.
3. Improving widespread public communication using web and mobile devices. This kind of documentation is highly valuable in terms of communication, and allows people to easily access cultural heritage data and scientific information.

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