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Historically informed digital reconstruction of the Roman Theatre of Verona. Unveiling the acoustics of the original shape.

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Abstract. The Roman theatre of Verona is one of the most beautiful open-air theatres, still in operation by keeping the artistic programs throughout the winter and summer seasons. Inaugurated during the 1st century BC, the theatre fell in disuse caused by natural (e.g. fire, earthquake, flooding) and human (e.g. barbaric devastations, private properties) destructions. During the following centuries, many iconographies and drawings interpretations have been made in form of sketches by painters and architects (i.e. Caroto, Palladio, Guillaume), other than amateurs (Monga, Pinali) of the arts. Only recent excavations undertaken during the 20th century allowed a faithful reconstruction of the theatre owed to the critical and archaeological approach kept by scholars (i.e. Franzoni, Bolla) who compared the historical documents with the discoveries conveyed on site. On this basis, acoustics measurements have been undertaken in order to photograph the existing conditions of the incomplete *ima cavea*, which is what has been left by the original monument. The first digital model has been realized in order to calibrate the absorption coefficients of the applied material with the results obtained by the survey. Additionally, another 3D reconstruction has been realized digitally, with the performance of the acoustic simulations that allow restoring the listening environment inside the theatre at its primordial shape. A comparison between the existing and the original volume size highlights the difference of the acoustic parameters, telling that better listening conditions would be if attending a live performance during the ages of the Roman Empire.

1. Introduction

The Roman theatre of Verona has always been subject to a discussion about its original shape since ever [1-3]. The different hypotheses of its reconstruction have nowadays been inherited by scholars and architects of the past, who based their knowledge upon iconographic documents and on a few monumental rests found from a poor campaign of archaeological excavations [4-6].

Contemporary studies carried out during the 20th and 21st centuries were mainly focused on the analysis of the drawings and the captions, without presenting any three-dimensional proposal other than a recalled hypothesis supported by Palladio and translated in a wooden scaled model realized in 1997 by the architect G. Anselmi, still preserved in the Civic Museum of Verona, as shown in Figure 1. Although this scaled model tried to understand the original shape, based on Palladio's vision, it should be clear that it remains one of many hypotheses of reconstruction given by one of the most accredited Italian architects of the 17th century. In spite of the good intentions that such wooden model claims to have, the authors of this paper would like to make a distinction between evoking and rebuilding, underlining that certain freedom of imagination is granted for the evocation of a historical building by using the imagery to fill the gaps of lacking information. What has misled the generations of scholars after Palladio is the diffusion of his drawings' illustration recognized as absolute and ultimate truth.

The concept of reconstruction, instead, follows rather the process of recovering the value of a certain building even if it is missing the completeness of its restoration because parts of it do not exist materially. As such, the authors' approach was not to fulfill the gaps of information with obvious or personal justifications but to compare official documents, iconographies, and archaeologists' publications with the site discoveries found by the excavations of the 20th century. The result is a faithful digital reconstruction based on the available documents and publications as the main resource that contributed to making this work possible.

Figure 1. 3D model reconstruction based on Palladio's studies. Realization in 1997 by the architect Gabriello Anselmi, with the collaboration of Sara Gottoli and Luca Savio. Civic Museum of Verona.

2. Historical background of Verona

During the first Roman expansion along the river Adige, Verona was a small village developed along two main roads, called *Via Postumia* and *Via Claudia Augusta* [1], as shown in Figure 2. During the republic age, in 89 BC Verona received the title of a Roman colony, which saw the birth of an important bridge (i.e. *pons lapideus*) connecting the two banks of the river [1]. The quick growth of the residents' number brought to the birth of a new center designed under the Roman urbanistic criteria, which is a perpendicularly squared grid based upon the two most important roads called *cardo* and *decumano* [1]. Under the influence of Julius Caesar, Verona was proclaimed a *municipium* (i.e. town) in 49 BC, to be governed by local magistrates [1]. As such, a great transformation began: the main doors of the external city walls became monumental and the civic spaces saw the construction of different public buildings [1].

Figure 2. City map of Verona.

In particular, at the foot of the hill of St Peter, the demolition of old buildings and the construction of a new theatre fell into the urbanistic strategy of the already planned layout. The idea of building a theatre out of the core of the village was primarily due to taking advantage of the natural slope of the hill to save as many construction materials as possible to support the steps of the *cavea* [1]. The possible period of the theatre construction would be between 27 BC and 14 AC [2].
The theatre was surrounded by a temple honored to the god *Janus* or *Serapeum* or *Sun,* built on top of the hill [1], as shown in Figure 3. The hypothesis that the temple was dedicated to the three main gods (i.e. *Jupiter*, *Juno* and *Minerva*) was compromised by the excavation of 1851, on the occasion of the construction of the Austrian military barracks in replacement of the original temple [1].

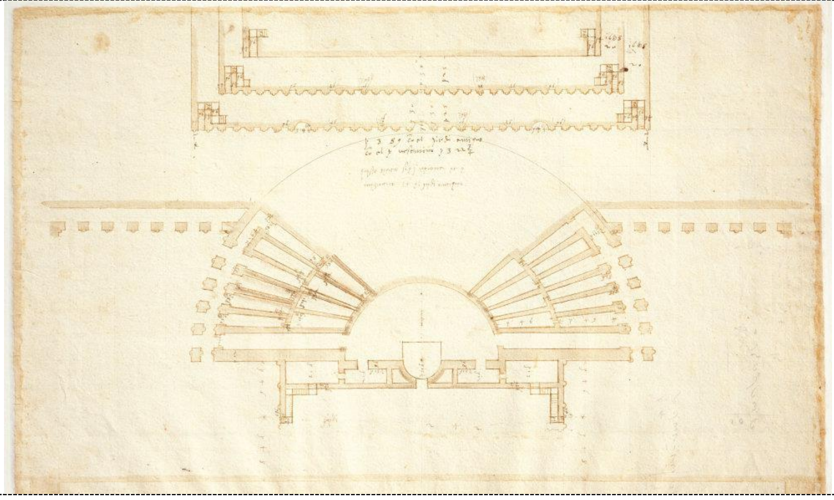


Figure 3. Roman theatre of Verona drawn by Palladio. Provision courtesy from RIBA.

