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METHODS AND TOOLS FOR GENERATING THE DTM OF AN ARCHAEOLOGICAL SITE: THE CASE-STUDY OF THE PHOTOGRAMMETRIC SURVEY OF NORA (SARDINIA, ITALY)

1. Introduction

The project aims to produce a high-resolution (<10cm/pixel) Digital Elevation Model of the Nora peninsula (Pula, CA), which covers an area of over 14 hectares, and surrounding seabed[1]. The process will build and provide a database of raster and vector files for localizing current, historical, and future archaeological discoveries. The 3D model will help to understand the complex relationship between the peninsula, humans, and the sea. This relationship played a fundamental role in the birth, development, and disappearance of the ancient city and the model provides a valuable tool for studying this continuously evolving connection between humans and the environment.

Different techniques were used to achieve the project objectives due to the diversity of the environments studied. The photogrammetric method with Unmanned Aerial Vehicles was used for the mainland, while intertidal areas were surveyed with a total station. Seabed surveys were conducted using an echosounder (Church, Warren 2008; Drap *et al.* 2015). The survey of the Nora peninsula and surrounding seabed is useful for planning protection and consolidation measures against coastal erosion. This phenomenon has been active for centuries and has caused the submergence and destruction of many ancient monuments (Antonioli *et al.* 2012). Several studies have already proven the efficiency of this survey method as a monitoring tool for coastal erosion phenomena (Casella *et al.* 2016; Scarelli *et al.* 2017; Young *et al.* 2021). Aerial photogrammetry has many applications as a tool for studying archaeological sites and for mapping purpose (Campana 2017, 2020; Ahmad *et al.* 2018; Lou *et al.* 2019; Marin-Buzòn *et al.* 2021) and it can provide results in different areas: 1) to document cultural heritage (Hatzopoulos *et al.* 2017; Ali 2020; Bakirman *et al.* 2020; Kanun *et al.* 2021; Petrovič *et al.* 2021; Ulvi 2021; Pervolarakis *et al.* 2023); 2) to detect new sites in vast areas (Darwin *et al.* 2014; Colica *et al.* 2021; Vavulin *et al.* 2021); 3) to preserve, enhance and promote ancient sites (Olivito, Taccola 2014;

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[1] Author Contributions: conceptualization: G.A.D.V, A.Z., J.B.; survey: C.M. and A.P.; survey analysis: G.A.D.V.; interpretation of the model: G.A.D.V. and J.B.; supervision, J.B., A.Z., E.F. Drafted section 1 G.A.D.V., A.Z., E.F. and J.B; drafted Section 2 A.Z.; drafted Section 3 A.P. and C.M.; drafted section 4 E.F.; drafted sections 5 G.A.D.V.; drafted section 6 G.A.D.V., A.Z., E.F. and J.B. G.A.D.V. realized Figures 1-10. All authors collaborated to the revision of the manuscript, have read and agreed to the published version of the manuscript.

Themistocleous *et al.* 2014; Nikolakopoulos *et al.* 2017; Chiambrando *et al.* 2018; Langhammer *et al.* 2018; O'driscoll 2018; Pena *et al.* 2021; Orsini *et al.* 2022).

The research project on the Roman site of Doclea (D'Eredità 2020) in Montenegro is particularly interesting because aerophotogrammetric techniques were integrated with GPS and total station surveying. This approach has yielded high-resolution orthophotos, 3D models and terrain profiles like those obtained at Nora using comparable instruments and methods. The high resolution of the Doclea survey output allows zooming from an overall view to individual elements and it is possible to contribute at the diachronic reconstruction of Doclea and its territory from the Bronze age to the Medieval period. Beyond the scientific results and their dissemination to the public, the project has contributed to promote its touristic and cultural fruition.

2. Archaeological background

The archaeological site of Nora lies on a peninsula of about 14 ha (Bonetto 2021b) along the southern coast of Sardinia (Pula, CA), connected to the mainland by a narrow isthmus at the south-western edge of the Gulf of Cagliari. The landform of the ancient city is shaped by two headlands, and the peak of the easternmost is 36 m asl (so called 'Torre di Sant'Efisio cape'). A smaller mound is located near the core of the peninsula (so called 'Tanit hill', 9 m asl), while a low-lying ground sits further S, between the central and the easter district of the site (today, Roman forum area). The surroundings of Nora were inhabited at least since the late Nuragic age, but the oldest settlement dates to the mid-8th c. BC, during the first phase of Phoenician presence on the island (Bonetto 2021a). At first, Nora was a commercial settlement, in which seasonal outposts were built of perishable materials, and have been archaeologically identified by postholes carved into the bedrock. The first proper urban centre dates to the Punic Age (late 6th-5th c. BC): masonry structures were built, with clay paving, stone foundations, and mudbricks in the upper part of the walls. Warehouses, silos, wells, cisterns, and a cobbled road were built in the same area later occupied by the forum; a housing district developed along the SE coast, while three shrine areas were placed at the urban fringe (Bonetto 2021b).

