Cultural Heritage Through Time

Project Deliverable

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Introduction

Four different case studies have been considered in the “Cultural Heritage Through Time” project: the Roman Circus in Milan (POLIMI), the City Walls of Avila (USAL), the Adrian’s Wall (NCL) and the Fortresses in Krakow (SSSA).
Each partner collected different data from archives, historical images, topographic and 3D surveys to produce the 4D reconstruction of the sites.
POLIMI dealt with mainly historical data and photograph combined with topographic, photogrammetric and laser scanning survey to reconstruct in a CAD environment the area of the Circus in its different phases.
USAL used historical data and laser scanning to analyse the development of the city walls, integrating these data with a CAD reconstruction.
NCL used historical photography, UAV images and LIDAR to study the differences in time in two sites of the Adrian’s Walls (Birdoswald and Corbridge).
SSSA combined CAD drawings and laser scanning to reconstruct two Fortresses in Krakow (Kościuzko and Wegrzce).

Polimi

The Italian unit used the huge amount of material collected during the previous month to make an accurate reconstruction of the Roman Circus of Milan. The building is no longer visible except for few remains in private gardens, apartments and basements. The first step was related to the creation of a GIS to merge all the different data sources into layers, georeferenced to the reference system used by the administration in Milan (UTM WGS84 32N). The architecture of the GIS was organized starting from the archival data, to produce the first step for the 4D reconstruction. Two different archaeological maps have been georeferenced and digitized to have the first idea of the structure of the ancient building from the data collected during surveys and excavations done between the 30’s and the 80’s of the last century (Figure 1). The first map realised was the one from De Capitani in 1939, with an update by Mirabella Roberti in 1984. The two maps show discrepancies in the orientation and in the total length of the building.

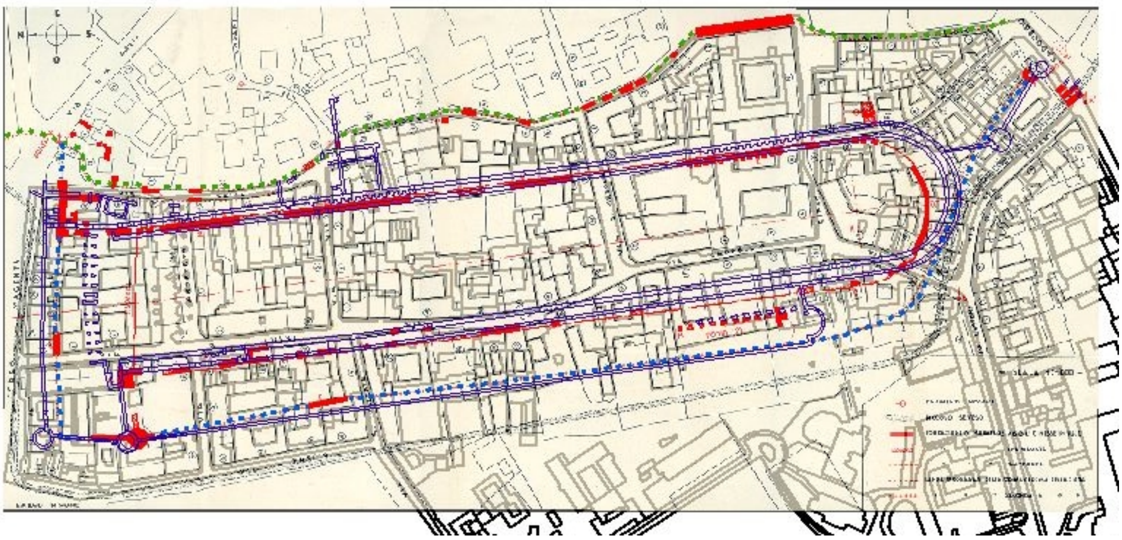


Figure 1. The georeferencing of the old maps on the cadastral map provided by the municipality of Milan.

The digitized maps of the circus were then integrated with the topographic reconstruction of the roman city during the Augustus' and Maximian period, in order to have a complete description of the ancient town (Figure 2), an important passage to understand the development of the city during the centuries.

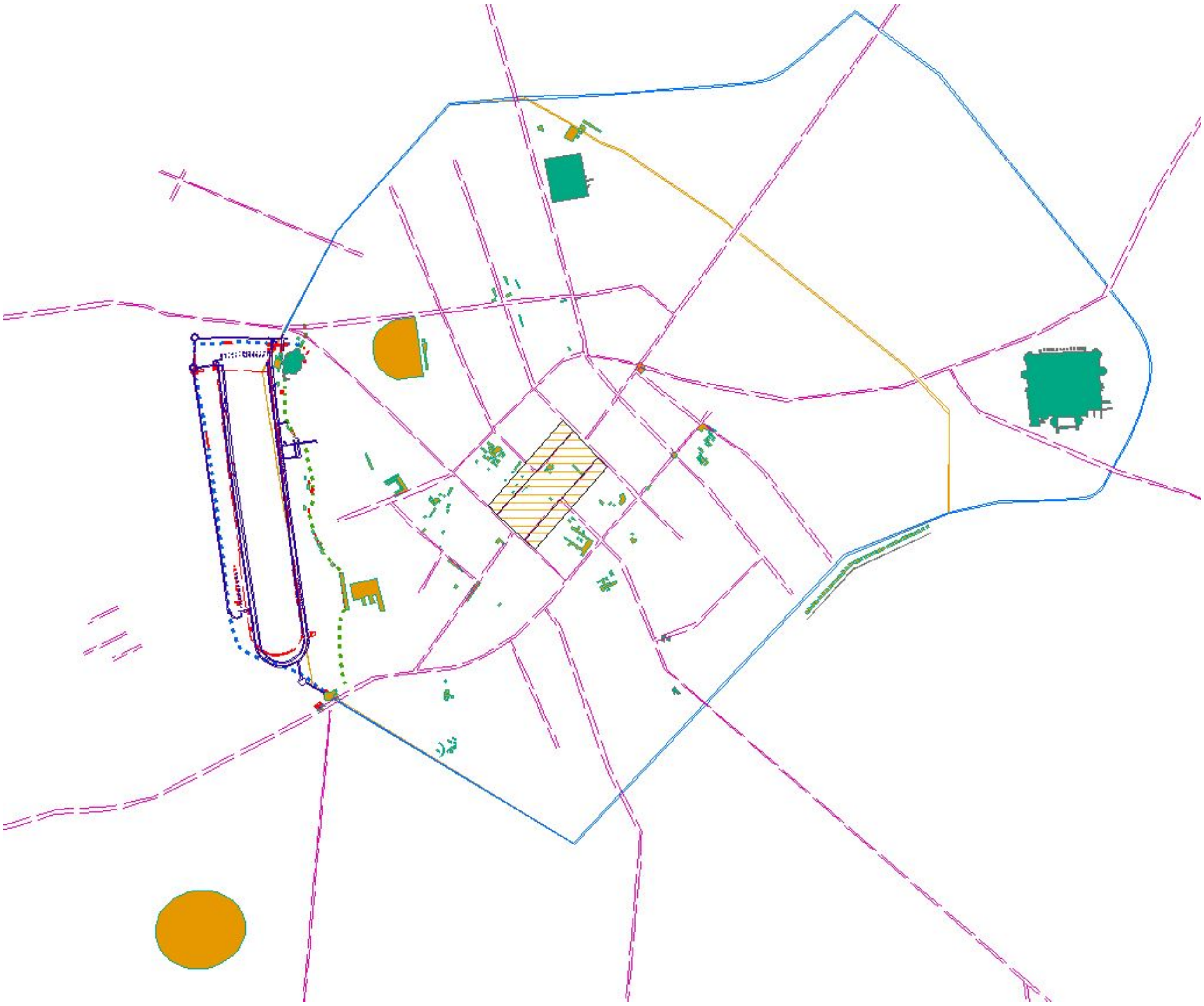


Figure 2. The vector map of the city of Milan showing the path of the city walls during Augustus (in orange) and during Maximiam (light blue). In purple are shown the streets while the monuments are indicated in orange (Augustus' period) and in green (Maximian).

After the digitization of the ancient maps, a Geodatabase was created containing all the information about each single portion of the walls visible today. The position of each single wall is indicated on the map with yellow triangles (Figure 3).

Figure 3. The points indicating the position of the remaining portion of the walls of the circus.

Each point is connected to a series of tables containing all the description and information of the wall, linked to the information about historical images and the survey done during the project (Figure 4). The main table concerns the Cultural Heritage, so the description and all the information about the ancient walls. Then two tables have been related to the main one: the first regards the images collected during the project, with the description, the information and the link to the old photographs, the other to the survey.