3. The history of a theatre

The Roman theatre during the republic age was simply composed of a wooden stage with a curtain in the background while the audience was sitting on benches [1]. The theatrical shows have been performed in Rome since 264 BC, but a masonry construction was built only in 174 BC and soon demolished after the *ludi* (feasts) [1]. The first solid theatre was built by *Pompeius* around 55 BC and after two decades the theatre of Verona has been built following the same concepts [1]. Both theatres of Verona and Trieste were considered the most important of the Augustan Region X [1]. Similar to the Greek culture concerning the structural typology and construction techniques, in Verona the Romans used the slope of the hill to dig the semicircular upside-down cone, finding in the natural stone the support to the *cavea* [1]. Vitruvius in his book *De Architectura* cites the theatre as the first public construction to be built after the *forum* [2]. It has been said throughout the centuries that the theatre of Verona is an admixture between the Greek and Roman theatre, but conversely, it confirms the Romans' capacity in adapting the architectural proposal to the difficulties of the natural sites [4]. The total construction should cover an area of 150 m width and 100 m depth, with a height difference of 60 m [2].
The name of the person who promoted the construction of the theatre is unknown [2]. He should be one of the municipal committees awarded with honors [2]. The high quality of the architecture and of the sculptures indicate that the committee should have a closed relationship with Rome, being a spokesman of Roman politics in another part of the empire [2].
The scenic building became a solid structure built in front of the river and the orchestra was between the scenic building and the *cavea*, occupied by movable seats for the aristocracy [1]. The scenic building is survived only in few parts, which allows us to imagine that it should be divided into three niches, having the central one (*valva regia,* used by the main character) deeper and round, and the lateral niches (*hospitalia*, reserved to the actors coming from the countryside) were smaller and with rectangular shape [1, 2, 3, 5], as shown in Figure 4. The orchestra level in Verona was approximately 1.4 m below the *proscenium* level [1] and the diameter of the orchestra was 29.64 m [6].

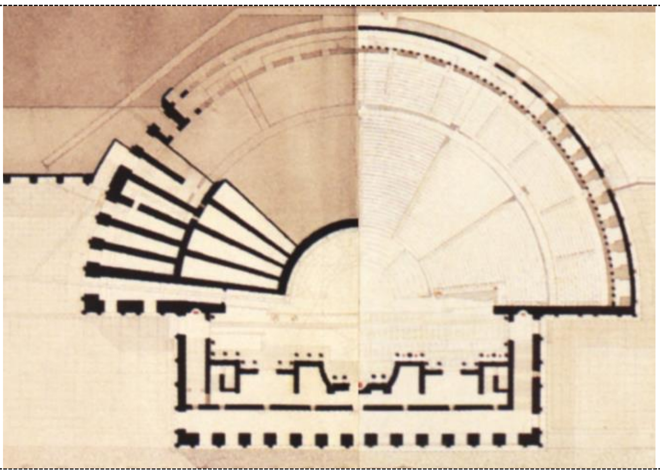


Figure 4. E. Guillaume, plan of the lower (left) and upper (right) floor of the Roman theatre of Verona [5].

Regarding the scenic building, it was 6 m wide, 27 m high and 72 m long. The dimensions reflect the *Vitruvian* rules [7], where the length of the scenic building should be twice the diameter of the orchestra [3]. The *proscaenium*, which is the space in front of the scenic building, was extended to sides with two foreparts called *parascaenia* [3]. In Verona the width of the *proscaenium* was minimum 9 m against the front elevation and a maximum of 15 m against the depth of the semi-circular niche at the center [3]. The access to the *proscaenium* was given by two lateral stairs starting from the orchestra level, or from the *parascaenia* [2]. The front elevation of the stage (*pulpitum*) was decorated with carved marble evoking the archaic Greek-style (see Figure 5).

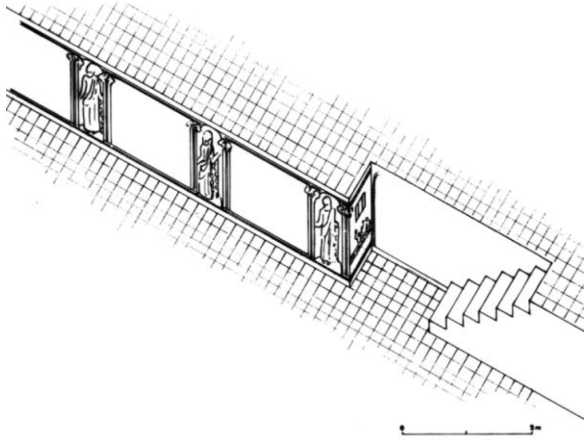


Figure 5. Reconstruction of the decoration at the basis of the *pulpitum* [2].

Horizontal corridors (*praecinctio*) subdivided the *cavea* into two main sectors [1, 2], called respectively *ima* (lower) and *summa* (upper) *cavea* [1], giving a total capacity of 3000 seats as it was set originally, but today reduced to 2000 in relation to what has been preserved [2].
The *ima cavea* in Verona was divided into 6 wedged areas by 5 stairwells [1]. There is another hypothesis that subdivides the *ima cavea* into 5 wedges by 4 stairwells [8]. The steps were composed of a white stone while the stairwells were in red marble of St Ambrosius [1]. The central stairwell started from the 3rd step, meaning that there should be an imperial tribune [1, 8]. In Verona, the *ima cavea* should be composed originally of 25 steps, actually reduced to 23, while the *summa cavea* should be of 12 steps [1, 3]. The height of the 1st *praecinctio* was 9 m above the orchestra level [3]. At the back of

the last step of the 1st *praecinctio*, there should be a *balteum* erected for 1.5 m on the *praecinctio* itself [9]. The 1st step of the 2nd *maenianum* had a walkway function instead of a sitting space and, hence, it required another *balteum*, as shown in Figure 6, to protect people because the height difference between this step and the level of the below *praecinctio* was 3 m [9].

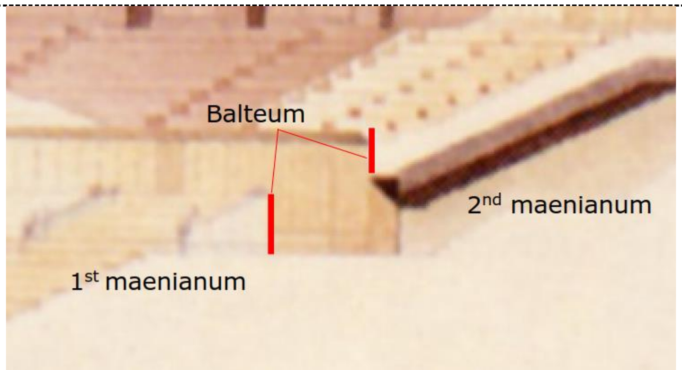


Figure 6. Scheme of the *baltea* reconstruction at the junction of the 1st *praecinctio*.

About the disposition of the wedges of the 2nd *maenianum*, researchers (hypothesis by Saletti) say that there would be 12 stairwells dividing the *summa cavea*, with correspondence of two wedges for each belonging to the *ima cavea* [9]. Another hypothesis raised with the restoration of 1934, reckoning a different geometry for the organization of the wedges; in particular, the staircases running inside the 2nd *maenianum* and arriving at the corridor of the 2nd *praecinctio* ended with a certain width, which would be replied as many times as it would be included by the curved total length [9]. A 3rd hypothesis sustains that probably the design of the 2nd *maenianum* follows the Vitruvian scheme, which would have the same distribution of the 1st *maenianum* [9].