Between the first and the second Punic wars, Sardinia became a Roman province (227 BC), but Nora did not look like a Roman town until the second half of the 1st c. BC, when it became a *municipium civium romanorum* and was endowed with the town's main public monuments, such as the forum and the theatre (Ghiotto, Zara 2020). The peak of the monumental refurbishment of the city dates to the Severian age, but developed throughout the whole 3rd c. AD (Asolati *et al.* 2018): in this phase, the road network of

Nora was paved with andesite flagstones and it was equipped with sewers; an aqueduct from suburbia was built, supplying new thermal baths, both public (so called 'Terme a Mare', and 'Terme Centrali') and private (so called 'Piccole Terme'). In this phase, the main temples of the city were also rebuilt (so called 'Esculapio sanctuary' and 'Roman Temple'), using building materials from the Phlegraean area, but the monumental renovation also involved the private constructions: in that respect, the richest *domus* renovated in Middle Imperial age is the so called 'Casa dell'Atrio Tetrastilo', marked by mosaic floors, a central court, and a roadside portico with monolithic columns. The city's decline started in the 5th c. AD, during the Vandal's invasions, the crisis furthermore deepened in the Byzantine period, until it was finally abandoned in the early 8th c. AD (Bonetto, Ghiotto 2013).

The remains of the ancient city were never completely buried. After some research around Punic tophet and necropolis at the end of the 19th century and an excavation campaign by G. Patroni in 1901, extensive excavations in the city centre only took place after the mid-20th century, when G. Pesce led activities aimed at turning Nora into the first archaeological park in Sardinia (Mazzariol, Zara 2024). Since the earliest investigations, there was a need for an archaeological map of the ancient city, in which morphological features and ancient remains could be shown together. In 1901 the surveyor F. Nissardi drew the 'Piano archeografico dell'antica Nora', using the plane table and the graduated ruler and working both on land and on boat (Patroni 1901). Further, topographical surveys of the ancient city were drawn during the excavations by G. Pesce, using traditional systems (Pesce 1972), while the first digital aerial photogrammetric survey was carried out in conjunction with the new inter-university archaeological mission, which started in 1990 and is still ongoing (Gualandi *et al.* 1996; Tronchetti 2000). This survey, supplemented by direct acquisitions by total station and semi-differential GPS, was used to create the first digital terrain model of the peninsula (Kirschner 2008).

Since the beginning of the 2000s, excavations were greatly increased (Marchet, Zara 2020), and research has also been carried out in the suburban space (unavailable until the disposal of a military base in 2012) and in the marine space surrounding the peninsula (Bonetto *et al.* 2022a). On these premises, the ever-rising complexity of archaeological and geomorphological research in Nora calls for an increasingly up-to-date topographical documentation of the ancient city, which today cannot do without a high-resolution digital model of the entire peninsula.

3. The survey: data acquisition

The photogrammetric survey of the peninsula was conducted during the excavation campaign in October 2021 using an UAV (Unmanned Aerial

Vehicle) instrument – the DJI Matrice 300 RTK equipped with a Zenmuse P1 camera (Kersten *et al.* 2022). During data acquisition 61 markers were placed and geo-referenced with a differential GPS in WGS 84/UTM zone 32N-EPSG:32632 and then reprojected into Gauss-Boaga Monte Mario/Italy zone 1-EPSG:3003 in line with the one used by public authorities in Sardinia. The UAV has maintained an altitude of 100 m and a speed of 10 m/s; the flight paths were aligned along the SW-NE axis with a spacing of 25 m between them, ensuring a photo overlapping of 80% in the forward direction and of 70% in the lateral direction (Fig. 1).

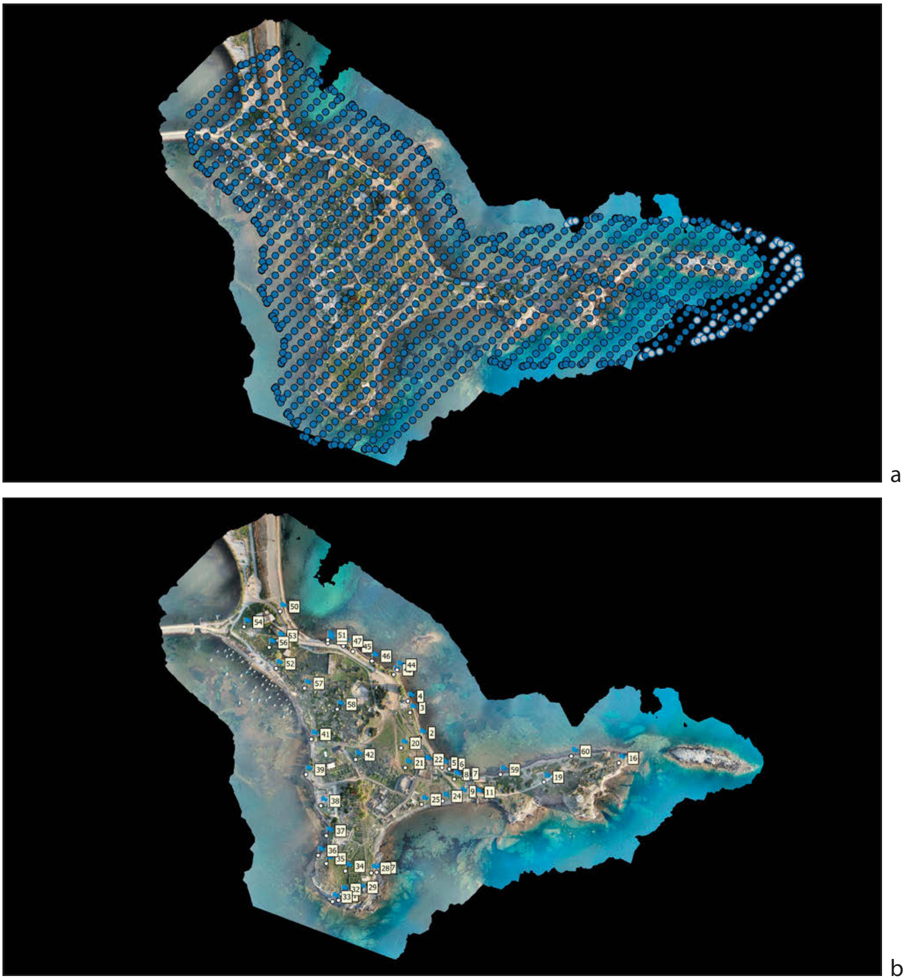

Fig. 1 – The orthophoto showing the positions of all GCPs (a) and all acquired photos (b).