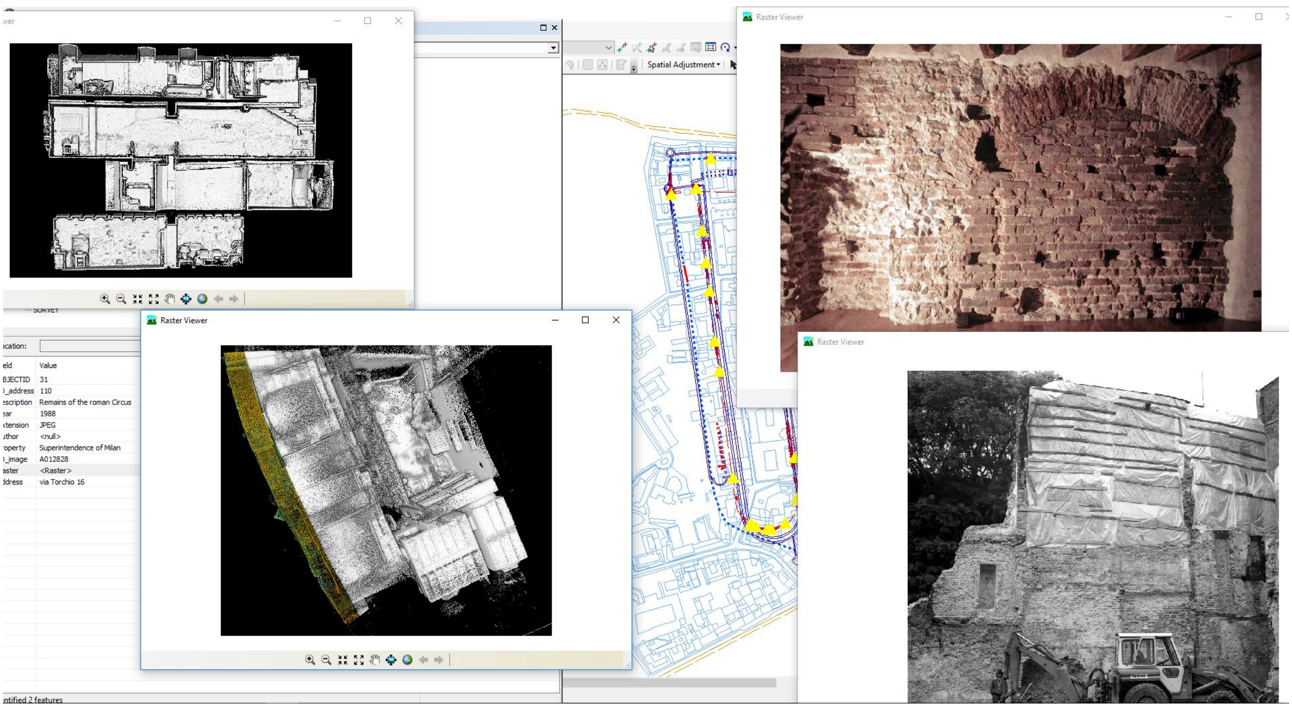
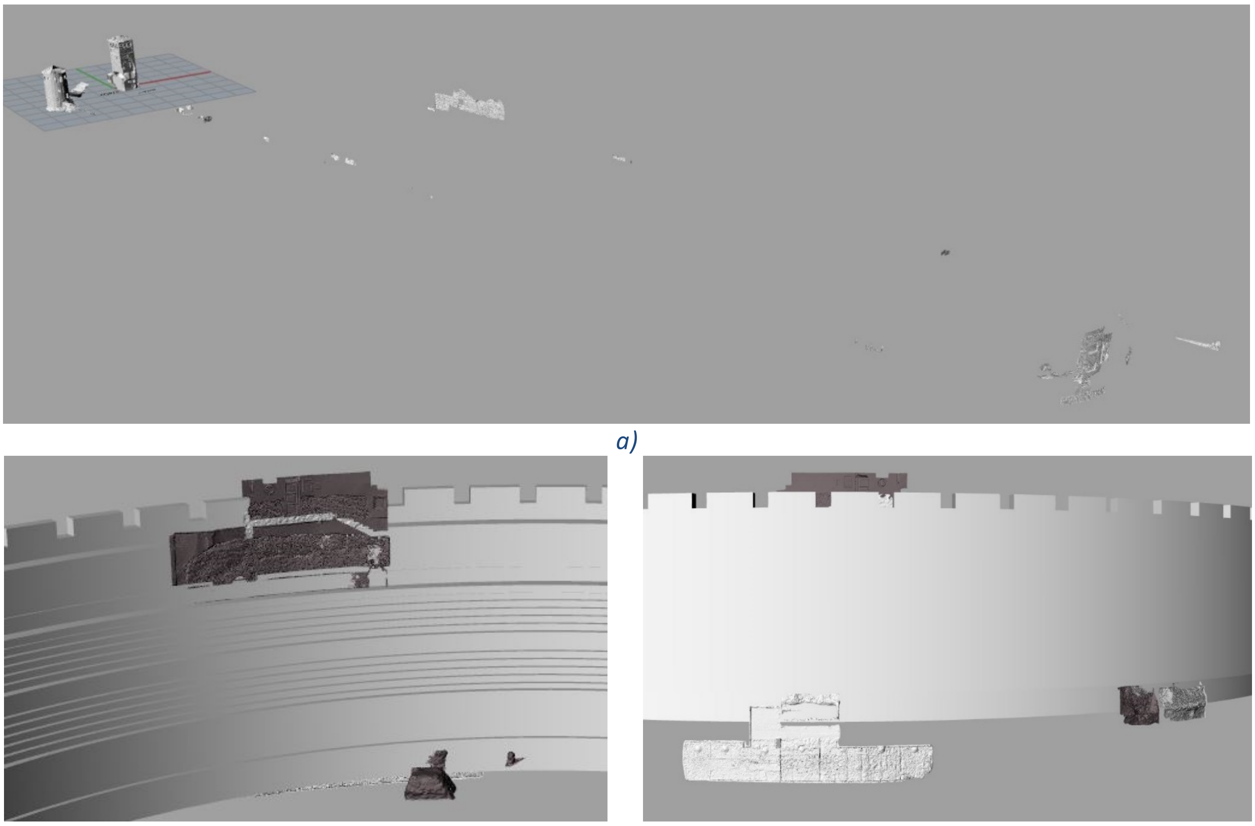


Figure 4. The table and the images in the geodatabase.

The geodatabase is an useful tool not only for the 4D reconstruction but also for the Superintendence, that can, in this way, have an updated collection of documents regarding the circus, georeferenced to the actual city.

But the main source of information for the 4D reconstruction of the circus was the survey described in detail in D3.2, where the underground 3D scans of all the remains available of the circus walls and foundations, were aligned together and georeferenced through a high precision differential GPS.
This operation has been never done before in any of the surveys for the lack of this specific technology and the resulting data revealed details on the shape of the building never hypothesized by previous archaeological studies. This has been considered a very valuable contribution to the understanding of the area from the Archaeological Superintendency of Lombardy and allowed to define some details of the 3D reconstruction that otherwise would have been undetermined.
The 3D reconstruction of the circus started from this data (Figure 5), integrated by the geodatabase, that helped in the completion of the 3D model by adding accessory information.



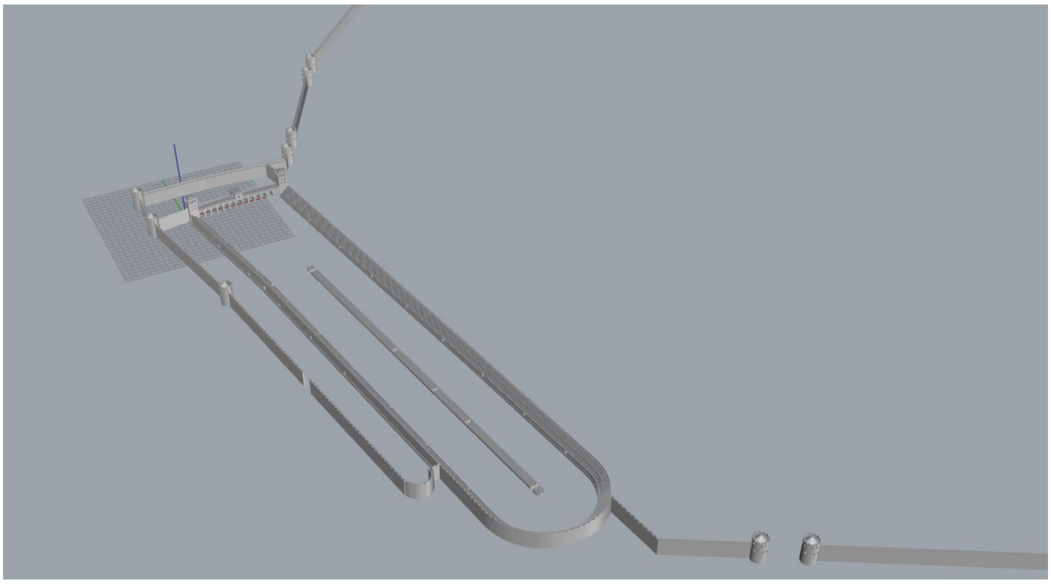
a)

b) c)

Figure 5. Reconstruction of the CAD 3D model over the measured remains of the circus: a) remains still visible in the outdoor; b-c) reconstruction of the curvature of the circus with the exact length of the structure using as reference the 3D reality-based data.

The final model of the circus was then integrated with the city walls and then superimposed on the 3D model of the actual city (Figure 6), done using aerial photographs georeferenced using natural features of the landscape as tie points.
In this way, the continuity in the topography and the identification of the correct areas in which the archaeological remains are still visible have been done in an accurate way for the first time.

a)