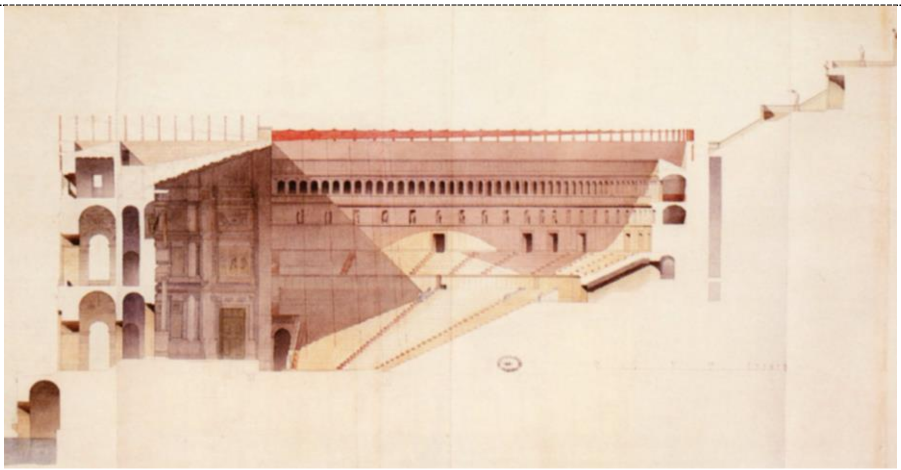


Figure 7. Transversal section of the St Peter's hill drawn by E. Guillaume [5].

The access to the orchestra was through two wide galleries partially covered (*cryptae*) [2], which should be crowned by balconies (*tribunalia*) facing the orchestra [1] and reserved for the aristocracy [3]. The vaulted *cryptae* finished at the line of the 8th step of the *cavea* [3].
The imperial tribune was at the center of the *cavea* and developed onto the first 3 steps of the *ima cavea* [3]. Dimensions of this tribune were 4.05 m × 2.55 m (L × W) [3], having a depth equal to 3 steps [8]. Where the construction is welded to the terrain there were two right-angle stairwells, up to the 1st *praecinctio*, most probably covered by a barrel vault [3].
The structure completing the *summa cavea* was a semicircular ambulatory (*ambulacrum*) that was 2.3 m high and 2.95 m large [3], having the decking level approximately 4 m above the second *praecinctio*

[3]. Above the ambulatory, there was a gallery 5 m high, highlighted and decorated by arcades [1, 6], as shown in Figure 7. With these latest structures, the theatre was 27 m above the orchestra level [6], a height equal to the scenic building [6], based on the *Vitruvian* canon [3]. The theatre, at the level of the upper gallery, was covered by a *velarium*, a cloth of natural fiber awning supported by wooden sticks inserted in holed shelves [2]. *Velaria* were used in both theatres and amphitheaters during the Roman Empire Age as a measure to protect people in the *cavea* against blistering sun and heat [10]. The holes into the stone were intended to hold wooden masts from which the awning was suspended by ropes and pulleys [10]. All the given dimensions are translated from the Roman measuring system [11].

4. Ruins and disuse

Earthquakes, fires, river flooding, and barbaric invasions brought to the slow destruction of the theatre [1]. In particular, the fire provoked by the Germans in 258 AC was one of the main causes of the partial devastation [2], followed by a river flooding in 589 [3] and by a heavy earthquake in 1117 [6]. But during the 4th century, the theatre was already occupied by a cemetery (*necropolis*) that caused the destruction of the marble decorations of the building [2]. In the next centuries, the situation was aggravated by the construction of private properties and religious buildings, as the convent of St Jerome and St Siro & Libera's church (built-in 913 AC) [6], although since 405 AC the Christianism was considered immoral in all the theatrical shows [3]. The convent of St Jerome and the development of his religious congregation started during the 15th century with the occupation of the *romitoria* (caves excavated in the tuff) on St Peter's hill [4]. The basement of the convent is at the level of the 2nd *praecinctio* of the theatre; it became a private residence first, and then was purchased by Monga who gave it museum's functions [4].

5. Archaeological findings and imaginary insights throughout the centuries

One of the first views of the Roman theatre of Verona is given on the Raterian iconography (see Figure 8), which is painted a parchment, belonged to the Benedictine abbey of Lobbes, in Belgium, attributed to Raterio, who was bishop of Verona during the 10th century [12]. With the French Revolution, in 1793 the archive of the abbey has been destroyed, but fortunately, Scipione Maffei and Biancolini had a copy of the iconography in Verona [13]. The buildings on the parchment are urban stenograms, representing the symbols of public buildings inspired by real constructions [12].

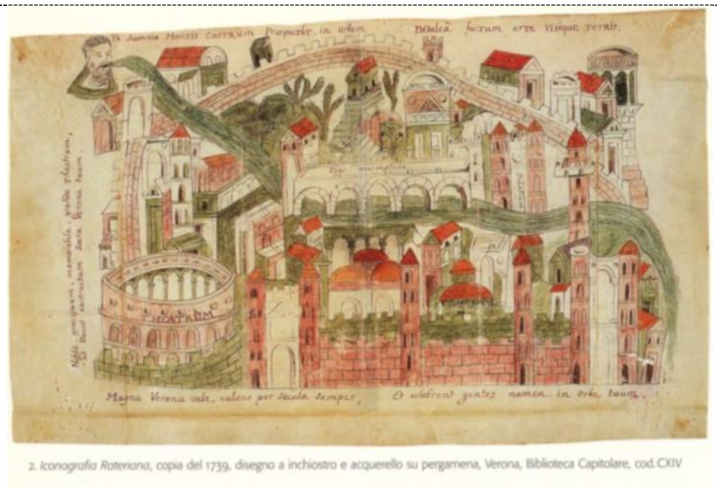
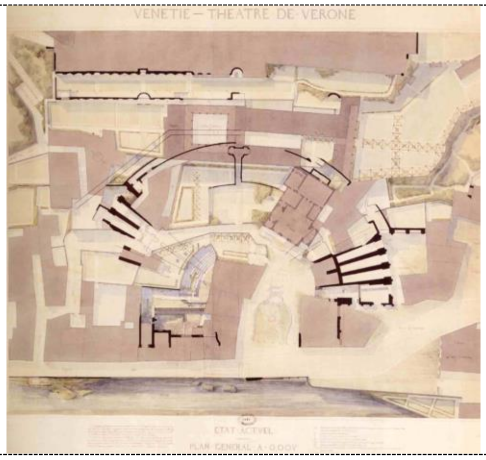


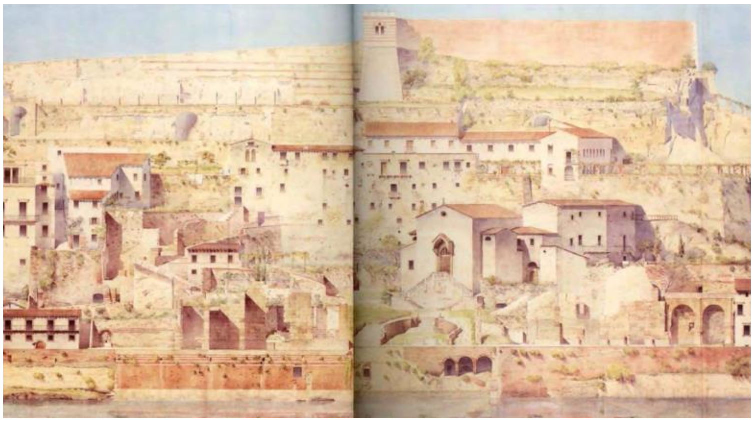
Figure 8. Copy of the Raterian iconography. Watercolors drawing on parchment, Capitolium Library of Verona, cod. CXIV, 1739 [12].