Seabed depth data around the peninsula was obtained from a hydrographic sounding and a following shoreline survey using a total station (Bonetto *et al.* 2012). The Syqwest SingleBeam Bathy 500MF echosounder (frequencies of 208 kHz, 3° emission lobe and a resolution of 1 cm) was used to investigate the seabed from -4 to -10 m on a 10×10 m grid. For depths ranging from -0.8 to -4 m, a Syqwest echosounder was employed in a Sweep System configuration (frequencies of 208 kHz, 10°/18° emission lobe and a resolution of 1 cm). The Sweep System extended the seabed survey to an average depth of 0.5 m using net soundings for depths below -0.8 m. Topographic measurements were carried out for the remaining survey area from -0.5 m down to the coastline. The investigation was handled using a differential GPS+Glonass TRK Leica System 1200 and a total station.

4. Methods. Data processing: software and tools

4.1 *Generation of the 3D peninsula model*

The dataset, consisting of 1208 images, was processed with Agisoft Metashape© (Kingsland 2020) producing a sparse point cloud made up of about 1,302,979 points, a dense point cloud consisting of 250,709,397 points and a resulting textured mesh with 17,412,567 triangles. From the mesh thus processed a georeferenced orthophoto and a Digital Elevation Model with a resolution of 1.5 cm/pixel were obtained.

4.2 *Generation of the Digital Terrain Model (DTM)*

Three different software were used to obtain the Digital Terrain Model from the 3D model: CloudCompare for point cloud editing, Agisoft Metashape© for generating the DTM of the peninsula, and QGIS to combine the new DTM with the previous one of the seabed. Sea areas shown in the DEM were excluded as they are considered unreliable for creating the DTM due to optical distortion in reconstructing underwater objects in the photogrammetry process.

4.2.1 CloudCompare

CloudCompare (v. 2.12.1) was the preferred choice for its specific tools for editing the point cloud. The data set of the peninsula was segmented by removing positive and negative points along the z-axis associated with anthropic features such as buildings, wells and cisterns. Furthermore, points corresponding to plant elements like trees and bushes widespread in the northern and south-eastern regions of the peninsula, were deleted (Figs. 2, 3). The following step in the editing process was the filtering phase using two different tools. The first one was the Noise filter to reduce noise by deleting the point with a significant deviation from the mean value. The second tool employed was the SOR filter for decimating the point cloud by calculating the average distance between points

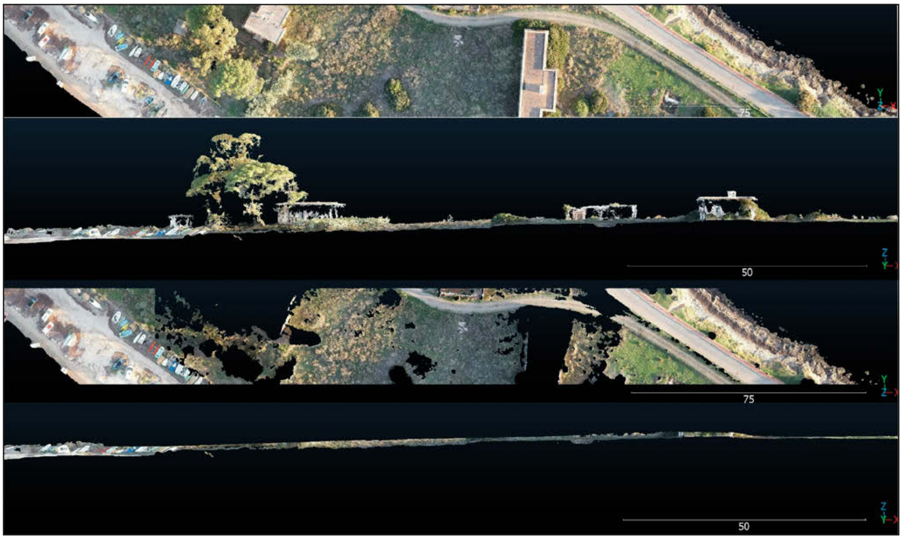

Fig. 2 – Processing workflow; from top to bottom: azimuthal view of the area; side view of the cloud before segmentation; azimuthal view of the point cloud after segmentation and side view of the cloud after segmentation.

Fig. 3 – The cloud resulting from the non-ground point deleting activity; a considerable part of the cloud has been removed.

and deleting those whose distance from neighbouring points exceeds. In this case, a mean value of 6 cm was chosen for decimating the cloud.

4.2.2 Agisoft Metashape©

The point cloud resulting from the editing process in CloudCompare was imported in Agisoft Metashape and then meshed in a polygon network of 1,813,850 triangles. The model presented holes in areas where buildings and vegetation had been removed, and in order to have a 3D model devoid of gaps the filling holes tool was applied considering Z-values from neighbouring points. The reconstructed areas were then decimated and smoothed (Fig. 4). From the mesh thus processed the DTM was calculated with a resolution of 6 cm/pixel (26,507×21,170 pixels).

