GEOMETRIC ANALYSIS OF THE ORIGINAL STANDS OF ROMAN AMPHITHEATER IN TARRAGONA: METHOD AND RESULTS

1. INTRODUCTION

Due to society's awareness of the cultural and civic values of world heritage, archaeological activity is now common in our cities. In some cases, the historical continuity of urban areas in Western Europe has led to the existence of historical sites within dynamic contemporary cities. One example is the city of Tarragona, which was Roman Tarraco. This city contains potential information about inhabitants from even earlier times than the foundation of the Roman city. Consequently, a working archaeological method is required that can be applied to all archaeological studies, to obtain thorough knowledge of the city. Standardized criteria should be used for the architectural representation of remains, as archaeological data span a range of disciplines, including urban planning, architecture and restoration.

We can use geomatic methods to achieve this goal. Such methods have advanced rapidly in recent decades [1][2]. Current topography allows us to capture quickly and accurately a large amount of spatial geo-referenced information, using total stations, GNSS receivers and terrestrial laser scanners (TLS). Photogrammetry can be used to document archaeological excavations metrically with minimal interruption of fieldwork. It is a much faster process than traditional manual drawing. Furthermore, all structures are photographically documented, which provides a historical archive of the different phases.

In this paper, we propose an archaeological survey methodology based on using instruments and methods to capture 3D information and accurately obtain a site's geometry, which can then be analysed rigorously. When we have good graphic and geospatial data on our cities' cultural and historical heritage elements, we can analyse how they were built and what changes they underwent throughout their history. The Tarragona study allowed us to validate the methodology. The establishment of alternative to terrestrial laser scanning (TLS) methods may help us to develop cheaper work systems. Our study focused on the Roman amphitheatre of Tarragona. The knowledge of the construction of this amphitheatre is incomplete, and a full 3D model is required to obtain more detail. Although the geometric shape of the amphitheatre's ground plan has been studied by many authors [3][4][5][6][7][8], elevation plans, i.e. sections of the stands, have not been analysed in depth. Regarding the surveying techniques, many projects have also been undertaken in which 3D scanners have been used to document Roman amphitheatres [9][10].

Metric information about plane elements (mosaics, wall paintings and facades, among others) can be obtained using a single photograph by correcting its perspective. Naturally, errors (for example, in depth) occur for elements outside the plane of work, and, to solve this, multi-image photogrammetry have to be used to obtain a three-dimensional model of an element. Today, digital photogrammetric systems can obtain a cloud of points, similar to that resulting from a TLS scan, through a process of automatic image correlation. So, the operator has a minimum task, he only needs to draw the representative lines of the object. This vector information can then be used to obtain a model practically identical to the original, with incorporated texture.

The use of a specific method and instrument should be evaluated according to the precision of the results [11].

The first consideration is study of which is the best technique to obtain information with enough accuracy to carry out the geometry analysis. The binomial cost/accuracy has to be considered, the first part entails the cost of the capture and management of the data. Since, a continuous model is necessary to obtain as many sections as the study needs the possibility of a topographic survey is discarded. Photogrammetry and TLS allow similar results, however the ratio cost/benefit makes us opt for the first technique.

The following sections describe work carried out to obtain a 3D model of the Tarragona Amphitheatre, which can be used in a geometric analysis, and to draw conclusions about its construction process.

2. THE ROMAN AMPHITHEATRE IN TARRAGONA

The Roman amphitheatre in Tarragona was built in the first third of the second century AD in a small peri-urban hollow, when the city was the capital of the largest province in the Roman Empire. A road, with its corresponding funerary area, passed close to the site. The construction of the amphitheatre represented the beginning of the architectural history of an area, whose characteristics have led to it being continuously occupied by humans. The amphitheatre was the last of the Roman city's great public compounds for urban leisure. The location of the building was chosen because of its proximity to the city (Fig. 1), accessibility, and the use of the mountain itself to cut out part of the stands [12].

Fig 1. Amphitheatre localization in Tarragona and top view of the amphitheatre

The amphitheatre is currently one of the most important monuments of Catalonia's past and its classical roots. In 2000, the structure was included in the UNESCO World Heritage Site of Tarragona. It is also on the list of the Seven Wonders of Catalonia, which was promoted in 2007 by the "Capital of Catalan Culture" foundation. It is one of the most visited historical sites in Tarragona. For example, in 2011 it was visited by around 137300 people.

Despite its cultural and tourist appeal, the Roman amphitheatre is difficult for visitors and experts to understand. The building has been considerably transformed by architectural restoration and attacks to the original structure, so the remains that are currently standing represent only a small portion of the original volume. From the perspective of history of architecture, it is difficult to understand the relation between the partially preserved and reconstructed remains and the original body. Thus, the amphitheatre is an appropriate challenge for the application of new graphic representation technologies.

The building was in use during the third century. Between the fourth and fifth centuries, it declined progressively, due to the city's economic difficulties and the increasing influence of Christianity, which was opposed to the traditional amphitheatre games. In the middle of the second half of the fifth century, the building was abandoned and only a small sanctuary has housed in memory of three martyrs from Tarragona, who were executed in the amphitheatre during the Christian persecutions [13]. At the end of the sixth century, a Christian basilica was built in the amphitheatre to commemorate their martyrdom. This was the first major architectural transformation, as stone blocks from the amphitheatre were used to construct the basilica, and the skeleton of the stands was left in lime mortar.