In this drawing, the representation of the theatre is not clear, although a temple on top of a podium has been showing between palms. The 1st plan layout was drawn in 1320, and during the 1400 and 1500, the theatre was subject of interest by different humanists [2]. In fact, during the 16th century, the young

painter Giovanni Caroto and the architect Andrea Palladio redrew their hypothesis of the Roman theatre based on archaeological findings and personal insights [1].
During the 19th century, Andrea Monga bought 35 properties on St Peter's hill and started an investigation of the area focused on the discovery of the ancient theatre [1, 12]. The excavation demolished very few residences and the monument remained still buried [12]. Precisely, the excavations by Monga were undertaken between 1834 and 1842 [6]. By applying the theory of the symmetrical correspondences, Monga obtained specular results even if excavated in few zones; and, because the theatre is symmetric, his theory was correct [12]. Furthermore, a cavity having dimensions of 2 m width and 18 m height has been discovered, which should prevent rainwater infiltration [1]. In particular, the cavity develops in 3 segments [3] embracing the *cavea* from the rear [2]: that one parallel to the scenic building is 46 m long; then other two chunks started diagonally from the edges of the latest one towards the river [3]. If the west angled segment has been discovered to be 44 m long and, for symmetry reasons, there would be another mirrored below the St. Siro and Libera's church, the overall extension of the cavity would be approximately 134 m, producing more than 5000 m^3 of tuff stone to be utilized during the construction of the theatre itself [3]. The rainwater was conveyed at the bottom of this cavity and through a canalization system was ejected in the river [2].
In 1842 Monga and Pinali terminated the excavations without understanding clearly the plan layout of the theatre [12]. Monga died in 1861, when he was still collaborating with Guillaume, who elaborated a consistent number of drawings [12]. Monga provided Guillaume all his own data [12]. Edmond Guillaume, a French architect, was in Italy between 1855 and 1860, traveling from Sicily to Naples and then established in Verona [5]. From the data provided by A. Monga, Guillaume felt ashamed that so much information about the Roman theatre of Verona was not published [5]. With respect to the will of Monga, Guillaume elaborated a Memoire, providing important information about the monument at the conditions of the ruins as he found at that time, drawing all the fragments he could have access to other than accurate descriptions of where they were found [5], as shown in Figure 9.



(A)



(B)

Figure 9. E. Guillaume: plan (A) and elevation (B) of St Peter's hill showing the conditions observed when he reached Verona in 1860 [5].

When Andrea Monga died, the area was inherited by his three sons and after them, the negotiations to be sold to the local government started soon [12].
In 1885 Serafino Ricci published a book regarding the excavation plan which was realized afterward by the city council of Verona when bought the entire area [1]. S. Ricci recognized the merit of A. Monga in starting a serious campaign about the excavation of the archaeological site [3]. In 1893, when Ricci went to Verona, he undertook a photographic survey and soon published the documentation upon the theatre, which nowadays is left only an inventory book, but nothing in relation to plans [12].
Further works continued during the 20th century, involving the following activities:

- 1904: the Municipality acquired all the area [12]. The excavations were directed by Prof. G. Ghirardini of the University of Padova [3] who promoted the demolition of 18 residential properties [12];
- 1907: recovery of the arch near the west stairwell, which gives access to the superior *menianum* [12];
- 1912: composition of the 9 arches of the gallery at the line of the 1st terrace [14];
- 1914: the excavation works gave the first image of the theatre after centuries of burial [1];
- 1959: removal of the extraneous material filling the voids and cavities between the radial walls of the *cavea* [1].

6. A discussion upon the crowning ambulatory and the top gallery

A diatribe among archaeologists and researchers about the position and the shape of the upper parts of the *cavea*, including the ambulatory and the gallery is still open.

The ambulatory, as described by L. Franzoni in [3], was conceived as a lowered vault being 2.3 m high and 2.95 m wide [3]. Because it was an essential architectural element for the theatre, the ambulatory would coronate the *cavea* by having the decking level approximately 4 m above the 2nd *praecinctio* [3]. By L. Franzoni, the design of the ambulatory front (below the gallery) would be composed of squared doors only, to be like *vomitoria* at the end of the stairwells of the *summa cavea* [14]. By getting on the stairs, there was a small landing space slightly below the decking level of the ambulatory [3]. Getting further on the stairs, nowadays there is a terrace, where 9 arches have been re-built at the borderline facing the *cavea* [3, 14].

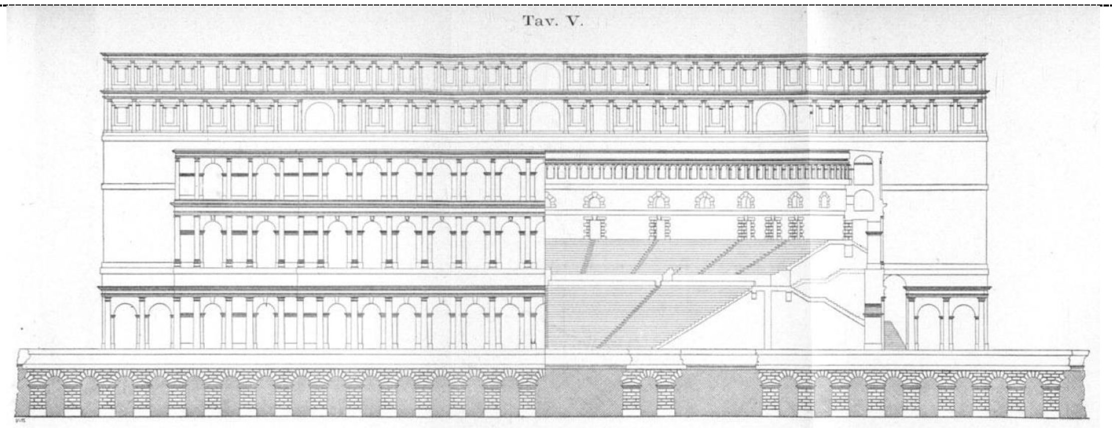


Figure 10. Tav. 5 representing the reconstruction of the elevation and its section in accordance with the hypothesis of A. Monga [15].

Figure 10 indicates the Tav. 5 of Ricci's book, where the gallery is shown to be above the other two. In this representation, the first gallery is at the 2nd *praecinctio* level and the second one is at the ambulatory level [14]. This hypothesis of A. Monga was clearly criticized by Ricci who sustained that there were only two galleries and saying that the exact position should follow the indications given by the painter G. Caroto [14], as shown in Figure 11.