4.2.3 QGIS: TIN interpolation tool

In order to create a detailed and accurate DTM of the emerged and submerged land of Nora, the model derived from Agisoft Metashape elaboration and the previous one, obtained with a LiDAR survey led by the Region of Sardinia, were combined together in QGIS environment. The dry land from the oldest DTM was isolated by extrapolating contour lines from the raster data with an interval between isobaths fixed at 0.25 cm. All isohypses above 0 m were removed to mark the bathymetric contour lines of the seabed. The same workflow was followed for extracting contour lines of the emerged area with 0.1 cm interval from the new peninsula DTM. The merged vector layer tool has hereby created a new layer that is the result of merging the two selected input layers. TIN interpolation tool was applied to combine the two surveys processed within the Gauss-Boaga coordinate system (Fig. 5). The tide-corrected seabed (adjusted by the tidal curve measured *in situ*) was referenced to the mean sea level of the IGM network (using the Cagliari 1956 tide gauge) using the geoidal undulation model Italgeo 1999.

5. Results

The peninsula's high-resolution orthophoto (1.5 cm/pixel) was used as a raster base for positioning vector elements, including the excavation sites. The orthophotos and DTM were employed to develop a GIS/WebGIS platform for the archaeological area. This integration combines historical cartography with digital excavation maps from over thirty years of university research on the peninsula (Fig. 6). The result is the first digital archaeological map of Nora, which aims to improve the knowledge, use, protection and promotion of the site (Howland *et al.* 2015).

Analysing a Digital Terrain Model in a Geographic Information System environment has proven to be useful in several ways. Firstly, the DTM was processed to create different basemaps. A shaded and false-colour representation

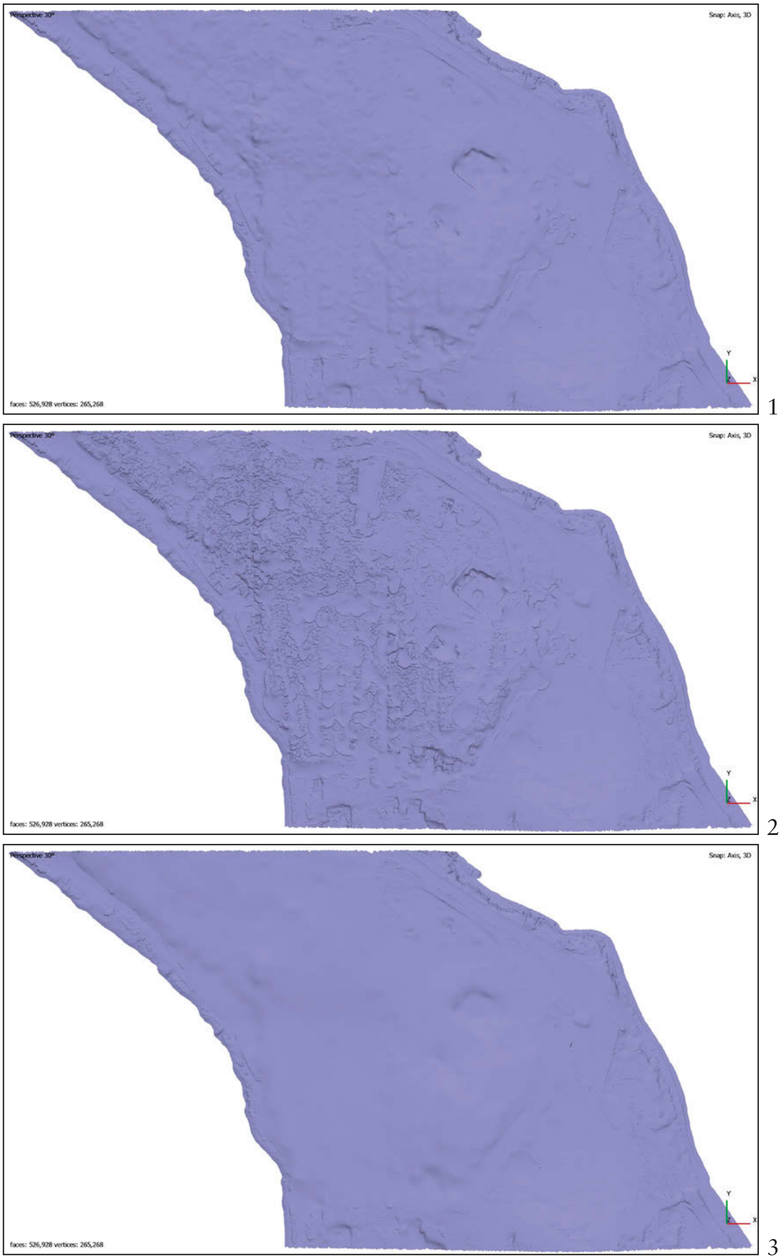

Fig. 4 – Example of the workflow: 1) the mesh with roughness due to the vegetation covering the Marina Militare area; 2) the area after a first attempt with value 10; 3) the area after a second attempt with value 50.