Due to the Arab occupation of the Iberian Peninsula, the city and its amphitheatre were abandoned between the eighth and twelfth centuries. In 1154, a new church, *Sanctae Mariae de Miraculo*, was erected on the site. The amphitheatre structure was further plundered for the new architectural construction, while new roads were opened connecting the site with the upper part of the city and its port area. We do not know what processes of degradation followed, but sixteenth-century descriptions or drawings of Tarragona indicate a very similar conservation level to the current time [14].

In 1568, the Congregation of “Puríssima Sang” was moved to the church in the amphitheatre, and in 1576, the Trinitarian Monastery occupied the space. New buildings were constructed throughout the area and pavements were raised. In turn, the amphitheatre floor was covered and the ancient buildings lowered. The Trinitarian Monastery remained in the amphitheatre until 1780. From 1792, the amphitheatre was adapted to accommodate prisoners of war. This new activity was the origin of the “Miracle prison”, which remained in use until 1908. At the request of the City of Tarragona, the Spanish government ceded ownership of the site to the city in 1910. To recover the full view of the medieval church, the old prison structures were demolished [15]. Unfortunately, the old walls acted as the church buttresses, and in 1915, the roof of *Sanctae Mariae de Miraculo* accidently collapsed. This marked the start of a period of degradation of the historical heritage that did not cease until 1948, when the Provincial Archaeological Museum undertook an intensive archaeological excavation of all the preserved remains.

In 1964, the Ministry of Education financed the activities of Artistic Heritage Brigades, who rebuilt part of the monument between 1967 and 1973. During the 1980s, the building was reconstructed and a scientific project was carried out by the Tarragona Archaeology Workshop-School [16]. The first topographic survey was carried out as part of the project. Since then, the historic site has been managed by the Tarragona Museum of History. All of these changes over the years have resulted in the preservation of the architectural plan, a segment of ima and media cavea, and the start of the summa cavea. No complete sections of stands remain, because the twentieth century restoration did not respect the original geometry of the monument. Consequently, the remains give the impression of an amphitheatre of a smaller scale than the original.

3. METHODOLOGY OF SURVEYING, MODELING AND REPRESENTATION

The archaeological planimetry that is currently available was drawn up in the last century, using typical instruments of the time. The “Tarraco Archaeological Planimetry” project revised the mapping, using global positioning with the ED50 reference system and UTM 31N cartographic projection [17]. Prior to this project, new technologies, such as digital mapping, digital photogrammetry and 3D CAD models, had never been used on the site. So Tarragona Amphitheatre had not been analysed before.

3.1. Work method

The model described below corresponds to the original Roman amphitheatre in Tarragona represented at a scale of 1:100. The survey was carried out using photogrammetry, supported by classical topography. Close-range photogrammetry is the most appropriate technique to obtain 3D information to the aforementioned scale, due to the quality/cost ratio [18].

With this technique the photographs are taken with standard non-metric cameras that had been calibrated by the operator to allow restitution with the required accuracy. The calibration is the process to determinate the internal camera parameters (focal, lens distortion and principal point dislocation) need to recover the geometric camera model. Off course, field and office tasks were required to complete the photogrammetric process correctly. An accurate study of the photographic coverage of the amphitheatre was conducted, to ensure proper scale and stereoscopic vision. We carried out the image orientation process to provide the same coordinate system for all models. Finally, stereoscopic models were obtained from which we could generate the model.

3.2. Photogrammetric surveying

To achieve a good stereo model, a suitable overlap is required between photos in each strip and between strips. In the case of the amphitheatre, a minimum longitudinal and lateral overlap of

60% and 30%, respectively, was considered adequate. Moreover, varying focal lengths had to be used to work with different distances and thus obtain a complete model.

A total of 167 pictures were taken using three different focal lengths. Of them only were used in the restitution and the obtaining of the several photogrammetric results those with the best resolution and higher scale. Two digital calibrated cameras were employed, the Canon PowerShot Pro1 with a resolution of 8 Mpixels and a focal length of 7.2 mm, and the Nikon D70 with resolution of 6 Mpixels with two focal lengths f = 30 mm for details and textures, and f = 70 mm for long distances. The firs camera was used from close range (2-15m) obtaining a pixel size of 1 and 6 mm in the ground. With the second camera the work distance allows to get a pixel size between 2 and 5 mm in the ground.