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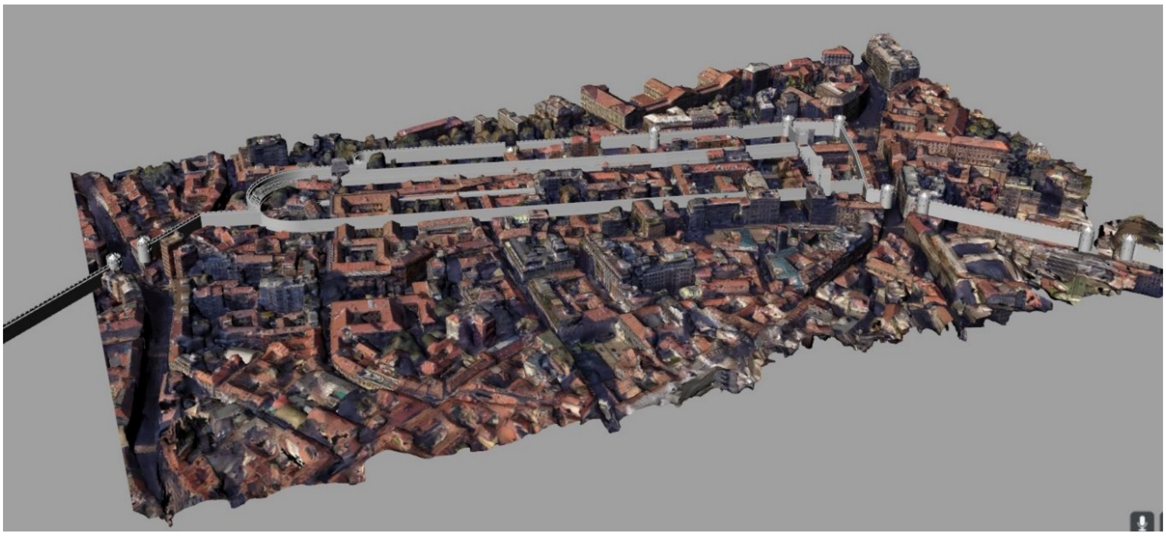
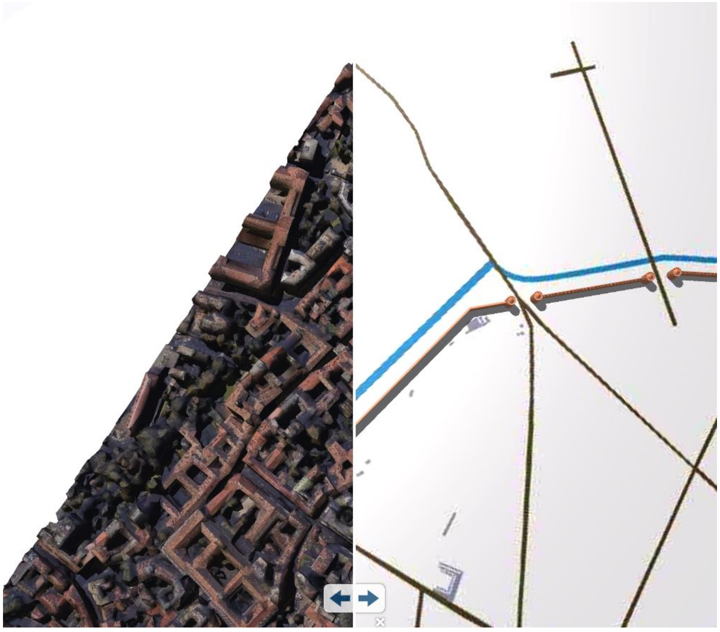


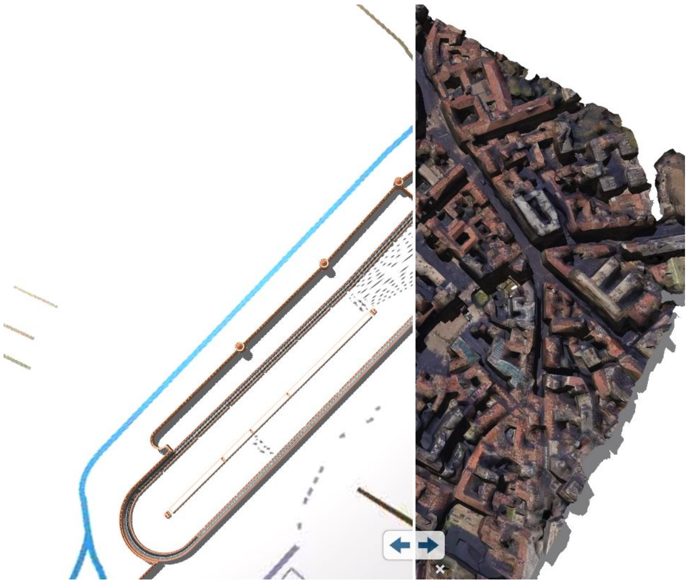
c)

Figure 6. 3D reconstruction of the area of interest: a) entire city walls and the circus; b) detail of the relationship between the city walls and the circus external walls, hypothesized as defensive structures; c) overlapping of the reconstructed building on the modern city.

All the data collected have been put in the project's website (Figure 7) to show the exact position of the monument inside the actual shape of the city for a better comprehension of its position and the location of the remains inside the modern buildings.



a)



b)

Figure 7. The overlapping of the (a) the 3D of the modern city and the shape of the roman city before the construction of the circus and (b)the reconstructed roman circus over the 3D model of the modern neighbour of the city. With the use of the sliding window is possible to see the changes and the position of the ancient building in the city.

The purpose of the digital reconstruction of the ancient Roman Circus of Milan was to give a visual representation to a structure whose formal details, although studied by several authors in the past 70 years, were not very clear. This large structure of the past had a huge impact on the city at the time of its construction, involving the change of the course of a river, and the complete redefinition of the southern part of the city of Milan.

The digital reconstruction of such monument was particularly complex due to the presence of the few remains in the underground of an active and lively city, mostly in the basements of private houses. It has been possible to relocate in space each small portion of the circus remains with a GPS, obtaining important clues related to the orientation and the length of the structure. Such information allowed to reconstruct the position of some elements of the circus, never studied before.

The integration of the heterogeneous data collected permitted to provide a realistic reconstruction of a monument that is not visible anymore. By merging data related with the current state of the monument with the archival material collected, a rearrangement of the historical representations has been made, like for example the normalization of historical plans in a uniform scale.

The work done with the Superintendence regarding the different hypothesis of the reconstruction is truly useful even for the scholars because it forces them to analyse all the documentation. On the other hand, the possibility to see the structure in 3D helps them to have a clear idea of the monument, and so to identify the best way to reconstruct the building.

Finally, this work will give the possibility to everyone interested to comprehend and appreciate a lost, important monument of their city, because most of the people do not even know the existence of the Circus. Having the perception of the structure among the modern streets and buildings is the best way to help non-experts to understand the dimensions, the importance of the monument, while the tridimensional reconstruction will help in a better comprehension of the building itself.

NCL

Quality assessment

Internal PhotoScan quality assessment of the absolute orientation results for all three UK study sites on Hadrian's Wall, as derived from the utilised SfM-MVS pipeline, is presented in
Table 1. The orientations of the archival imagery were generally found to be worse than for current-day datasets. This was particular evident for the Beckfoot site since the 2016 epoch comprised the UAV survey with larger scale imagery. This can be attributed to a number of factors, including the degradation of image quality over time, the lack of camera calibration data for some archive imagery, quality of A/D conversion, suboptimal imaging network configurations for SfM-MVS processing, availability of fewer ground control points (GCPs), and so on. For instance, the type of natural features that served as GCPs (e.g. corner of a traffic island, could not always be identified as precisely in archival imagery as they could in more recent imagery). Moreover, all study sites included some private land which was inaccessible and therefore did not allow an optimal distribution of GCPs. Hence, the dense image matching routines used in the SfM-MVS pipeline often performed poorly on archival datasets. Poor results were particularly apparent in the middle of open fields where high quality image texture was also lacking.

Table 1 – PhotoScan absolute orientation quality assessment at Beckfoot, Birdoswald and Corbridge.

Location	Year	X RMSE [m]	Y RMSE [m]	Z RMSE [m]	3D RMSE [m]	No. of GCPs used in orientation	Comments
Beckfoot	1948 B/W	1.425	1.512	1.755	2.720	16	Natural features
	1991 B/W	0.731	1.177	2.741	3.071	15	Natural features
	2016 UAV RGB	0.016	0.015	0.020	0.029	27	B/W targets
	2016 UAV NIR	0.010	0.010	0.011	0.018	27	B/W targets
Birdoswald	1946 B/W	0.942	1.168	2.824	3.198	12	Natural features
	1990 RGB	0.746	1.208	4.295	4.523	13	Natural features
	2016 RGB	0.733	2.070	1.755	4.745	11	Natural features
Corbridge	2016 RGB	0.224	0.338	0.102	0.418	33	Natural features
	2006 RGB	0.251	0.160	0.141	0.427	36	Natural features
	1984 B/W	0.648	0.846	1.916	2.192	14	Natural features

The SfM-MVS pipeline was not applied to the 1984 NIR and 1991 B/W single photographs at Corbridge, since fewer than three aerial photographs existed for those epochs. These photographs were georeferenced with respect to the 2016 orthomosaic using five common points, delivering a 0.70 m average planimetric RMSE.

As a result of sub-optimal archival dataset orientation results, alignments were refined using various data fusion approaches, including both in-house surface matching algorithms (Miller et al., 2008) and iterative closest point (ICP; Besl and McKay (1992)) routines in the OPALS software (Pfeifer et al., 2014), to ensure rigorous registration from epoch to epoch, thereby generating spatially consistent 3D time series for subsequent 4D cultural heritage analysis. Whilst the gently undulating landscapes of the Beckfoot and Corbridge sites lacked relief and therefore did not readily lend themselves to such data fusion approaches, the application of surface matching was found to improve the registration of multiple epochs in the majority of cases.

An example is illustrated in Figure 8, where the improvement in the co-registration of the 1984 and 2016 epochs for the Corbridge site is visually evident over an excavated archaeological area which was believed to be stable, i.e., unchanged through time, over the observation period. In this example the 1984 and 2006 dense point clouds were co-registered with respect to the reference 2016 dense point cloud. Buildings and vegetation were also excluded from all datasets. A seven-parameter Helmert transformation was applied when using the ICP approach in the OPALS software. To verify the ICP performance, statistics of the cloud-to-cloud differences over the region assumed stable were calculated with the aid of the M3C2 algorithm (Lague et al., 2013). The M3C2 distances of the 2016-1984 epoch pair, both before and after ICP implementation, are illustrated in Figure 8. The M3C2 statistics at all epoch pairs for Corbridge are reported in Table 2. Not only did the implementation of ICP clearly minimise the point-to-point differences (Table 2) but, especially for the 2016-1984 co-registration, it also removed an apparent systematic tilt error, as visually evidenced in Figure 8. The Helmert transformation parameters were then applied to the dense point clouds initially reconstructed from the 2006 and 1984 datasets. The transformed dense point clouds were reimported to PhotoScan and the MVS workflow was repeated without the necessity of the SfM and georeferencing steps. It is noteworthy that the processing of the 1984 Corbridge dataset was particularly problematic, the digital elevation model (DEM) displaying artefacts characteristic of SfM and dense image matching application such as apparent "doming" (see, e.g., James and Robson (2014)) and data voids in areas of low image texture. As a result, some residual errors are still apparent even after application of the ICP algorithm.