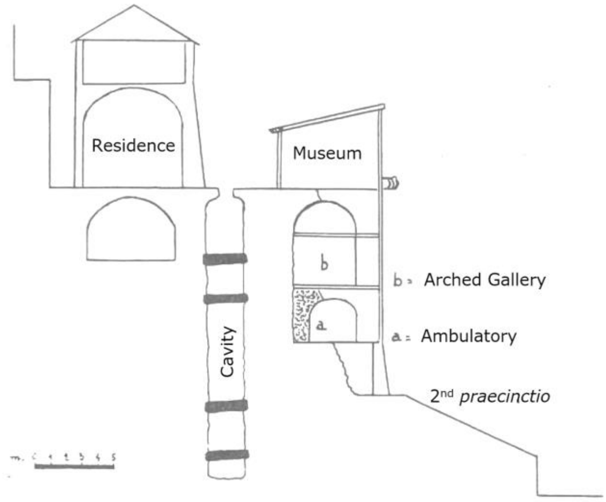


Figure 11. Scheme of coronation structures above the 2nd *maenianum* [14].

The Caroto's drawing shown in Figure 12, published at the beginning of 1540 by Torello Sarayna in *De Origine et Amplitudine Civitatis Veronae*, and then reprinted by Caroto himself in *Antiquita' di Verona*, is not considered very reliable because the painter Caroto added in his drawings what did not exist in the reality, although he should make use of the ruins which represented a form of traces [14].

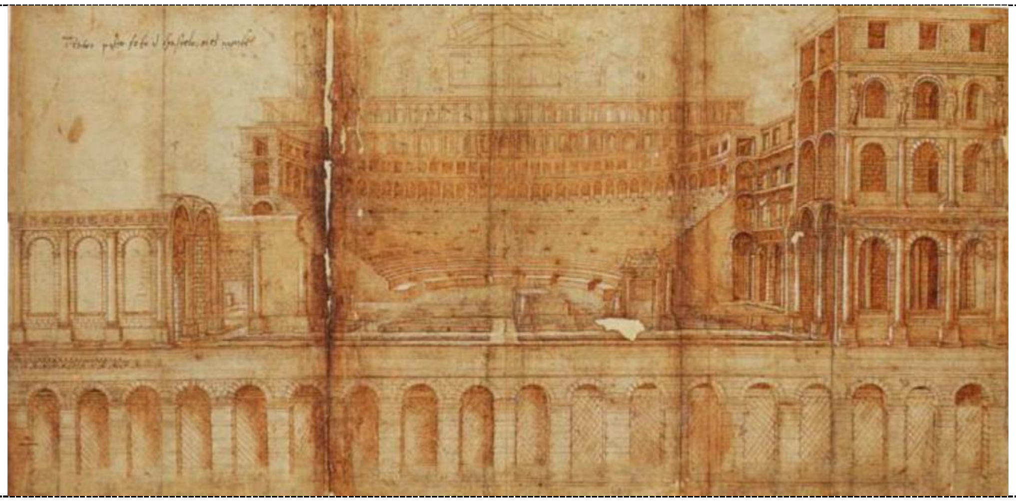


Figure 12. Reconstruction of Roman theatre by G. Caroto. Provision courtesy from the Civic Library of Verona [16].

Ricci considers that Caroto was reliable for the reconstruction of the two galleries crowning the *cavea* [14]. Above this gallery Caroto draw a second one, smaller and covered by an architraved roof, which should correspond to the ambulatory [14]. But this hypothesis has not any feedback with the reality, where the ambulatory stands on the solid and large tuff step and the gallery could be advanced with respect to the ambulatory, but not certainly to the front line of the ambulatory [14]. In addition, even the vault drawn by Caroto resulted wrong because above the arches height (i.e. 3.2 m) could remain only 70-75 cm between the upper limit and the ambulatory level which is not sufficient to host the development of a vault that would be 1.5 m high [14].

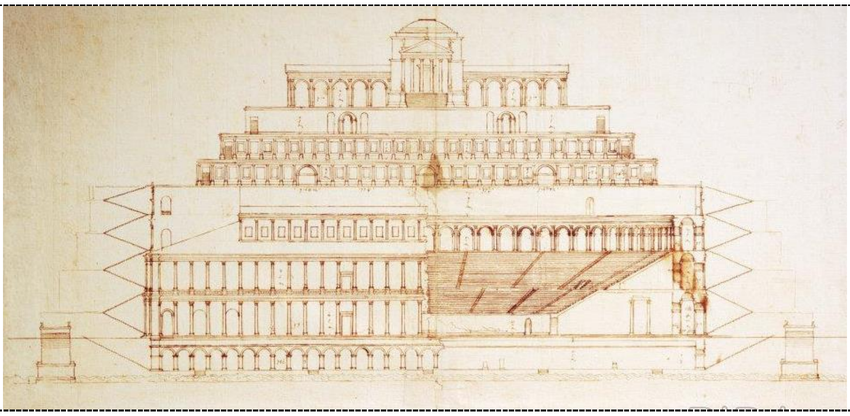
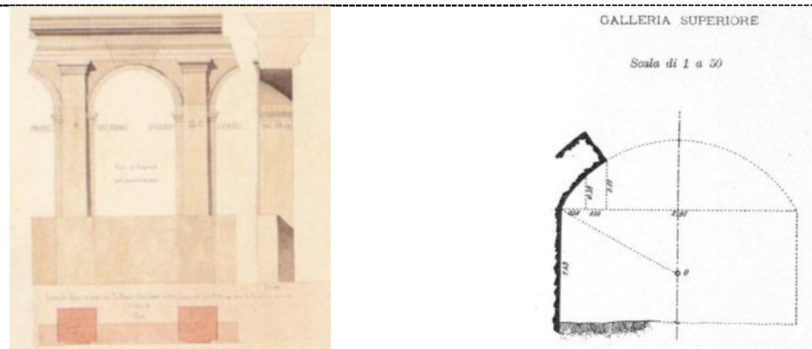


Figure 13. Elevation and section drawn by Palladio. Provision courtesy from RIBA.

After Caroto, also A. Palladio tried to reconstruct the Roman theatre of Verona, which drawings were published by L. Beschi [14]. Palladio solved the problem of the arched gallery by drawing a gallery, like what has been mounted in 1912 [14]. Similar to Caroto, Palladio as well placed the gallery at the level of the 2nd *praecinctio* [14], as shown in Figure 13. Above this gallery, Palladio drew a walkway, on the back of which only a smooth curved wall has been erected, having only 2 doors in a position correspondent to the ambulatory front line [14]. But also, this hypothesis resulted not robust because the development of the vault would be exceeding of 1m the ambulatory level [14]. In 1852 E. Falkener rediscovered Palladio's drawings and supported his theses [14].
Researchers confirm that Monga's hypothesis was correct in relation to the section of the 2nd gallery/ambulatory, provided by a few arched openings towards the *cavea* [14]. But above these 2, Monga believed that there would be a 3rd gallery, having an arched front 4 m high [14], as shown in Figure 14. This hypothesis has been suggested by the cut into the tuff operated by the Romans, which is 12 m deep, starting from the 2nd *praecinctio* [14]. From this element, Monga imagined 3 galleries to be standing to fill up the height of this tuff wall, which otherwise would be not in harmony with the rest of the theatre [14]. Against Monga, both Caroto and Palladio sustained the absence of a 3rd gallery [14].