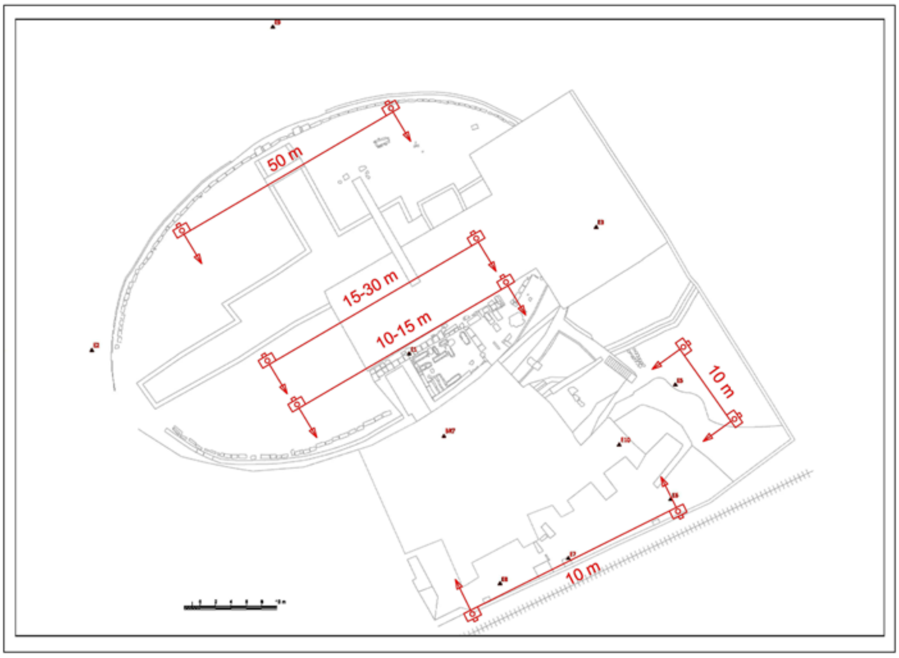

Fig. 2. Photographic cover. Each line represents the photographic base and the mean distance to the object.

The shoot was carried out as follows, Fig. 2:

Front facade: 3 strips using a focal length of 70 mm for the upper and intermediate strips, and 7 mm for the lower one. In total 22 pictures were taken.

Side facade: 2 strips using a focal length of 30 mm for the upper strip and 7 mm for the lower one. In total 5 pictures were taken.

Back facade: 3 strips using a focal length of 7 mm for all strips. A focal length of 30 mm was also used in the centre in 2 photographs. In total, 40 pictures were taken.

Grille: In this case, the detail was covered with a single strip with a focal length of 7 mm.

In total, 167 photographs were taken, of which 70 were used for the restitution and to obtain the model.

3.3. Image orientation

A topographic network, Fig. 3, had to be obtained before the image orientation process. The coordinates of control points that were identifiable in the photos were obtained from the bases of this network. These points where marked with targets to make easier their identification. More than 200 targets homogeneously distributed were measured with accuracy better than 1 cm. This allowed us to obtain support points and georeference models. The network consisted of two connected traverses. They were related to the reference system established by the Catalan Institute of Classical Archaeology (ICAC) during the “Tarraco Archaeological Planimetry” project, since two bases of the traverses made up the ICAC network.

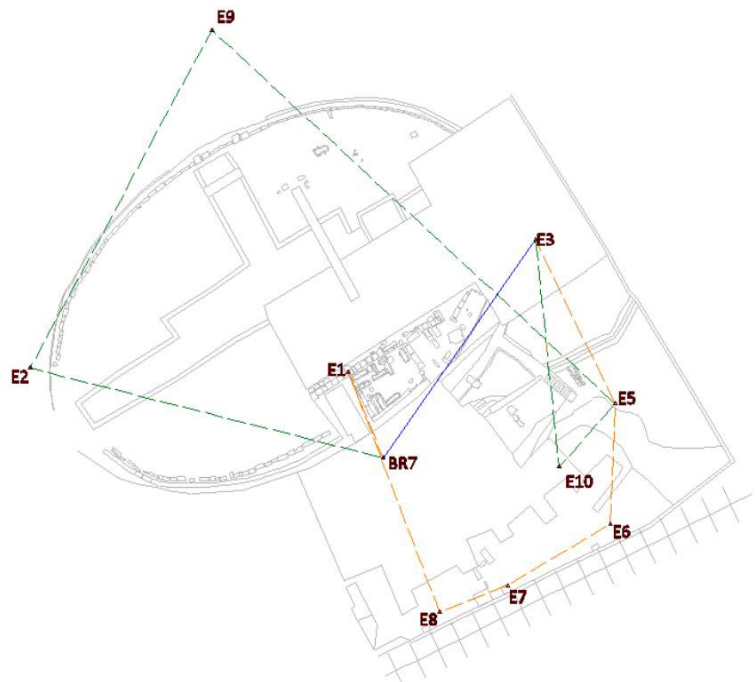

Fig. 3 Topographic network. Two traverses and a topographic base (BR7-E3)

The software used for the image orientation process was Topcon's Image Master. First, the relative orientation was obtained by measuring homologous points (15-25) between adjacent images. Then, the absolute orientation of each images was calculated using the control points. Thus, the images were oriented and the model was obtained. Finally, the block adjustment was calculated. After this process, Fig. 4, we checked that the parallaxes were less than 1 pixel and the residuals for the coordinates of the control points did not exceed 2 cm.