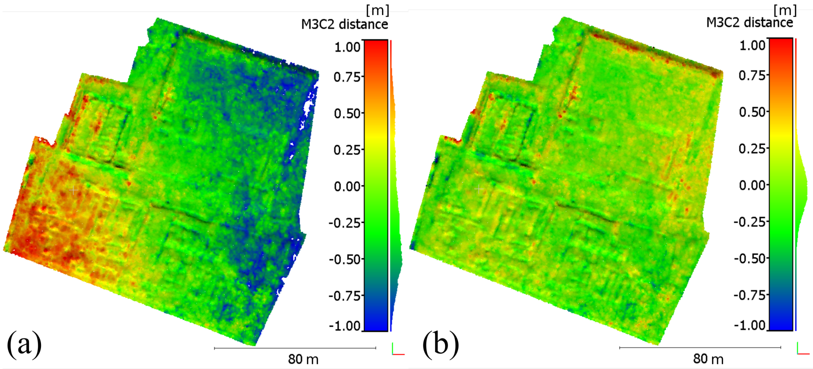


Figure 8 – 2016-1984 M3C2 distances (a) before and (b) after ICP over excavated archaeology at Corbridge.

Table 2 – Statistics of point-to-point cloud differences over excavated archaeology at Corbridge.

Epoch pair	Before ICP		After ICP	
	Mean [m]	RMSE [m]	Mean [m]	RMSE [m]
2016-2006	0.06	0.11	-0.02	0.08
2016-1984	-0.19	0.47	-0.03	0.20

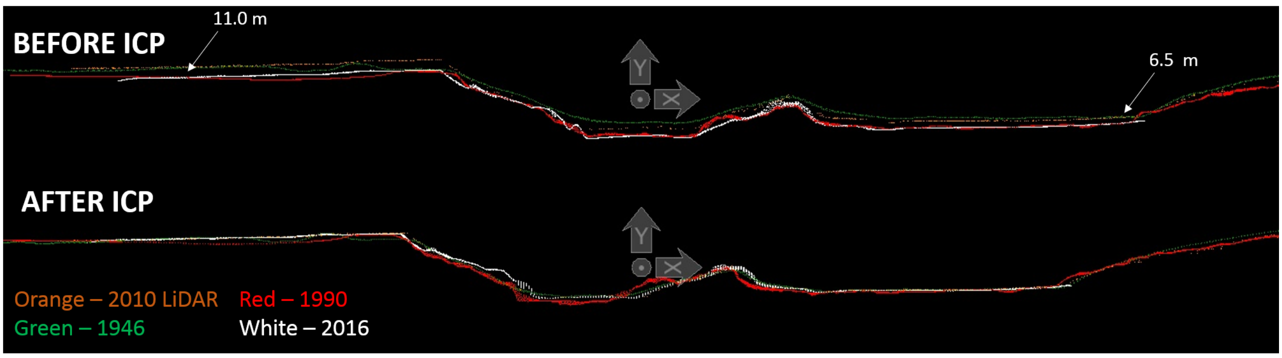


Figure 9 - Example cross-section taken at Birdoswald, over an area believed to be stable, before and after the application of ICP-based matching.

In a similar manner, ICP-based matching was also applied to the 1946, 1990 and 2016 Birdoswald datasets (Table 1) with respect to the 2010 Lidar reference dataset. Figure 9 illustrates that vertical offsets were significantly reduced over flat regions after ICP implementation. However, remaining vertical discrepancies between datasets over undulated terrain, as observed after IPC in Figure 9, can be attributed to landscape changes due to fluvial erosion, DEM "doming" deformations as a result of SfM-MVS processing, and errors caused by vegetation filtering. It should be noted that the process of vegetation filtering in SfM-MVS derived point clouds was performed differently to the filtering process in lidar-derived point clouds, as the latter is often based on multi-echo returns. Hence, noise caused by unfiltered vegetation in SfM-MVS outputs can adversely influence the vertical measurement sensitivity when implementing the ICP algorithm.

4D results

After the application of ICP-based matching, accurate landscape change determination could be performed. Inter-epoch elevation differences were generated by subtracting each DEM or digital surface model (DSM) from the immediately more recent DEM/DSM on a pixel-by-pixel basis. An example is shown in Figure 10a for the 2016-2006 epoch pair at Corbridge. In particular, negative changes of approximately - 1.0 m to - 0.6 m, as shown in red in Figure 10a, indicate crop growth / change. The most likely explanation for this is that the 2006 photographs were acquired in July during the growing season. By contrast, a positive change of +0.6 m to +1.0 m is apparent at the south towards the River Tyne (Figure 10a), while the ±0.2 m minimal change lies within the estimated maximum RMSE after ICP implementation (Table 2). As a result, it can be assumed that the 2016-2006 positive elevation differences represent changes in crop height. However, it cannot be directly deducted whether the negative changes have been solely caused by geomorphological/fluvial dynamics or anthropogenic activities.

Apart from the quantification of landscape change, time-series of georeferenced archival datasets provided useful semantic information advantageous for 2D/3D archaeological feature documentation. As evidenced in Figure 10b, both visible and NIR imagery illuminated linear features which are related to ancient Roman roads, remains of legionary compounds and civilian buildings. Figure 10b also shows linear traces in the NS direction located over the area of positive change observed in Figure 10a. It is speculated that these features are not related to archaeological remains and may represent sediment deposition, caused by fluvial floods from the River Tyne. Further analysis of flow accumulation and direction with the use of GIS tools could potentially support this statement.

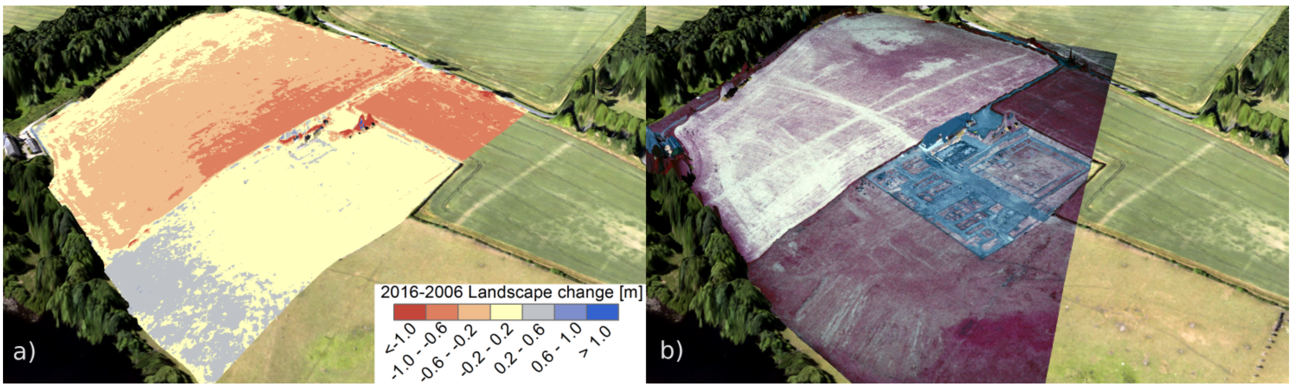


Figure 10- Perspective view of a) 2016-2006 DSM differences and b) 1984 NIR georeferenced single image, all superimposed over 2006 orthomosaic at Corbridge.

Another example of temporal landscape change is shown for Birdoswald in Figure 11, as a result of DEM differencing between 2010 Lidar and 1990 archive photography post ICP-based matching implementation (Figure 9). Vegetation from both datasets was filtered out with the aid of automated ground classification routines applied in Terrascan and Photoscan for Lidar and RGB point clouds, respectively. Further surface smoothing was implemented in PhotoScan to remove high frequency noise observed in the 1990 classified dense point cloud. This noise can be possibly attributed to various error sources associated with archival photography and SfM-MVS matching algorithms, as previously discussed. Due to smoothing, the pixel resolution of the 1990 DEM was degraded from 0.26 m to 1.0 m. Hence, the landscape change shown in Figure 11b has only 1 m pixel resolution. The colour scheme is based on the quantile classification. Remaining residual errors of high positive and negative elevation change are apparent even after the ICP-based matching at the edges of the site (top left in Figure 11b). Besides the difficulties in quantifying the actual change, as errors are propagated into the DEM differencing, Figure 11b illustrates significant erosion with magnitudes greater than 2.8 m over the slope. This is observed close to the remains of the Roman Fort, which is indicated in black lines in Figure 11b. The abrupt discrepancies of positive and negative changes along the top edge of the cliff indicates the continuous fluvial hazard taking place over the years, imposing a high risk of cultural heritage loss.