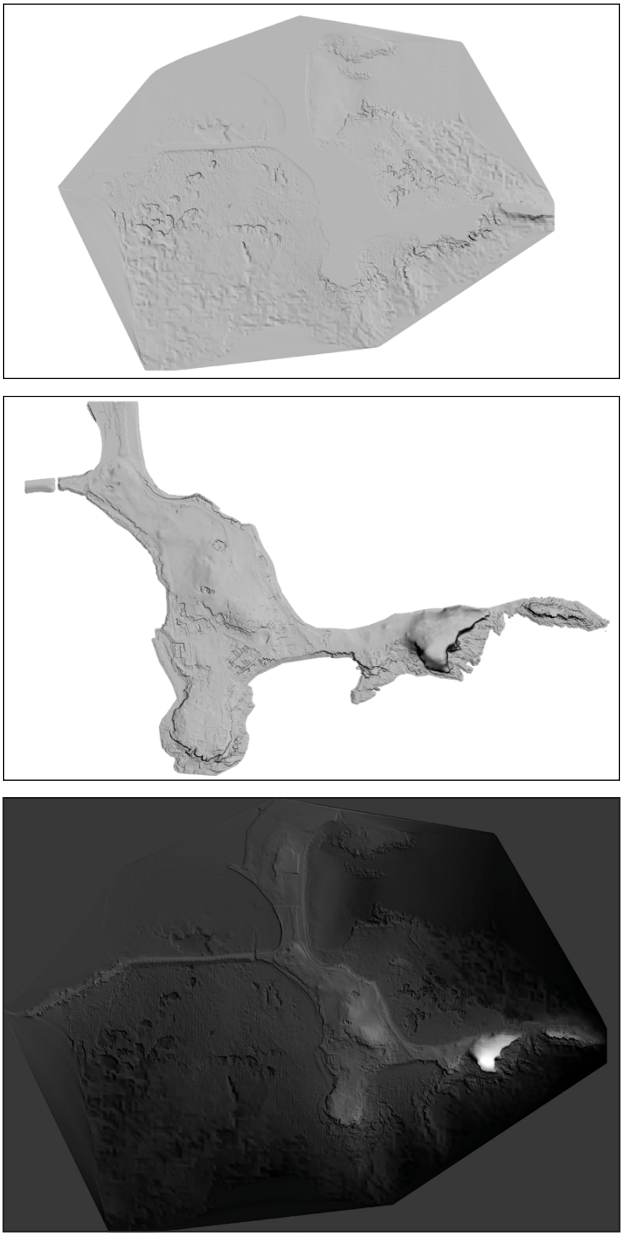

Fig. 5 – The three steps to obtain the complete DTM: at the top, the DTM of the seabed from which the landmass has been removed; in the middle, the model of the peninsula to be integrated into the seabed reel; at the bottom, the complete model.

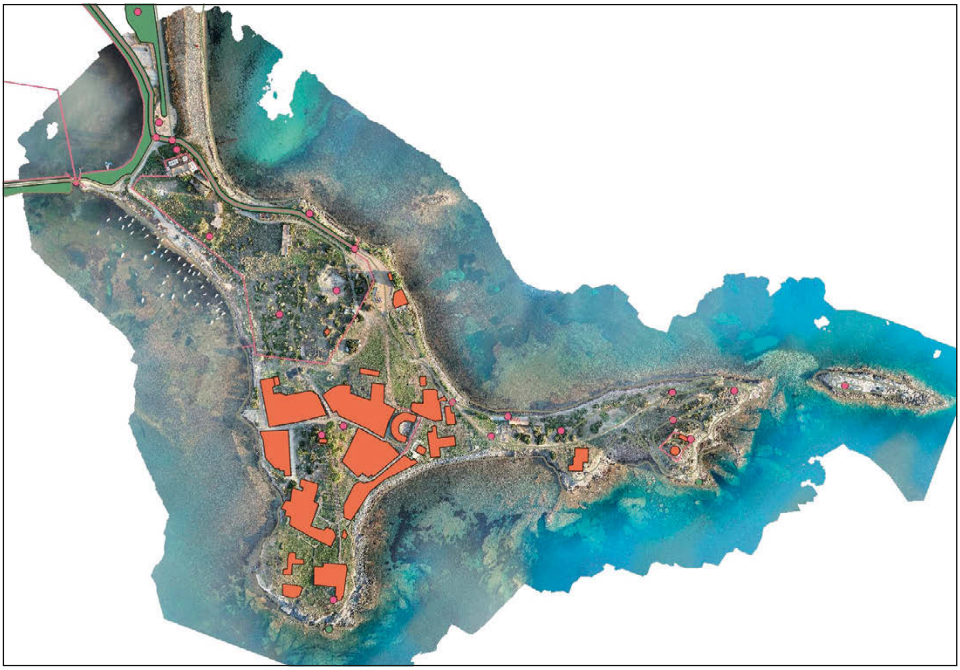

Fig. 6 – Orthophoto of the site with overlaid vector elements (excavation areas and Regional Trigonometric Vertices) of the Regional Technical Map (CTR) of Sardinia (reference system EPSG 3003).

of the peninsula was generated using a multidirectional approach with a light incidence of 30 degrees from the horizon. This technique enhances the three-dimensionality of the raster through the false colours, improving the perception of elevation. During the second phase of graphical processing, contour lines were extracted at intervals of 0.5 m, 1 m, and 2 m. The 2 m interval was used as a schematic base map, which was essential for producing a simplified map of the site without losing elevation data.