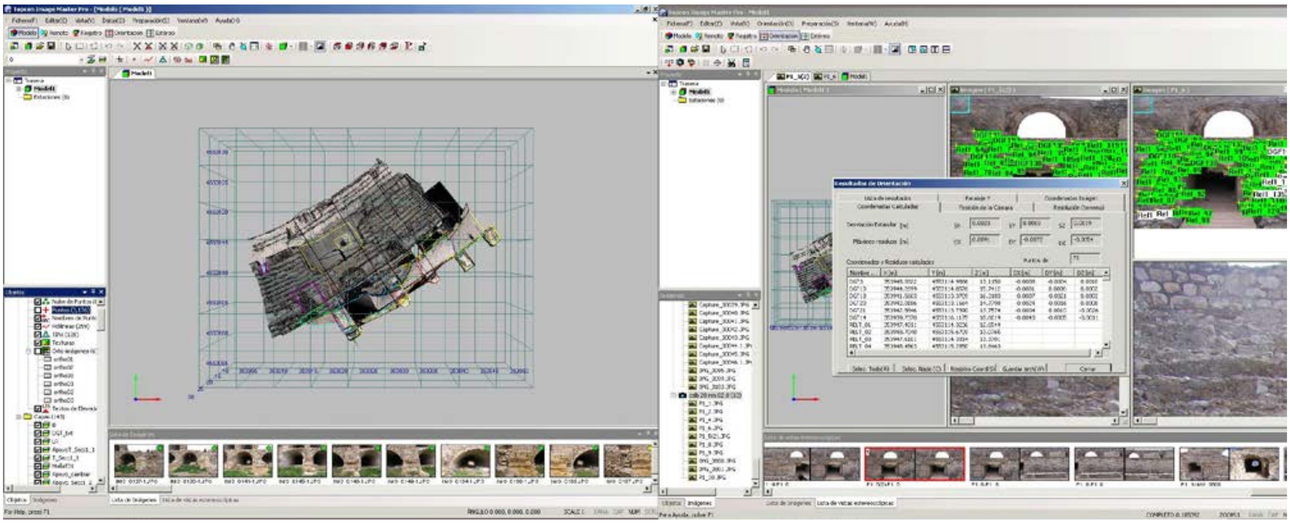

Fig. 4. Left, creation of the photogrammetric models, control and tie points used can be observed. Right, cloud of points obtained by photogrammetric correlation and the break lines used in this process.

3.4. Restitution and DTM (Digital Terrain Model) obtaining

Finally, the restoration was carried out to obtain a three-dimensional vector model, which was the basis of the subsequent graphical representations. So a set of drawn vectors obtained by topography and restoration were available to the next process.

The scale chosen to represent the model was 1:100. As in the cartography, the value of this scale determined the photographic shoot. The drawn vectors had two functions: a vector model was obtained, and they were used as break lines in the automatic correlation process that allowed us to achieve a spatial model with a resolution of 5 cm (Fig. 4). The use of break lines is essential to have a correct triangulation to obtain de model.

The complete model of the steps and the back facade was coloured from the images. In this way, a synthetic and realistic model was obtained, from which several products could be derived, such as sections, ground plans, elevations and isometrics.

3.4. Longitudinal and cross sections

The 3D photogrammetric model generated a corpus of documents and several geometric studies that increase our knowledge of the monument. For the first time, we have sufficient reliable data to successfully analyse a number of aspects that are fundamental to understanding the amphitheatre, both in terms of its geometry and calculations. Furthermore, we can study many aspects that have been overlooked in the past. However, in this paper we focus on analysing sections obtained from the 3D model, which are essential to define the amphitheatre geometric shape, from which calculate the building’s spectator capacity.

These sections were obtained from the DTM model of 5 cm, however there are zones with higher resolution, and the main lines obtained by topographical survey and photogrammetric restitution. This mixed model has served for the different sections without loss of important geometrical changes. Then they were edited and the completed sections were drawn. We generated four transversal sections and one longitudinal section to define the profile of the stands, because the high rate of erosion and various restoration and consolidation actions have distorted its original appearance (Fig. 5).