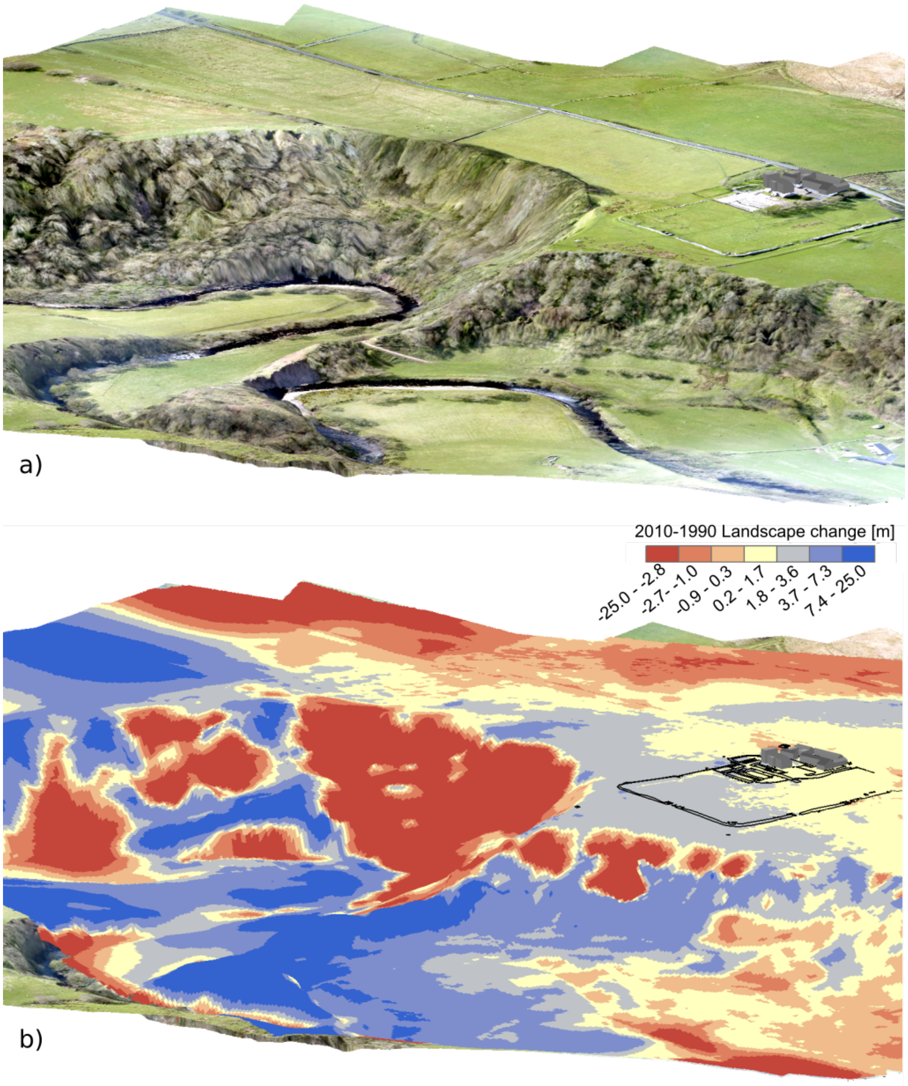


Figure 11- Perspective view of a) 2016 RGB orthomosaic and b) 2010-1990 landscape change as derived from DEM differencing between Lidar and RGB archival photography at Birdoswald.

However, it should be noted that automated ground classification routines can often produce noise, such as points which are erroneously classified as bare ground actually representing vegetation in reality. This is most likely to occur over densely vegetated areas, such as the cliff illustrated in Figure 4a. Erroneous ground classification, together with vegetation changes due to seasonal variations, can adversely affect the reliable estimation of temporal landscape change.

In an attempt to identify cultural lost assets due to coastal erosion, reflectance analysis was carried out at Beckfoot with the aid of recent UAV RGB/NIR imagery (Table 1, see also deliverable report 3.1). The analysis was based on the proposed methodology and in-situ reflectance measurements described in Berra et al. (2017). The analysis consisted of a) conversion from RAW image format to dark-image corrected linear TIFF format, b) image correction for vignetting effects to remove darker edges and c) RGB/NIR conversion to reflectance. This process resulted in corrected RGB/NIR reflectance orthomosaics which were then used to derive Normalised Difference Vegetation Indices (NDVI), with an example shown in Figure 12. NDVI values lower than zero indicate the presence of water, positive values close to zero [0-0.1] indicate barren areas of rock/sand, values within [0.2-0.3] represent shrub and grassland, while higher values indicate the presence of vegetation. Due to intense farming activity over recent years, buried archaeological features which were observed with geophysics over Regions A, B and C, could not be detected on NDVI orthomosaics. However, this reflectance analysis will be adopted in future investigations of coastal erosion at Beckfoot using an enhanced UAV-mounted multispectral sensor as part of the methodological approach of a Natural Environment Research Council (NERC) Iapetus-funded PhD programme.

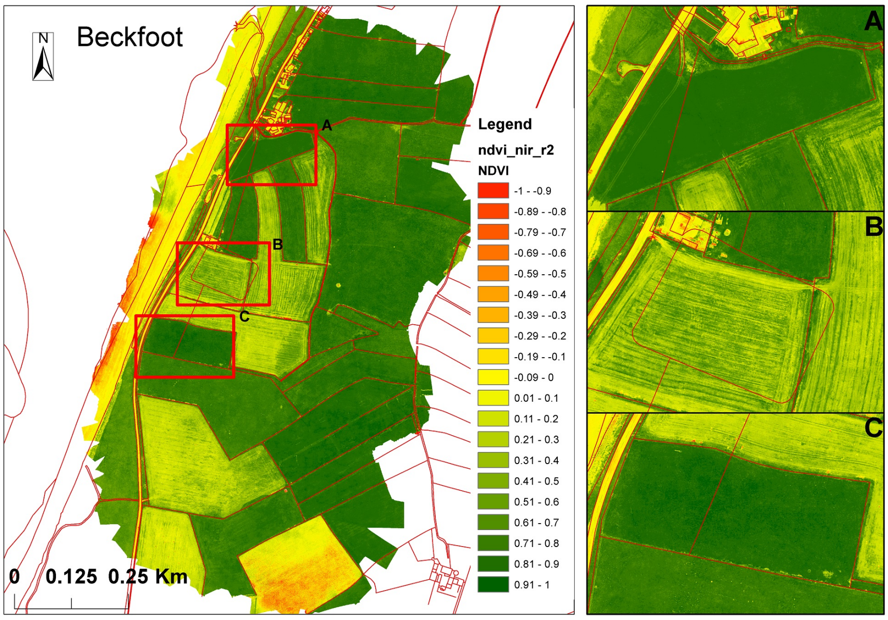


Figure 12- NDVI orthomosaic derived from 2016 UAV RGB/NIR imagery after reflectance analysis based on Berra et al. (2017).

USAL

From the different data sources stated previously in documents D3.1 and D3.2, the reconstruction process was divided in the following steps:

- Recording and 3D reconstruction of the current state of the *Alcázar* Gate and its intramural and extramural sections using different geotechnologies.
- 4D modelling of the *Alcázar* Gate based on the historical documents for two different temporal intervals.
- 4D modelling of the extramural and intramural buildings of the *Alcázar* Gate prior to their demolishment.

The reconstruction of the **current state** will provide the basis for the anastylosis process and also will be essential to anchor the plausible reconstruction of the lost building elements. This first phase required the classical steps of 3D modelling: to filter the non-desirable elements of the point cloud (e.g. pedestrians, cars, etc.) and the segmentation of the study area. The extraction of the basic primitives was done on the basis of cross sections. This process involves a generalization operation and a loss of accuracy due to the idealization of regular shapes (i.e. planes, cylinders, etc.). The addition of certain constraints, such as parallelism of the façades with the plumb line (Figure 13) also contributed to idealization and loss of reliability.

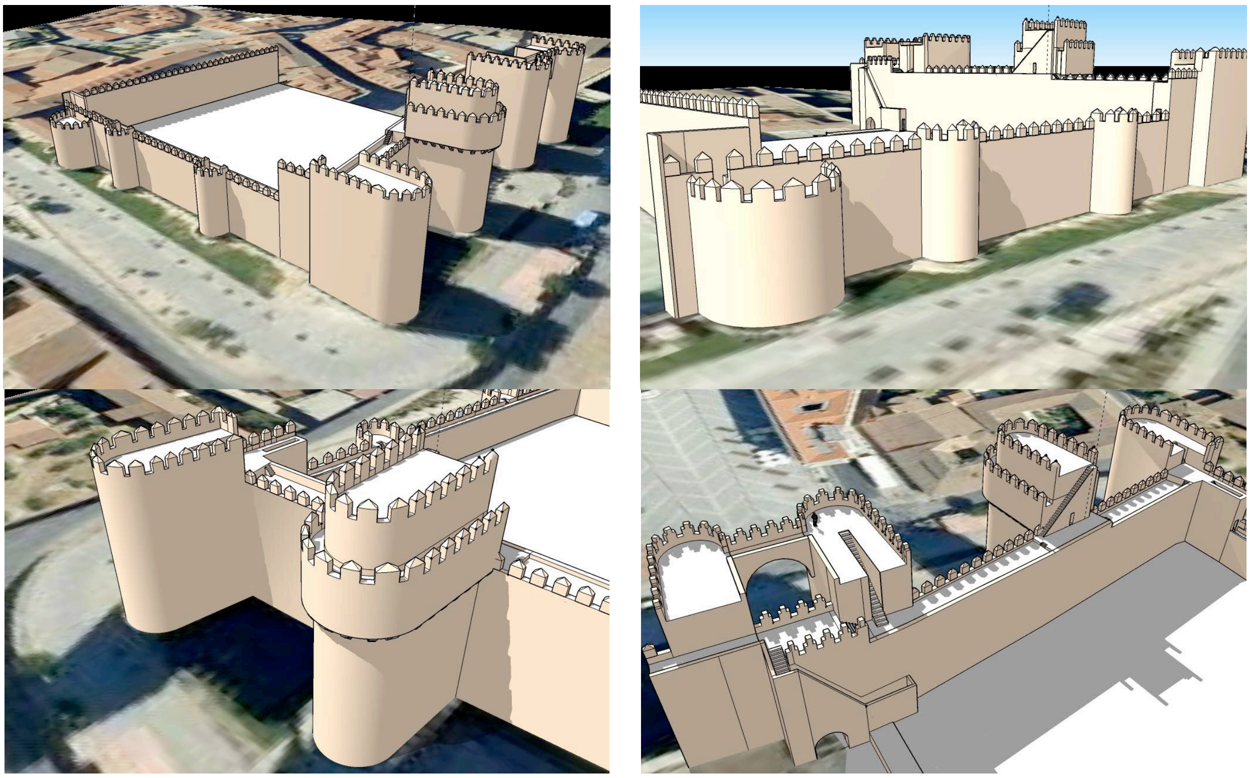


Figure 13 - Different views of the current state.