(a) (b)

Figure 14. Coronation gallery reconstructed by Guillaume and by A. Monga (a) [5], following published by S. Ricci (b) [15].

On top of the ambulatory there was an open gallery, having dimensions of 3.8 m width, 5.1 m height, and 27 m length [3], although L. Franzoni sustains that the height of the gallery should be 3.2 m, having the central vaults narrower than the external ones [14]. Researchers said that most probably the gallery should be extending only to the central part of the *cavea* rather than crowning all of it [3, 14]. The explanations why this thesis raised up are two: 27 m length would be the same dimension as the orchestra diameter; 27 m length is enough to hide the tuff wall of the hill that is 6m high, in order to create a better scenography of the entire complex [3]. L. Franzoni in [14] sustains that the top gallery should be a construction being opposing to the scenic building and, thus, to be a structure extraneous to the theatre and belonging to those works that improved the landscape of the theatre [14]. In fact, the gallery would be built organically to pass smoothly from the theatre to the top of the hill [14]. The stairwells getting on from the 2nd *praecinctio* should introduce symmetrically to the gallery [14].

7. Typological construction of Romans

A series of radial walls are supporting 4 vaults per side, with respect to the main axis, located below the *cavea* [1]. These radial walls are composed of a head in semi-column shape, surmounted by a tuscanic capital [3]. Above the 4 tuscanic arcades there were 8 arcades in ionic style [3].

Tuff stone, as it was quarried from the mountain, is a discrete quality material because it is subject to infiltrations and splitting [1]. For this reason, it was employed for the hidden structure of the theatre [1]. The surviving part of the scenic building is given by the overlap of big squared tuff blocks arranged with the technique of the *opus quadratum* [1] and coated by marble sheets [6]. Columns and semi-columns have a tuff shaft, a stone capital, and a stone basis [1]. Externally, the theatre should be composed of three architectural orders:

- the 1st level was composed of tuscanic semi-columns [1] without any base [3]. The order should be 8.88 m high, which corresponds to the height difference between the 1st *praecinctio* and the orchestra [3].
- at the 2nd level there were arcades made of ionic semi-columns [1]. Similarly, the ionic order should be 8.88 m high, starting at a quote of 1.8 m above the tuscanic order [3].
- the 3rd level was composed of semi-pillars crowned by Corinthian capitals [1]. The theoretical height would be 7.69 m in order to complete the height of the entire structure (i.e. 27.23 m) including the top gallery [3].

The same concepts should be applied to the front elevation of the scenic building [3].

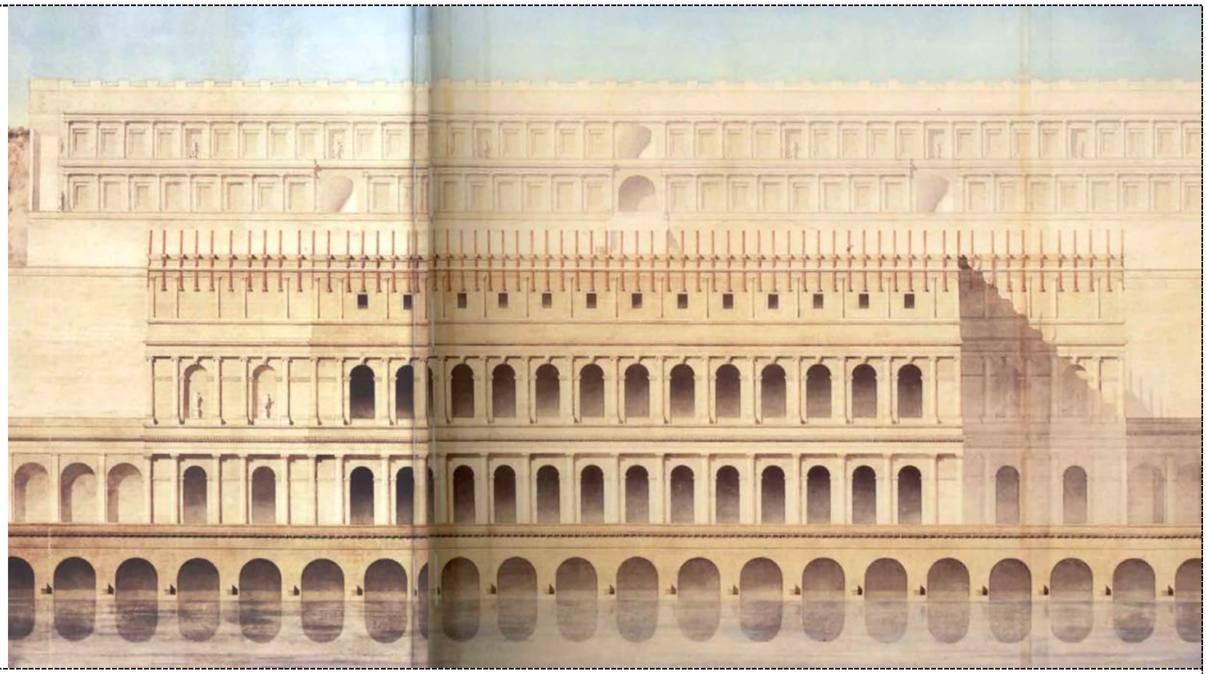


Figure 15. Reconstruction of the elevation drawn by E. Guillaume [5].

In the hypothesis proposed by Guillaume, as shown in Figure 15, the 3rd order shows semi-pillars framing walls with squared windows, instead of arcades [5]. This hypothesis was not agreed by Monga [5].

The *proscaenium* was the stage composed of a wooden deck standing above an empty resonance box having a geometry of an upside-down arch and running along its length [3]. Below the *proscaenium* area, there were underground enclosed areas: close to the orchestra there were water wells [2] surmounted by 4 stone pillars having squared cavities rotated by 45º [3]; they should be the support to the stage curtain (*auleum*), which was extended at the beginning of the show and rolled up at its end [3]. The *auleum* system was composed of wooden beams working like a telescope mechanism [3], as indicated in Figure 16.