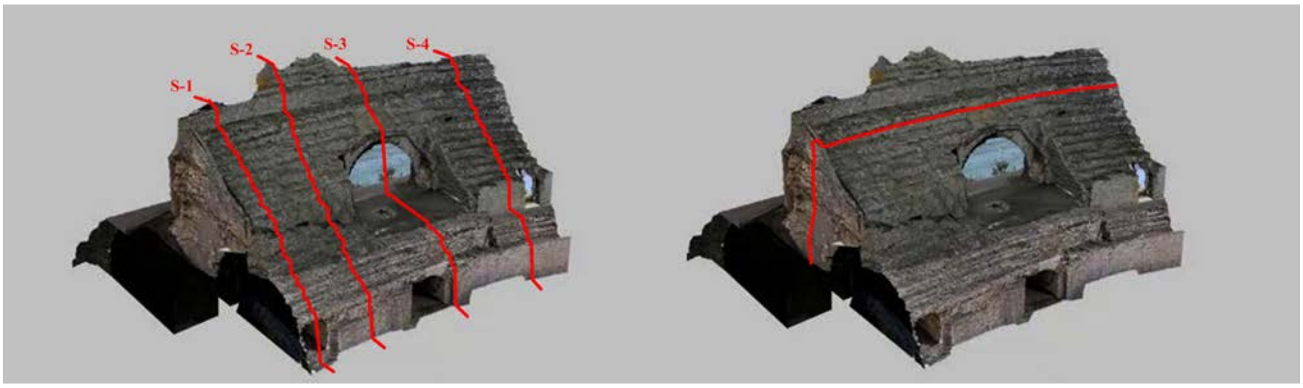

Fig. 5. Position of the cross and longitudinal sections

Section 1 crosses through the first series of preserved vaults (Fig. 6.1), Section 2 crosses the vaults' support walls (Fig. 6.2), Section 3 passes through the axis of the authorities' tribune (Fig. 6.3), and Section 4 passes by the area restored in the 1960s (Fig. 6.4). Finally, a longitudinal section crosses a separation point between the summa and media cavea (Fig. 7), where there is a change in inclination of the vault.

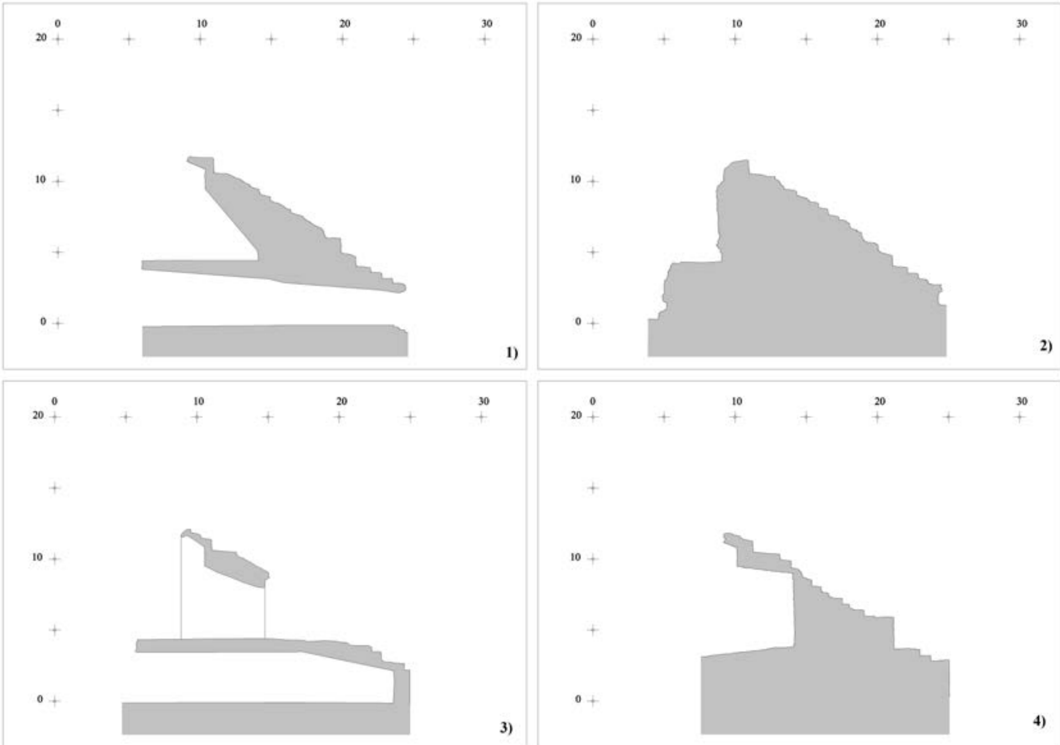

Fig. 6. Real cross sections of the cavea

4. GEOMETRIC ANALYSIS OF THE STANDS

An analysis of these sections allows us to reinterpret the stands in the maritime facade (Fig. 8). This would presumably be the scheme developed around the perimeter, even in the area where the building was cut into the rock. A comparison of these sections shows considerable divergence between the original part and the stands that were rebuilt in the 1960s (Fig. 6.1 and Fig. 6.2 compared to Fig. 6.4). There is no coincidence in the design of the vaults or the profile of the stands. For example, the separation wall between the ima cavea and media cavea differs by almost 1.30 meters (Fig. 8). This is because a documentation error in the architectural restoration confused the last row of the ima cavea with the remains of the separation wall. There is also a discrepancy in the size and number of stairs in the restored part.