Intramural buildings involved two temporal stages according to the amount and type of historical information available. The first 4D reconstruction corresponded to the most modern, after 1750 when the *Alcázar Gate* (or citadel) was converted to barracks. In this stage the ancient drawings were vectorized and fitted according to the present remains.

The ancient drawings were already digitalized, but the scalebar was in ancient units, so the vectorization was fitted to the current remains. In this step, the spatial invariants of the old drawings do not verify a simple geometric transformation, being the discrepancies very large and not homogeneous. As a result, they were used in a relative way, namely, reconstructing the relative position of lost elements considering the current

remains. Thanks to old photographs of the demolition process, the interior walls width was incorporated. Also, the written testimonies informed about the demolition of the two south towers c. 1792, being the amount of anchor elements reduced.
One of the main key issues of this stage was the lack of information about the heights of buildings. From written documentation it was reflected that the building consisted of three floors, except the officers' gallery which only had two. According to historical data its height was 11 feet. This measurement is not accurate but enough to provide a supported hypothesis. Moreover, in the old photographs was detected a passage concordant with the written testimonies about the officer's gallery that allowed the communication among the buildings avoiding the courtyards. This hypothesis is reasonable in terms of both military and climatological conditions. The final plausible reconstruction is shown in Figure 14.

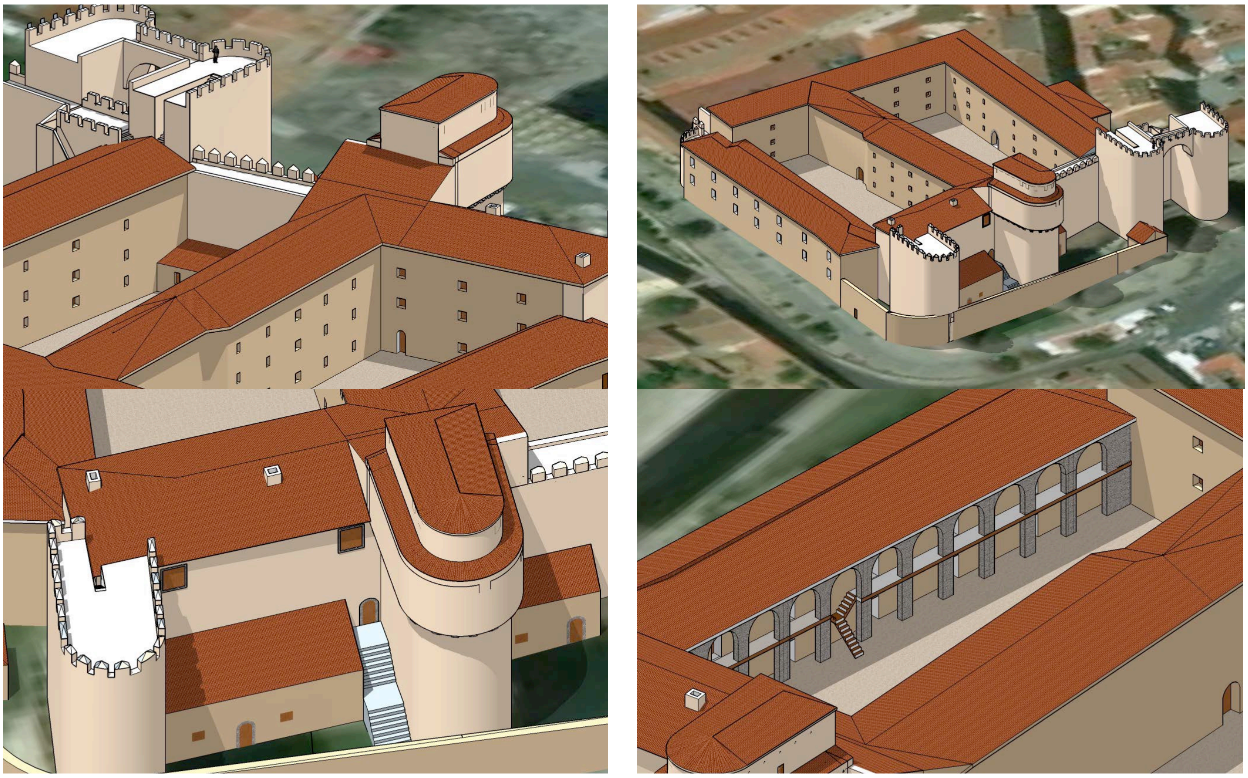


Figure 14 - Different view of the Alcázar after 1750.

The second 4D reconstruction refers to the "real" *Alcázar Gate*, when it was used as a citadel. The main problem of this stage was the lack of reliable historical information. We hardly had a few written testimonials and some stones that gave us clues to the volume of the *Alcázar*. There was necessary to employ constructive hypothesis based on similar medieval military constructions, such as the interior defensive walls, or the existence of the northwest turret (supported by the presence of a foundation). The likelihood of the 4D model generated (Figure 15) was reduced, as expected, by the combination of surveyed data and philological analysis.
On the basis of the current remains, the 4D modelling of **extramural buildings** was carried out based on several photographic sources which reduced considerably the uncertainty associated to the final 4D model. The process is similar to described in the previously, being the most remarkable difference caused by the nature of the historical source, in this case, old photographs.
The first issue is that extramural buildings disappeared and there are not current remains. The only anchor elements are the walls, which will be used to estimate the photographs scale. Secondly, the historical images have vanishing points, being necessary their identification to carry out the reconstruction.

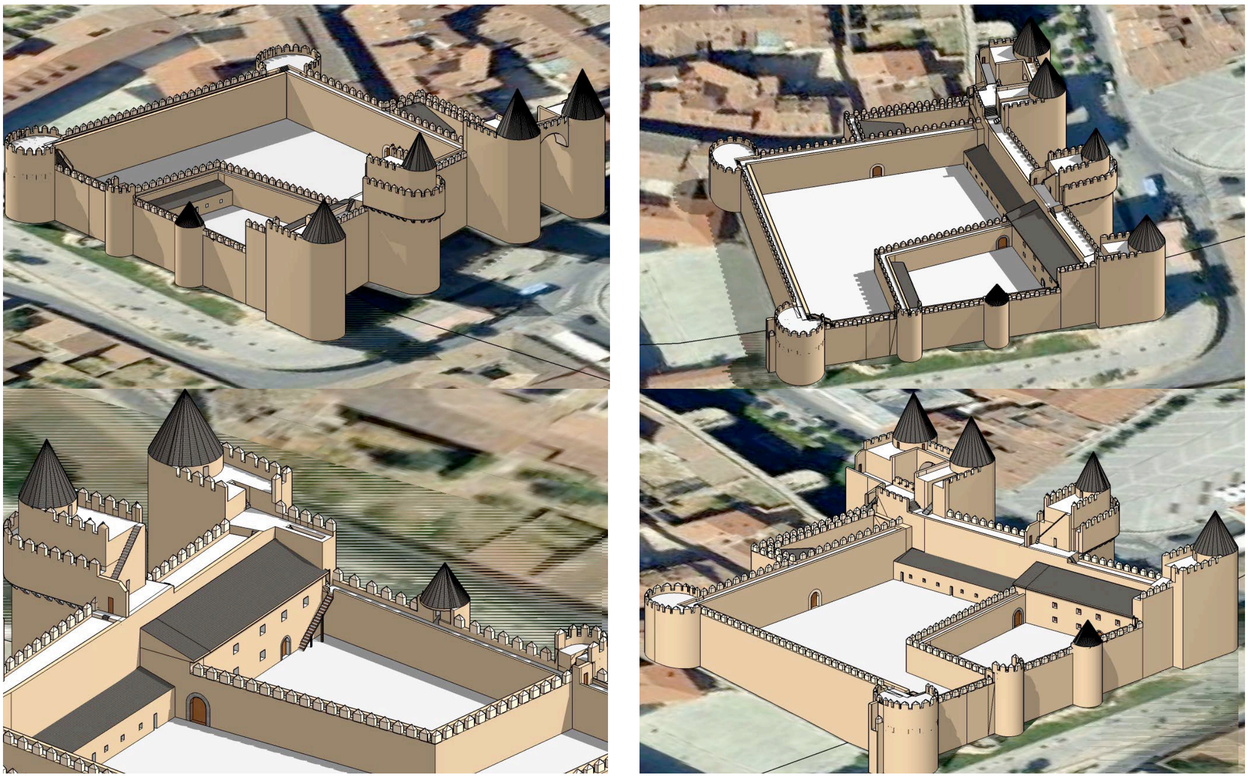


Figure 15 - Different view of the Alcázar previous to mid-eighteenth century.

The modelling was carried out in two phases, being the first the coarse modelling of building blocks, as idealized prisms (e.g. orthogonality between façades, round angles, etc.). They were scaled on the basis of identifiable elements of the Wall. The older the photograph, the higher the uncertainty due to the changes suffered by the Wall, especially by the rehabilitation and conservation interventions. For the older images, there was employed the distance between some stones. That allowed a reasonable reconstruction of the 4D model.

For the most representative extramural building, the *Alhóndiga*, the old photographs were used to vectorize and reconstruct the façade (e.g. elements doors, windows, columns, etc.). The different façades were segmented and projected according to their vanishing lines and the sub-image was fitted in the 3D model to add the details. Due to the different point of views, not the same historical photographs were used for all the buildings. Besides, the historical photographs were used to map texture, improving the realism of the final result (Figure 16).