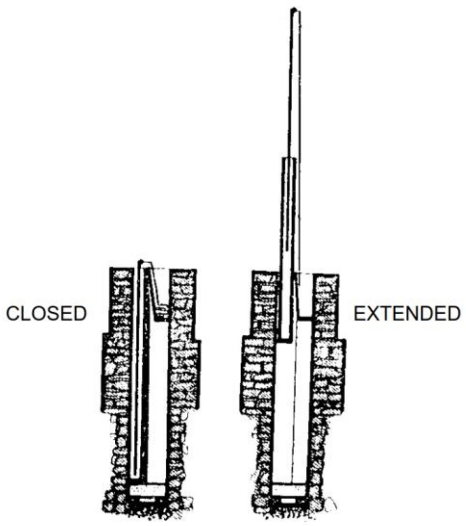


Figure 16. Operational sections of the *auleum* system

Along the 1st step, the theatre of Verona has the *euripo*, which is a semi-circular pit used to collect the rainwater of the *cavea* [3]. Figure 17 shows all the description details. In front of the *euripo*, there was a parapet (*balteum*) having the function of closing back the seats reserved to the aristocracy (*proedria*) [3]. Not all the Roman theatres were provided with the *proedria*; in Verona its existence is proved by the semi-circular foundation of 2.4 m width [3]. The *proedria* should occupy the first 3 steps of the *cavea*, separated from the rest of it with a *balteum*, which is a curtain composed of big stone sheets [2].

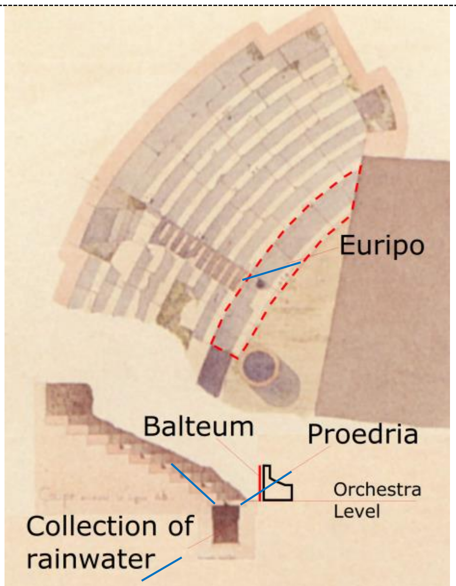


Figure 17. Detail of the junction between *ima cavea* and orchestra. Schematic reconstruction based on a drawing by E. Guillaume [5].

The seats reserved for the aristocracy were composed of multiple white marble pieces, which could be either covering the monolithic blocks or be supported by lateral braces having animal paw shapes [2]. The other type of seats, for common people (*plebei*) were made of monolithic blocks in white or pink limestone, which were carved by lines in order to separate seats (about 46 cm large) [2].

8. Completing constructions around the theatre

28 m above the orchestra level there was a 20 m wide terrace, decorated with a nymphaeum. Above this 1st terrace, there were other two terraces [1]. The design of the 1st terrace would be a series of windows framed by Doric semi-columns [3]. Important discoveries on the east side of the *cavea* were attributed to the existence of a potential Odeon (i.e. an enclosed theatre of small size [4]) or a thermal building, while on the west side the presence of fountains (*salientes*) should be very closed to the *Iseum et Serapeum*, a small temple honored to the alexandrines divinities [6].

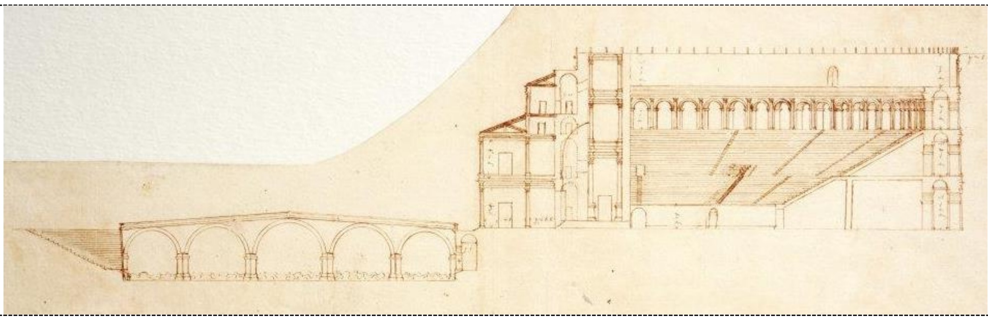


Figure 18. Section of the opposite riverbanks drawn by Palladio. Provision courtesy from RIBA.

Another small mirrored theatre has been drawn by Palladio, as shown in Figure 18, to be on the opposite riverbank of the Adige, but the architect fancied a development of water games involving sealing boats (*naumachie*) in the area of the river between *pons lapideum* and *pons postumio*, which is a pure invention [17]. Similarly, Sebastiano Serlio sustains the hypothesis of naval games between the two bridges, admired by the spectators sit on the stepped theatre placed on the opposite side of the scenic building (called *contra theatrum*) [12].

9. Discovery of ornamental sculptures

Different sculpture fragments have been discovered, but it cannot be confirmed where they were placed, although they are related to the scenic building area and *cavea*, including those that should be hung to the exterior arcades (*oscilla*) [19]. The large number of sculptures' types discovered are in marble, having decoration function [19]. Additionally, on the stage, there should be probably some fountains composed of tubs and big decorative vases, in which a few fragments are still preserved [2], as shown in Figure 19.

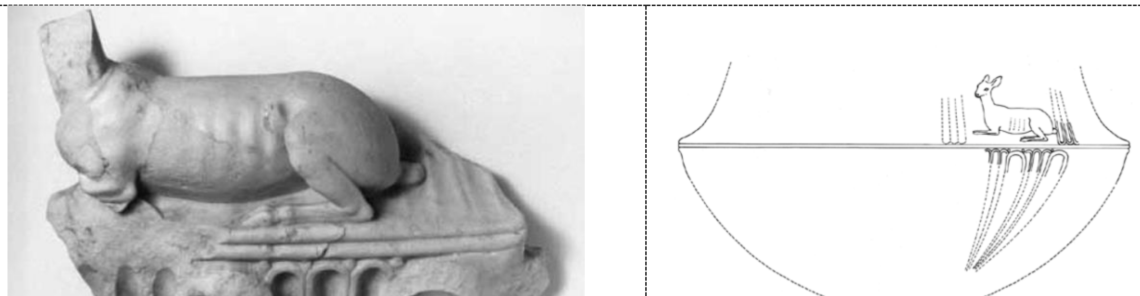


Figure 19. Fragments of one of the decorative fountains of the scene [2].

Another important discovery is the frieze of the 1st order of the scenic building, showing winged griffins, battle scenes [19], palms, oak trees honored to *Jupiter* and laurel trees given by the Senates to Octavius in 27 BC [2].

Figure 20. Fragments of one of the six sphinxes with the function of closing the *proedria* [2].

There is a sphinx recovered and assembled by A. Monga [19], as shown in Figure 20. By the assembly, archaeologists assume that they should be placed onto the 3 steps of the *proedria*, having the function of closing the row of seats [19], made of Turkish marble [2].

10. The actual situation of St Peter's hill and acoustical measurements
A geometric survey of the archaeological site reports the existing conditions of the Roman theatre, which represents the same architectural background where the acoustical measurements were undertaken, as shown in Figure 21.