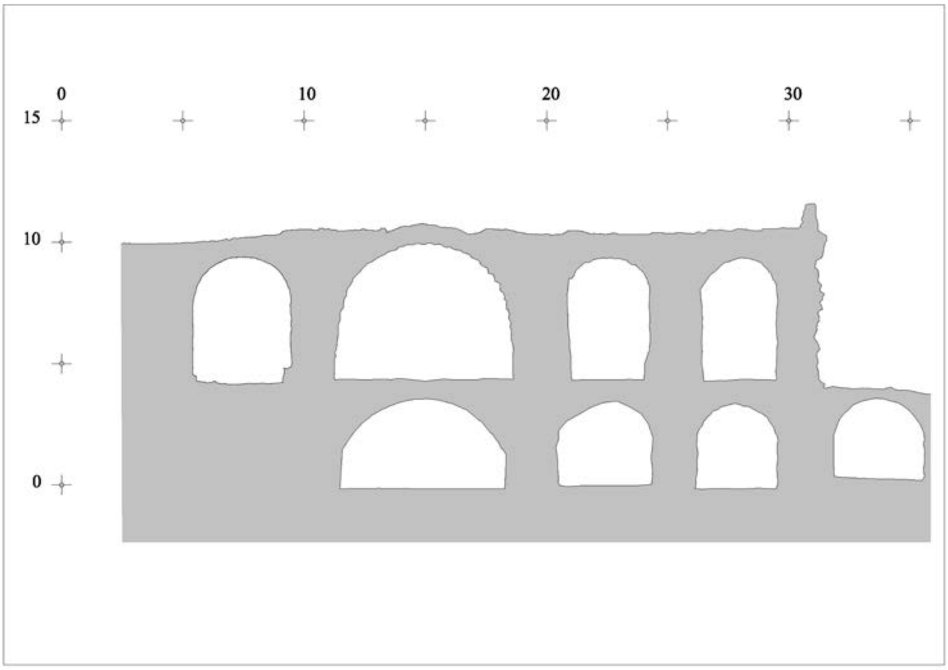

Fig. 7. Real longitudinal section of the cavea’s vault

A metric analysis of the remaining original structure identified a cavea divided into three parts by corridors or praecinctionis. The dimensions are given in Roman feet, because this was the unit used when the monument was planned and built. A Roman foot “p” (pes correctus, in plural pedes) is 0.296 meters. Thus, 15 p are 4.44 meters. As was common in buildings for Roman entertainment, the ima cavea, media cavea and the summa cavea were separated by walls that formed the railing of the first row of seats. Ima cavea were approximately 15 p wide, with three rows of 3 p wide and about 1.5 p high. The current height is between 1.2 and 1.3 p, due to natural and anthropogenic erosion. A distribution of heights of 1.5 p fits the general scheme, and is coherent with the metric system used in the overall design of the stands. We should also add the measurements of the stone seats, which were about half a pes correctus in height. The stones were reused in the walls of the Visigoth basilica. In the upper of the three cavea, there could have been a praecinctio that was about 3.5 p wide and slightly raised to facilitate the distribution of the audience. The media cavea would be about 6 p above the ima cavea level and would consist of 8 or 9 rows of about 2.5 p wide and 1.5 p high. At the top would be another praecinctio about 6 p wide. The summa cavea is difficult to define because only two rows are preserved. It is about 5 p above the media cavea and the only way to deduce its size is from the intersection of the overall width of the building with the slope of the stands documented in the 3D model.

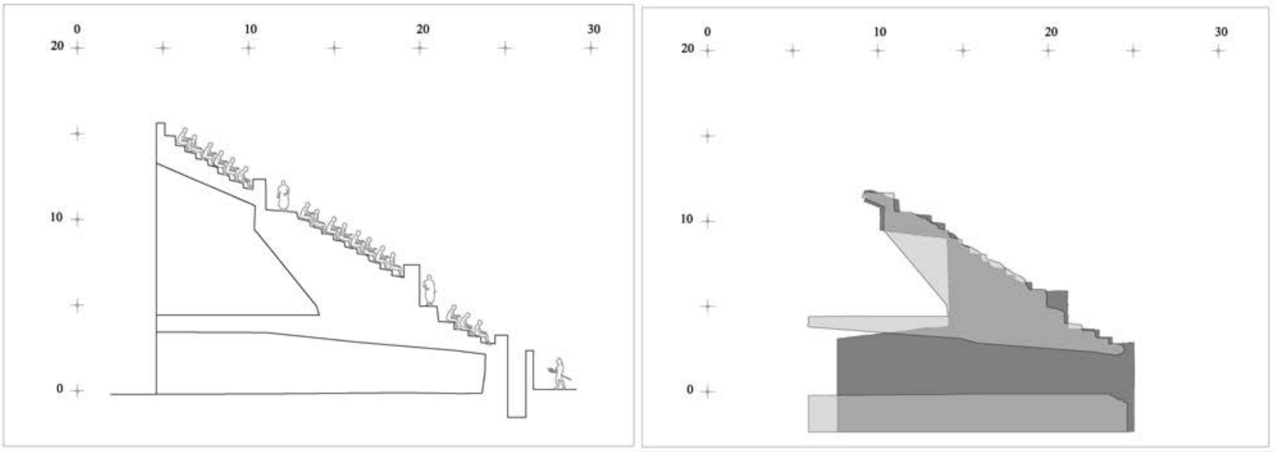

Fig. 8. Left, theoretical longitudinal section from the analysis of real sections. Right, overlap of the sections between the original and reconstructed areas, comparative study.

The current width of the stands is about 20.5 meters (70 p) and their slope angle is around 32 degrees (Fig. 9). These measurements allow us to hypothesize a suma cavea that was 20 p wide and 50 p above of the level of the amphitheatre floor. From the theory of a seating section of 2.5 and 1.5 p (Fig. 9), the summa cavea would have 6 or 8 rows of seats more than the upper praecinctio. This result differs from those found in current capacity studies.