Several geomorphological analyses have been carried out on the DTM. These analyses are useful both for the archaeologists working at Nora and for the protection and management of the site. The 'slope analysis' (Fig. 7) was the first tool used to identify the most erosion-prone areas of the peninsula: the southern coast, particularly around the two promontories, shows large erosion fronts and slopes, and the eastern Phoenician necropolis in the N has been destroyed by meteorological and marine action. Consolidation work was carried out on the erosion front along the southern and western coastline to protect the remains of the Terme a Mare and the early christian Basilica. The Digital Terrain Model is a useful tool for monitoring these destructive phenomena that

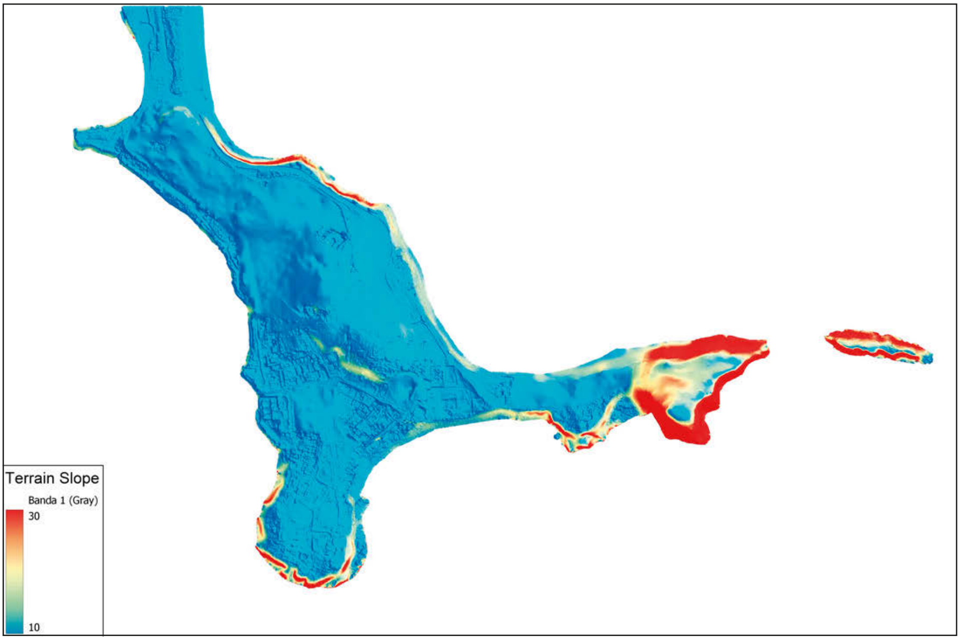

Fig. 7 – The slope map of the peninsula shows the main changes in slope at the erosion fronts. The overburden of the so-called Kasbah is in the centre of the peninsula and is highlighted in red.

threaten the archaeological remains. This allows authorities to compare future surveys with previous ones, calculate the rate of progress of these phenomena and take appropriate measures to protect the site (Young *et al.* 2021).

The tools for geomorphological analysis were useful in studying the settlement from an urban planning perspective and investigating the site spatially. The 'slope analysis' tool revealed an anomaly on the south-western side of the Tanit Hill. This irregularity resulted from two distinct human interventions: the northern step delineates the limits of excavation, while the S-shaped anomaly is the result of terracing in Punic times. The intervention aimed to adjust the slope of the hill for future constructions, resulting in the formation of the Kasbah quarter. The tool for calculating exposure identified that the slopes have different levels of exposure to light. By replacing light with wind, it also determined how they were exposed to weathering. The Phoenician settlements are associated with the most sheltered areas from the mistral (W-NW). This is the strongest and predominant wind throughout the year. The structures found at Tanit Hill were probably huts, as evidenced by the remaining pile holes, and the correlation suggests that the choice of location was deliberate and influenced by the limited resistance of the structures to the occasional

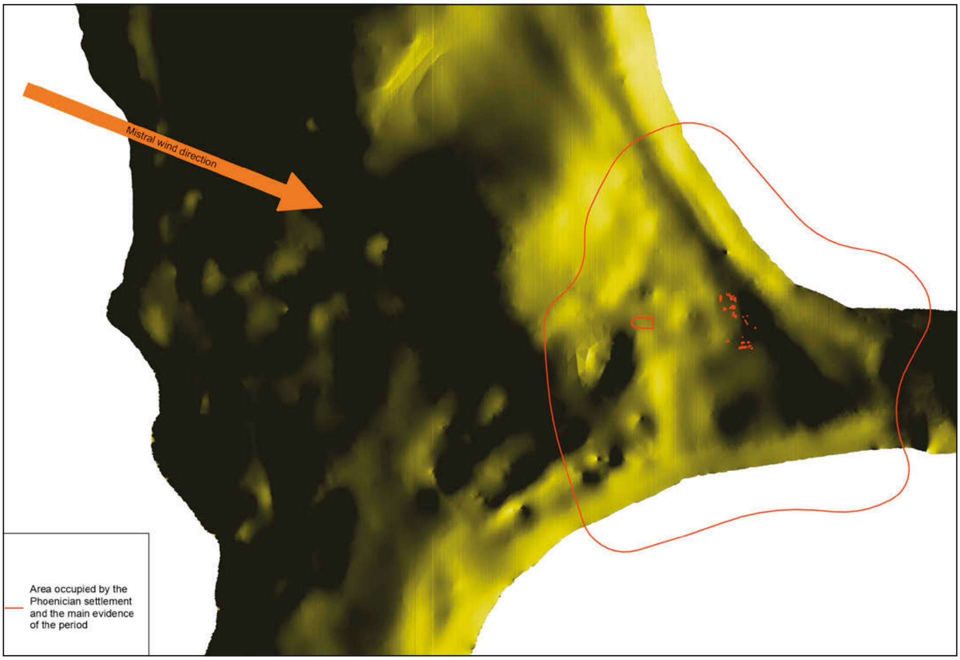

Fig. 8 – Detail of the peninsula. Yellow areas are protected from the Mistral wind as they face in the opposite direction (S-E); red areas indicate evidence from the Phoenician period and the hypothesis of the settlement's extension.