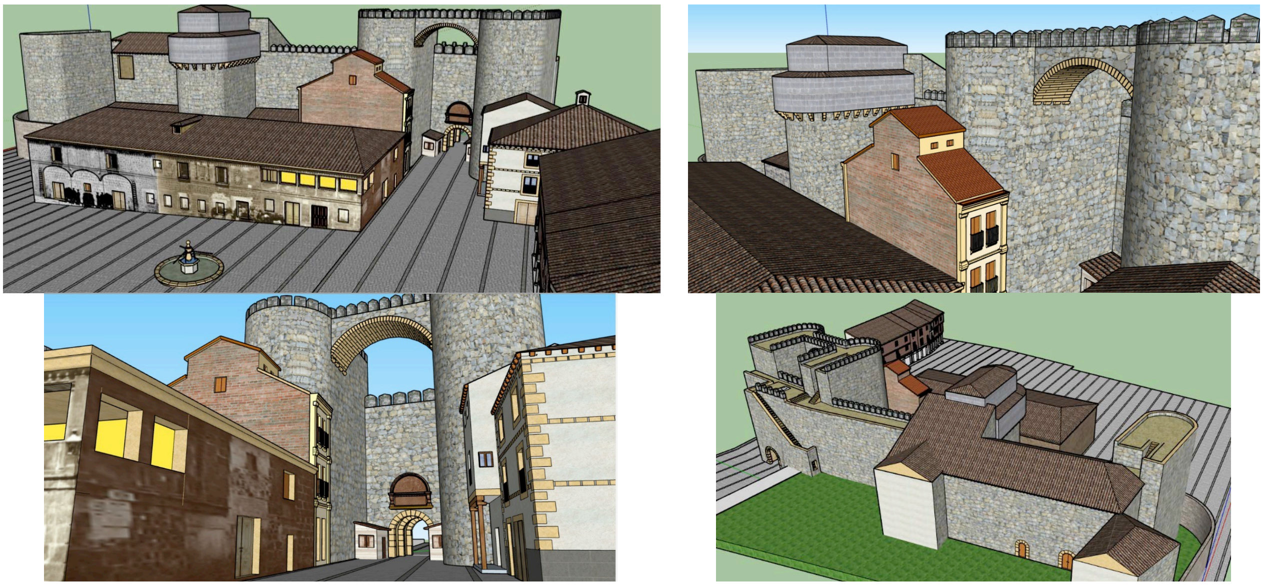


Figure 16 - Different view of the Alcázar previous to mid-eighteenth century.

In the case of overlapping between different photographs, there was not carried out any blending process or radiometric modification. Since, the historical images were registered in relation to the 3D coordinate system, it was possible to replicate the original point of view and compare both or add a current image (Figure 17).

Figure 17 - Extramural buildings: Old photograph texture integration (Laurent, c. 1865, Ruiz Vernacci Archive, VN-17214) with 4D modelling for the extramural section of the Alcázar Gate.

SSSA

In the study historical plans, maps were collected, and new data gathered (ALS, TLS, UAV RGB imagery). Historical models were prepared (interpreted and digitized) by history specialist of this period (Austrian times when the fortresses were built). ALS, TLS and UAV were used by specialist of photogrammetry, remote sensing and GIS. 3D models based of new measurements were interpreted and digitized under control of history specialist. Students also helped with some field works preparing their engineering works. The quality of data is different and we divided them into 2 groups: proper model with acceptable quality and some data still in the preparation stage (need some improvements) and failed data from data accuracy reasons or data completeness.
3D models of the following fortresses were prepared with success (Fig. 18 - 23):
- Fort Kosciuszko: 1856, 2017
- Fort Wegrzce: 2017
- Fort Sudol: 1895-1897, reconstructed for ALS and historical plans
- Łysa Góra: reconstructed for ALS and historical plans

Table 3 – 3/4D models obtained with different techniques for selected forts (in yellow with success, in light brown still in preparation or failed from data accuracy or completeness).

Name of object	CAD	TLS	ALS	UAV
Kościuszko	+	+	+	+
Batowice	+	+	+	+
Węgrzce	+	+	+	+
Bastion III	+	+	+	-
Marszowiec	+	-	+	-
ŁysaGóra	+	-	+	-
Sudoł	+	-	+	-

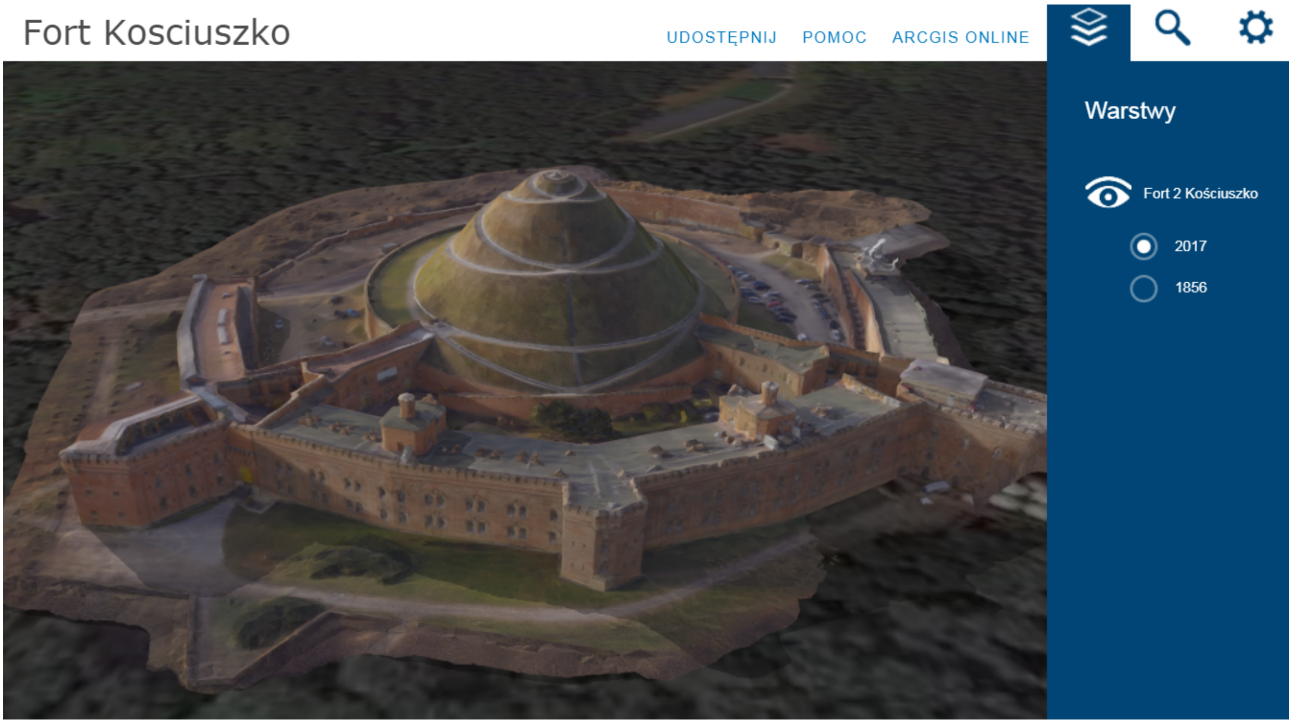


Figure 18 - Fort Kościuszko – UAV, TLS - 2017.

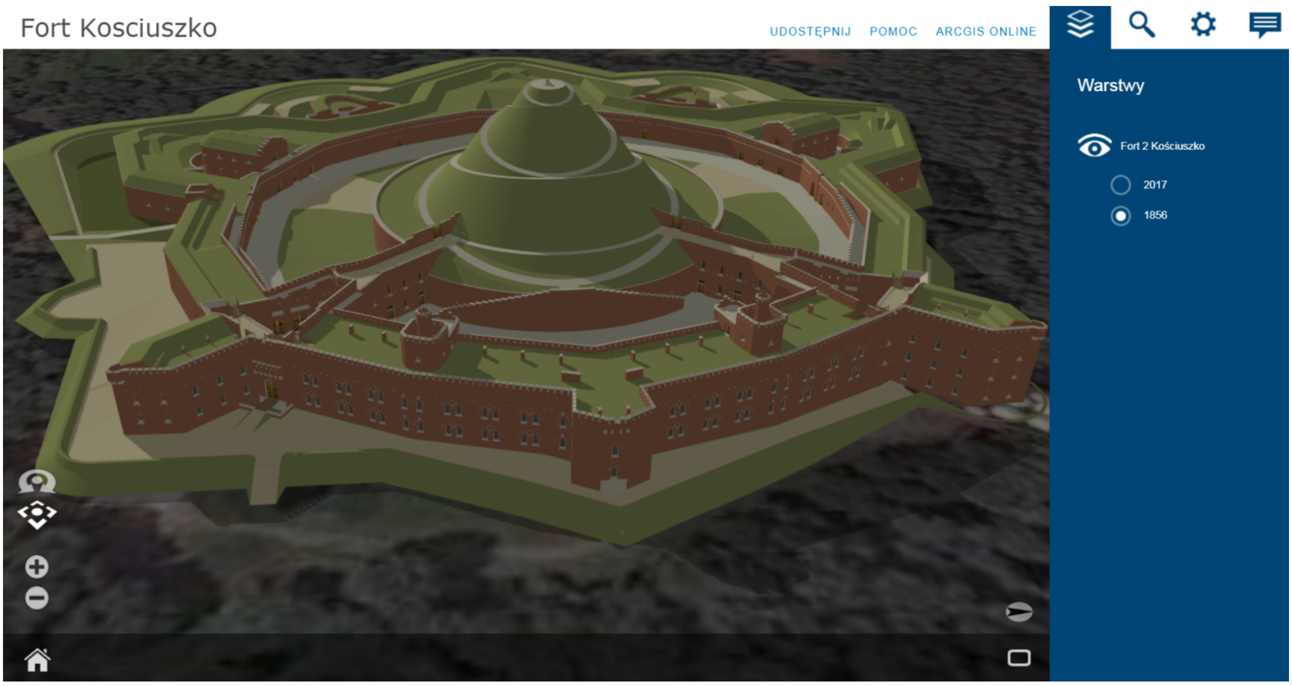


Figure 19 - Fort Kościuszko – historical plans 1856

Figure 20 - Fort Wegrzce – UAV, TLS – 2017.