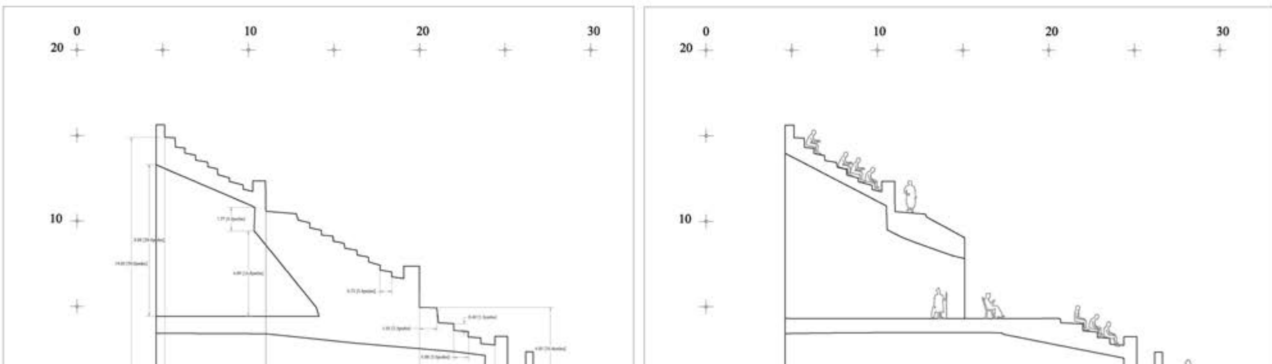

Fig. 9. Left, theoretical section with indications of the heights in meters and in romans feet (1 roman foot= 0,296 m.). Right, theoretical section of the pulpitum area and distribution of public

The redefinition of the stand's profile, as well as the interpretation of the overall geometry of the building [19] has allowed us to specify the theoretical number of spectators. The hypothetical number is between 10500 and 11800, which could be reduced by 5%, due to empty spaces in stands (doors and vomitoria). This amount is significantly lower than that established by other studies [20][16]. The capacity of the amphitheatre of Tarragona was significantly lower than that of other Hispanic amphitheatres in provincial capitals. It was even smaller than the amphitheatre of Italica, which was built in a similar period [21].

The theoretical section coincides with the original stands, but not in the pulpitum area (Fig. 9), where you can see the remains of two lower rows and it is difficult to define the ima cavea. Although elements that separated the authorities from the other spectators can be imagined, there are no remaining evidence of them. The pulpitum vault is higher than the media cavea and there was only one upper circulation corridor.

The photogrammetric survey was also carried out inside the support vaults of the stands, which allowed us to find out more information about the substructure of the amphitheatre. The vaults that supported the ima and media cavea have been documented, as has the start of the summa. Furthermore, in alignment with the axis pulpitum, a low vault communicates the amphitheatre floor with the outside of the building. This could not be documented by photogrammetry, since is not accessible.

These vaults have undergone consolidation and reconstruction works that altered the original geometry and are difficult to define precisely. However, we have established that vaults that were 10 p wide, no more than 12 p high and separated by about 8 p, supported the ima cavea. The media cavea had the same system, but with slightly higher vaults of 17 p (Fig. 10.1). A vault higher than the media cavea (4.4 - 5 p) sustained the summa cavea, but the 1960s restoration in the area prevented us from defining it better. We cannot deduce the maximum height of the upper vaults from the outside. However, they would have been approximately 30 p high. The vault system differs slightly in the pulpitum area. The bottom is a low vault, which is located over approximately 9 feet of lateral surface. The vault is 23 feet wide and about 12 p high. The vault that covers the pulpitum is 8 p away from the other vault. It is the largest and highest of all, and the only one visible from the stands. It measures 25 p wide and a maximum of 19 p high (Fig. 10.2).