wind pressure. Wind protection may also have been a factor in the reduction of heat loss during the colder months. It is important to note that Tanit Hill is a relatively small relief, standing at only 9 m high. The evidence for Phoenician settlement in the area is limited. Therefore, the boundaries of the occupied area, which currently coincide with the plateau on the south-eastern slopes of Tanit Hill, remain hypothetical (Fig. 8).

DTM analysis has greatly supported the study of the relationship between humans and the environment. In a recent study (Bonetto *et al.* 2022b), the coring and dating of sediments have provided extensive data on the gradual rise of the sea level within the peninsula and the surrounding wetlands. The researchers used the previous DTM, which was derived from LiDAR data of the Region of Sardinia, to produce a graphic representation in false colours. This representation shows how the land mass of the peninsula has changed in relation to average sea levels over time. Coastal profiles were calculated for different historical periods, including Nuragic, Phoenician, Punic, Republican Roman, Imperial Roman, and Late Antique. The reconstruction helps to explain the decrease in inhabitable land over years and will aid in organizing

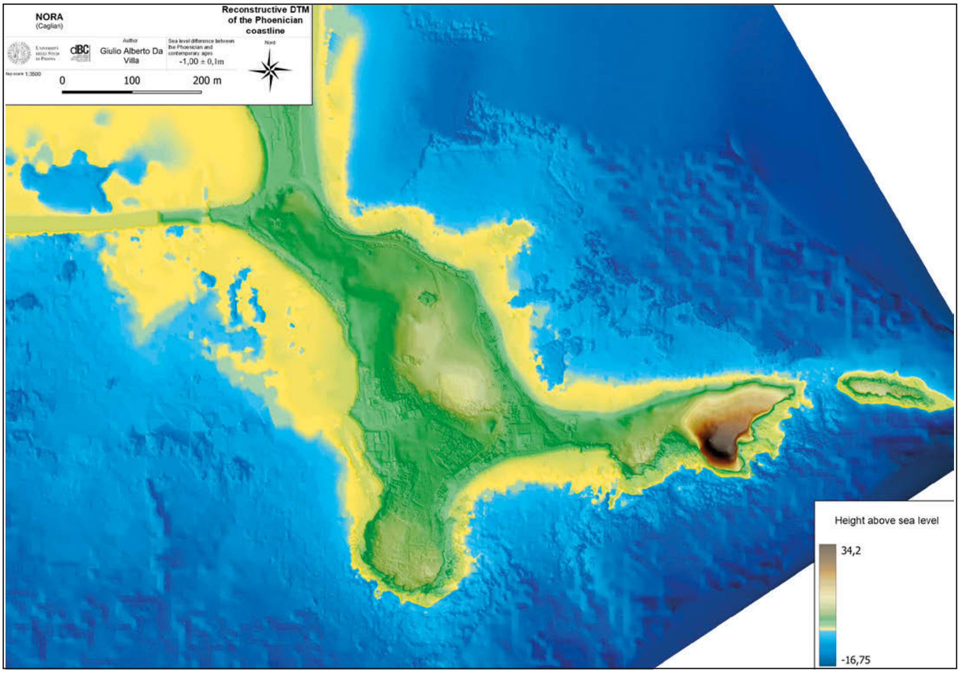

Fig. 9 – False-colour DTM of the Phoenician peninsula with yellow areas indicating submerged land.

future archaeological investigations (Bechor *et al.* 2020). The new DTM allows reviewing data from previous research on the ancient coastline and other unpublished information on submerged areas near the Peninsula and this provides new tools for analysing the archaeological site (Fig. 9).

The model can be made interactive by integrating geomorphological features and archaeological information based on classifying the evidence and can be further developed to virtually enhance the site. Within the DSM, buildings can be categorised chronologically, allowing the temporal alignment of shoreline and structures to be visualised. This feature would provide a consistent representation of historical periods. In addition, the cartographic outputs, orthophotos, and 3D model are useful tools for improving and updating the visual content of the panels on the site, which are currently being renovated.

5.1 *Printing*

The Department of Civil, Environmental and Architectural Engineering at the University of Padua collaborated on a printing test using a chalk powder printer (ZPrinter450). Based on the texture applied to the 3D model, the printer applies colours to the model during printing. The print file was obtained from the DTM raster file processed using QGIS software and the dedicated plug-in: DEMto3D. The printer was chosen for its potentials and large print volume (203×254×203 mm). The model's texture uses false colours, with a blue scale representing bathymetry. The colour map ranges from yellow at sea level (0 m above sea level) to brown at 32 m above sea level, with areas in between at 15 m in green. The palette chosen aims to make the peninsula's elevation easily understandable to anyone, regardless of expertise. In addition, the model can be coloured to highlight specific aspects; for example, the orthophoto can be used to give a photo-realistic aspect to the printed model (Fig. 10).