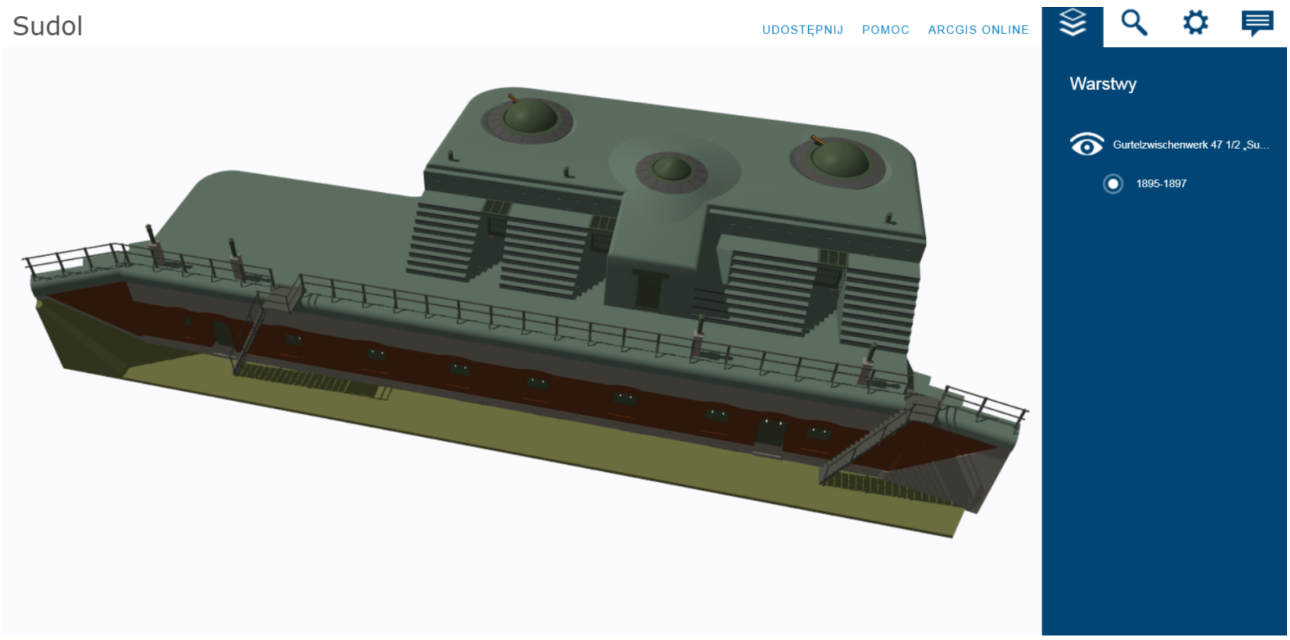


Figure 21 - Fort Sudol: 1895-1897 – 3D model.

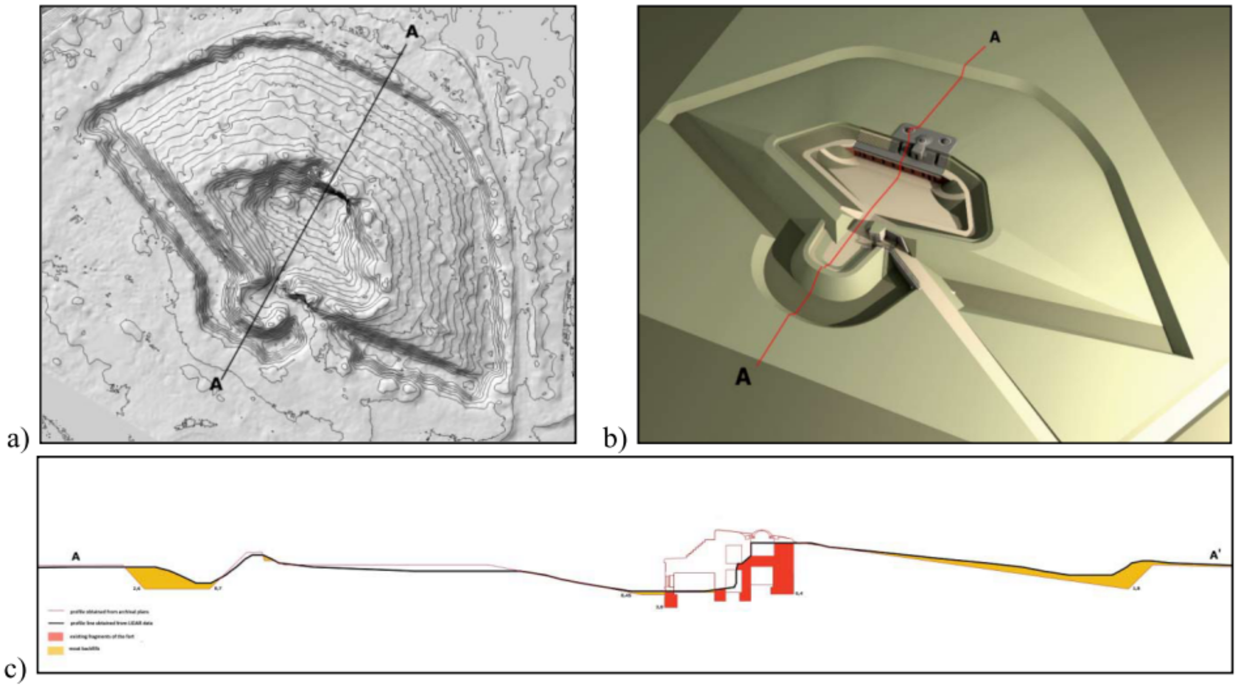


Figure 22 - Fort Sudol: a) 3D model of LIDAR data, b) 3D model of archival data, c) the profile along A-A line marked on a, b, showing changes between archival plans and the current state.

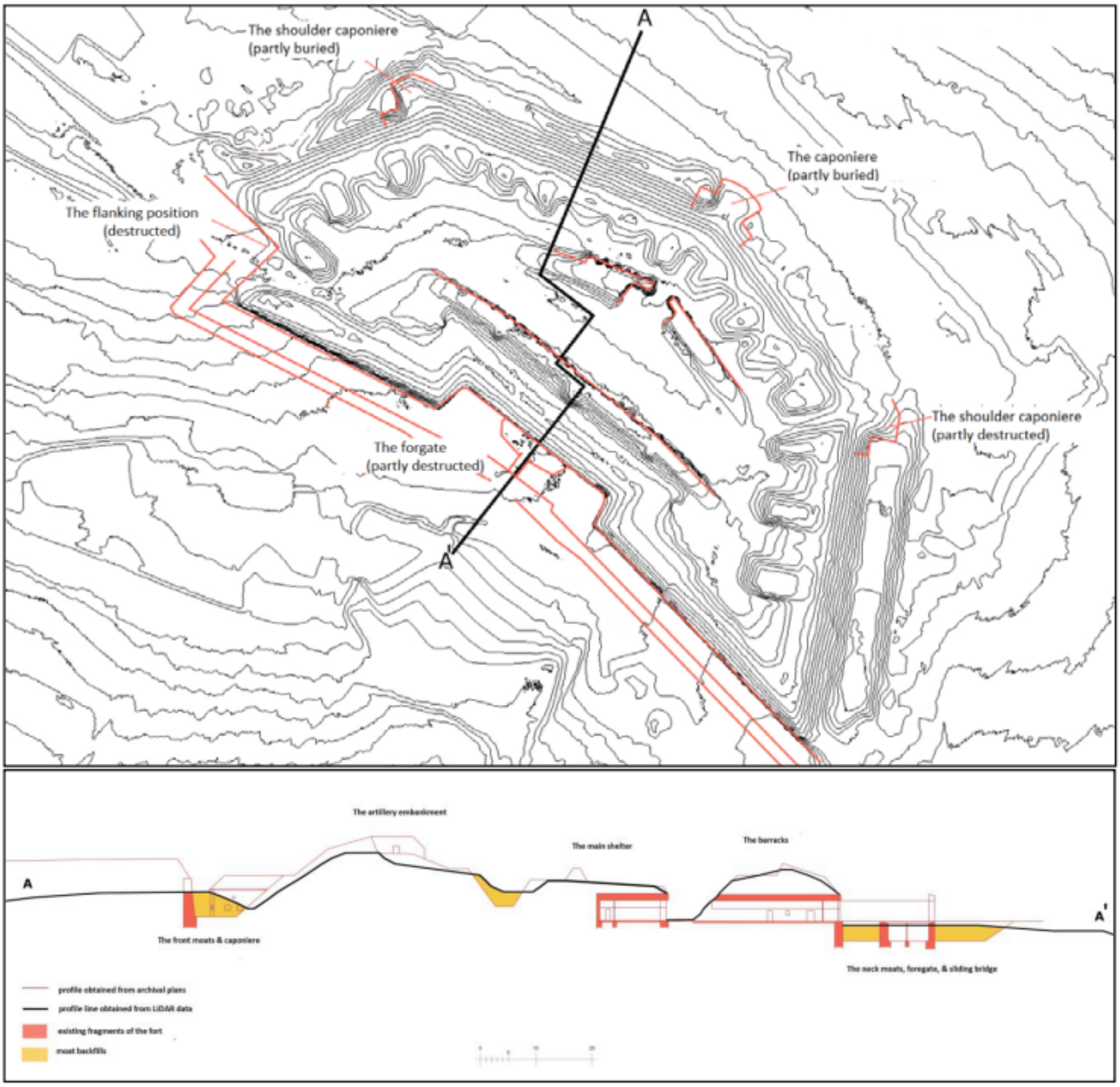


Figure 23 - Lysa Gora Fort: a) the isolines map obtained from LIDAR date, b) the profile along the A-A' line showing the changes between the archival plans and the current state of the object.