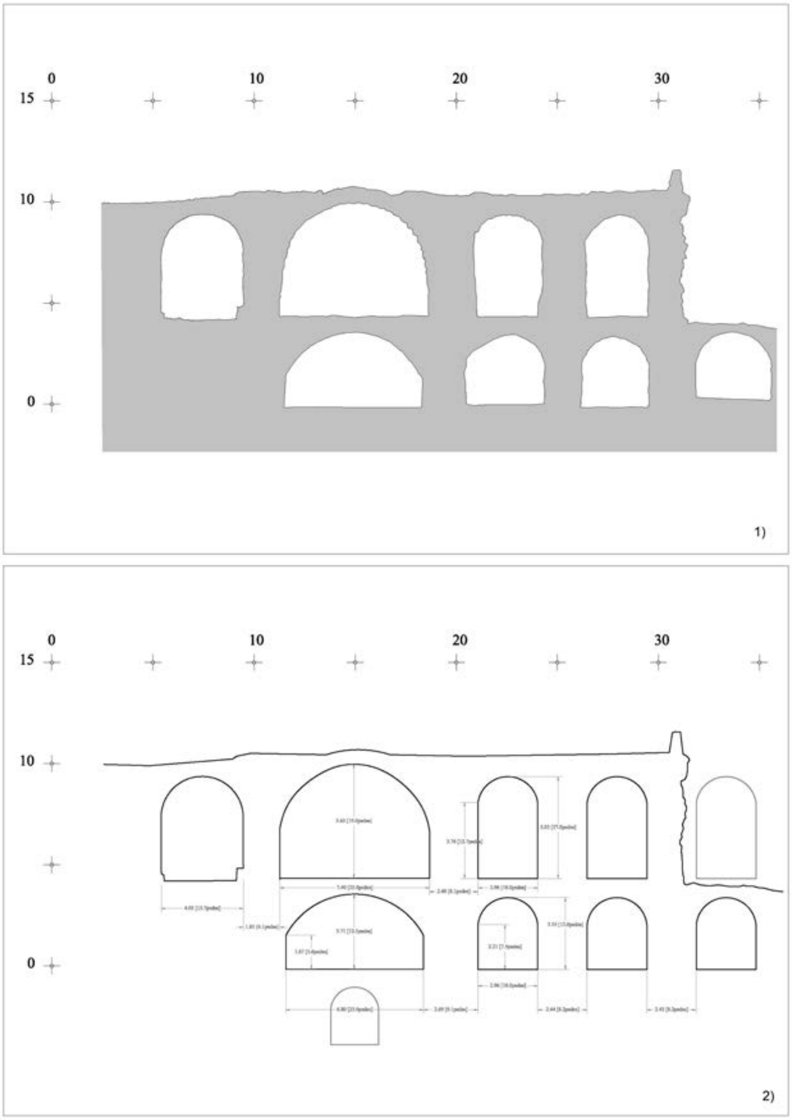

Fig. 10. Theoretical longitudinal section with indications of the heights in meters and in romans feet

5. CONCLUSIONS

In the documentation of a historic building, the main concern used to be to obtain the highest quality geometry and precision of architectural detail. However, with the development of massive data capture systems, the similarity between numerical representations and architectural reality has become sufficiently close to speak of a generation of digital "clones". In other words, we can create near perfect copies of reality. There is no doubt about the documentary value of these digital products, which are mnemonic elements that can be interpreted anywhere and at any time. However, graphic documentation is much more than a purely descriptive element and, in fact, it is not an end in itself. Carrying out a survey is generally hard work and its cost has to be offset by the benefits that can be obtained from its subsequent use.

This article does not focus exclusively on the process of obtaining a digital model. It also addresses the conclusions that can be drawn from a specific monument. The original area of the stands in the Tarragona Amphitheatre was the subject of a digital photogrammetric survey. The results were a digital model that was useful for archaeological analysis. The model provides a detailed geometric study with a restoration proposal that defines the architectural section formed by three bodies: the cavea, separated by praecinctionis. The ima cavea would have consisted of three rows of seats, the media cavea of eight and the summa cavea of six. We must take into account the size of the original stone blocks. Hence, each of the seats would have been 3 p wide and 1.5 p high.

In addition, the maximum dimensions of the stands may have been about 50 p high by 70 p wide. If we add the theoretical width of the upper praecinctio, and the ashlars from the lining of the facade, we can hypothesise that its separation from the amphitheatre would be nearly 80 p. These height and width values can hardly be coincidental, because their relationship is too close to auric proportion. In addition, it has been demonstrated that architectural reconstruction in the 1960s was carried out without taking into account any previous studies. Consequently, the reality was distorted and the restored section does not match the original construction.

The architectural section of the pulpitum area is another singular element, where the media cavea disappears completely, while the ima cavea almost spans the entire section. This arrangement is logical, because the area received a distinct architectural treatment to create a privileged field of view for the authorities. From the perspective of construction, we identified the pattern of separation of the supporting vaults from the stands. They are regularly distributed with a constant width of 10 feet, except in the pulpitum area, whose singularity led to the construction of vaults of greater width.

All these data illustrate the significance of the building. The definition of the perimeter of its external façade, and a lower audience capacity, set Tarragona Amphitheatre in the lower-middle stage of such constructions in the Western Empire [22][23]. The fact that the sum capacity of the cavea is possibly lower than the media cavea highlights, although we believe that this architectural reality does not correspond with the importance of the political capital of Hispania Citerior, reflected in its Provincial Forum of 12 hectares, the construction must be assessed in its chronological context. The current data indicate that the Tarragona Amphitheatre was built in the first half of the second century AD and is one of the later amphitheatre to be constructed in the Hispanic provinces [24]. The economic situation in second century Hispania was very different to that of the previous century, and in this case, it appears that the amphitheatre was constructed with the patronage of the Provincial flamen or priest. This indicates the difficulties that the local elite had in financing a building with one of the most practical leisure acceptance of Roman society. Thus, its size is significantly different to that of the amphitheatre of Italica, birthplace of Emperor Hadrian.

Finally, the data obtained from the photogrammetric model analysis increase our knowledge of the monument. The analysis is an important step forward, but insufficient to gain an overall understanding of the site. Nevertheless, it is an essential methodological stage within the scientific process. A future study of the Tarragona Amphitheatre, using the results of the study presented here, will define the original building project and the logic of its construction.

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