6. CONCLUSIONS

The research has led to the creation of a new tool for investigating, protecting, and managing high-impact sites. This tool can be summarised as follows:

– The university team and the Superintendence have conducted extensive research on the Nora site since 1990. However, until now, there has been a lack of highly accurate, geo-referenced, three-dimensional cartographic support. The survey and restitution activities have provided a complete and highly precise working basis for developing multi-thematic cartographies. This is now available to the scientific and official community. The geo-referenced point cloud is in line with the reference systems used by the universities and

Fig. 10 – The 3D printed tile displays clear levels and colours.

public authorities in Nora. This will make it possible to keep the database up to date with new acquisitions, even if different methods of data collection are used. It also provides an important basis for future surveys.

– In terms of research, the advantages are immediately evident on the detailed landforms features produced by the survey. The site is laid out on a system of low hills and maritime shores, where geomorphological aspects played a crucial role in settlement forms from the Nuragic age to the early Middle ages. The resulting DTM will enable researchers to comprehend the influence of the natural context on occupational dynamics. Furthermore, studying the layout of the ancient structures, the alignment of the Roman road system, the course of the hydraulic systems, and other crucial details is useful for the historical interpretation of the site. The elevation model provides significant advantages, particularly in two specific areas: a) in the northern area, where there is over 4 hectares of unexplored land, the micro-relief is an essential tool for predictive purposes due to the effects on soil generated by ancient presences; b) accurate elevation measurements of emerged and submerged areas in coastal and intertidal zones aid in comprehending the coastal land and seabed. This also enables the calculation of shoreline progression caused by rising sea levels over time. By studying the historical relationship between marine and terrestrial space, it is possible to predict future coastal advancing scenarios and prevent potential impacts on ancient coastal structures. In summary, a tool that provides a comprehensive and detailed understanding of landforms in a site of high geomorphological complexity has the potential to significantly enhance the research. In the context of the Nora site, where four universities are conducting ongoing studies, this aspect is particularly significant.

– The photogrammetric survey of the site has provided a useful tool for site management practices. It allows the analysis of the location and consistency of the deposits, the verification of the position and depth of the ancient multi-layered remains, and the planning of the technical networks and service infrastructures. This is particularly important for a site that is visited by thousands of tourists every year.

– The 3D model obtained in this study is a useful tool for dissemination purposes. It can be presented as a virtual or physical image of the excavations and archaeological area (DSM), or as a model representing the peninsula in its various chronological phases (DTM). 3D printing allows the creation of tangible accurate models for educational and illustrative purposes (Themistocleous *et al.* 2015; Monturi *et al.* 2020; Wałek 2020; Higueras *et al.* 2021; Arias *et al.* 2022; Fernandez *et al.* 2022; Kantaros *et al.* 2023).

This research project also highlighted some of the limitations of photogrammetry and needs a consideration on the nature of the DTM obtained for a particular area, such as an archaeological site. Vegetation noise is a major challenge, and this aspect can be overcome by preparing the survey area before the flight or by selecting the areas to be surveyed during the planning phase. A preliminary LiDAR survey has been carried during this research project, for supplementing missing data in tree covered areas, but results are not presented in this paper because of the sensor was not able to penetrate bushes. It is scheduled in upcoming campaigns a new UAVs LiDAR survey with a different sensor hopefully able to acquire ground data under dense vegetation; this new acquisition will be planned based on the photogrammetric data described in this paper, combined with available satellite images. Moreover, archaeological. sites present a significant challenge in distinguishing between natural terrain and historical remains discovered during excavations. These remains, which can be thousands of years older than the surrounding terrain, make it difficult to accurately map unexcavated areas and reconstruct the peninsula's DTM without human intervention. Due to extensive excavations carried out in the last century, the morphology of the peninsula has been irreversibly altered, making it impossible to exclude historical elements. Therefore, the excavated areas have been preserved to reflect the modern layout of the land, which has been shaped over the last two millennia by various inputs as anthropogenic sedimentation, and removals, such as archaeological excavations. This approach also enables monitoring of the works' progress and preservation of the historical context.

Giulio Alberto Da Villa, Arturo Zara, Emanuela Faresin, Jacopo Bonetto
Dipartimento dei Beni Culturali
Università degli Studi di Padova
giulioalberto.davilla@studenti.unipd.it, arturo.zara@unipd.it, emanuela.faresin@unipd.it
jacopo.bonetto@unipd.it

Cristiano Miele, Antonio Persichetti
Archetipo S.r.l., Padova
info@archetipo-srl.com

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ABSTRACT

This paper describes the high-resolution survey of the archaeological site of Nora (Sardinia, Italy) using the aerophotogrammetric technique. The survey was conducted in October 2021 on a 14-hectare peninsula located in the Gulf of Cagliari. Previous attempts to survey the area, aside from the 1 metre/pixel LiDAR survey carried out by the Region of Sardinia, have been hampered by the challenges posed by the size of the area and the costs involved. The Digital Terrain Model was obtained from the 3D model created with the Agisoft Metashape© software by removing the buildings and the vegetation. The segmentation process was carried out using Cloud Compare and the resulting DTM was then analysed using the geomorphological analysis tools provided by QGIS. The seabed DTM was obtained through several survey campaigns between 2013 and 2015, using the same software. The terrestrial DTM was merged with the seabed DTM, resulting in a comprehensive 3D and 2D model of the peninsula and its surroundings. The final DTM was printed with rapid prototyping technologies to explore its potential use as a tactile model for promotion and dissemination in the field.