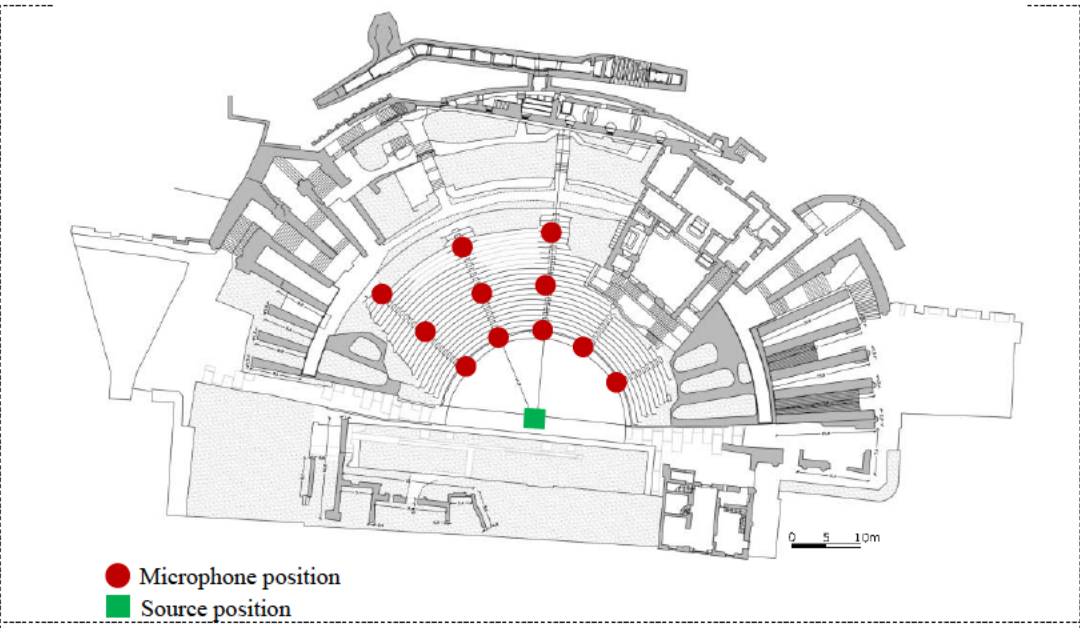


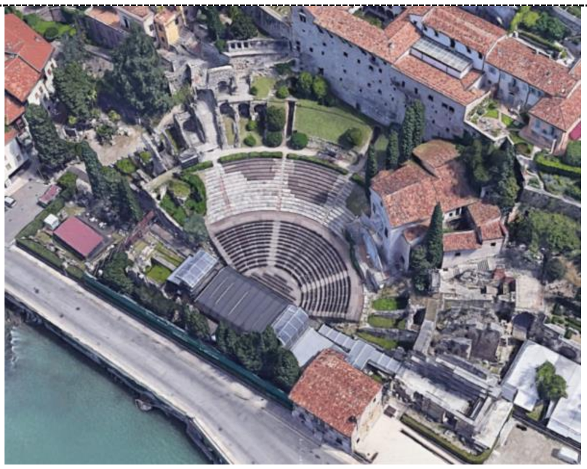
Figure 21. Plan layout of the site. Sound source and microphones positions indicated with green square and red dots, respectively.

To analyse the acoustic characteristics of the current environment of the theatre, an acoustic survey was carried out with the following equipment:

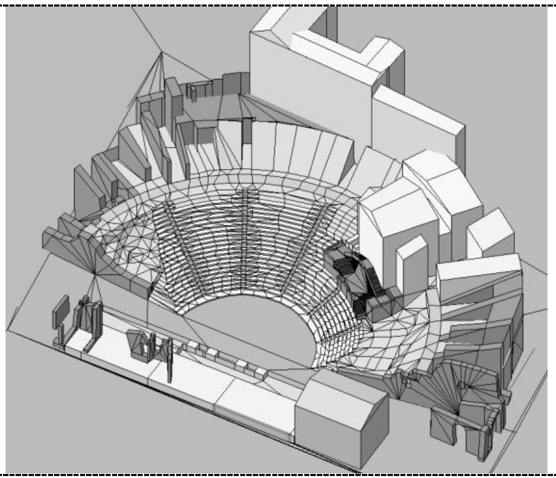
- Equalised omnidirectional loudspeaker (Look Line);
- Omnidirectional microphone (Bruel&Kjaer);
- Binaural microphone (Neumann KU100)
- B format microphone (Sennheiser Ambeo)
- Personal Computer connected to the loudspeaker and the receiver.

The measurements were conducted by using a dodecahedral sound source emitting an excitation signal (ESS) for the range comprised between 40 Hz and 20 kHz [21, 22].

The sound source was placed in one position (i.e. in the *proscaenium* area) at 1.4 m from the finish floor, while the microphone (at the height of 1.2 m from the finish floor) was moved to 11 positions, following the radial axes of the *cavea*. The acoustics measurements were carried out without any audience and any scenery installed, contrary to what is shown in the aerial view of Figure 22(A). Another difference that can be noticed between the two pictures is the presence of a corridor in Figure 22(A) created for the occasion of a temporary seat layout, not existing at the moment of the acoustic measurements.



(A)



(B)

Figure 22. Real (A) and digital (B) existing conditions of the archaeological site.

Figure 22(A) illustrates the existing conditions of the site. The addition of extraneous constructions (i.e. the convent of St Jerome at the back of the *cavea*, the St Siro & Libera's church built in the *cavea*, and the archaeological museum at the right side of the *proscaenium*, others) determine the results of the acoustical environment as it has been measured with the above instrumentation.

11. Acoustics comparison with Roman theatres of similar characteristics

A data analysis of the results has been compared with other Roman theatres that are in similar site conditions (e.g. destruction of *summa cavea*, lack of scenic building, absence of ambulatory or upper gallery crowning and bounding the entire volume) and that were built in other parts of the Roman territory. In particular, the existing acoustics of the theatre of Verona has been compared with the measurements undertaken inside the Roman theatre of Italica in Seville and with the Roman theatre of Benevento, located nearby Naples.

The theatre of Benevento was built during the 2nd century AC and externally it was composed of 25 arcades divided into three levels. The diameter of the orchestra measures 20 m [23]. The *ima cavea* in Benevento is composed of 19 steps, while the *summa cavea* of 8 steps. The volume size of the theatre allowed a total capacity of 10000 seats, now reduced to 8000 [24]. Differently from the theatre of Verona where the scenic building is completely lost, in Benevento the *scenae fronts* are partially erected, having in plan dimensions of 44.2 × 3.5 m [L × W], as shown in Figure 23.

Figure 23. View of the Roman theatre of Benevento.

Another Roman theatre comparable with the theatre of Verona is that one located in Seville, Spain, called Italic theatre because the Iberian territory was part of the Roman empire, specifically it was one of its provinces. In Seville, the diameter of the orchestra is about 15 m, definitively smaller than the size existing in Verona (i.e. 30 m) [25]. The Italic theatre actually has a total capacity of 3000 seats and the dimensions of the scenic building can be measured to be 42 × 5.6 m [L × W] in plan [25]. Fortunately, the Italic theatre has been preserved almost entirely, as it is possible to see in Figure 24.

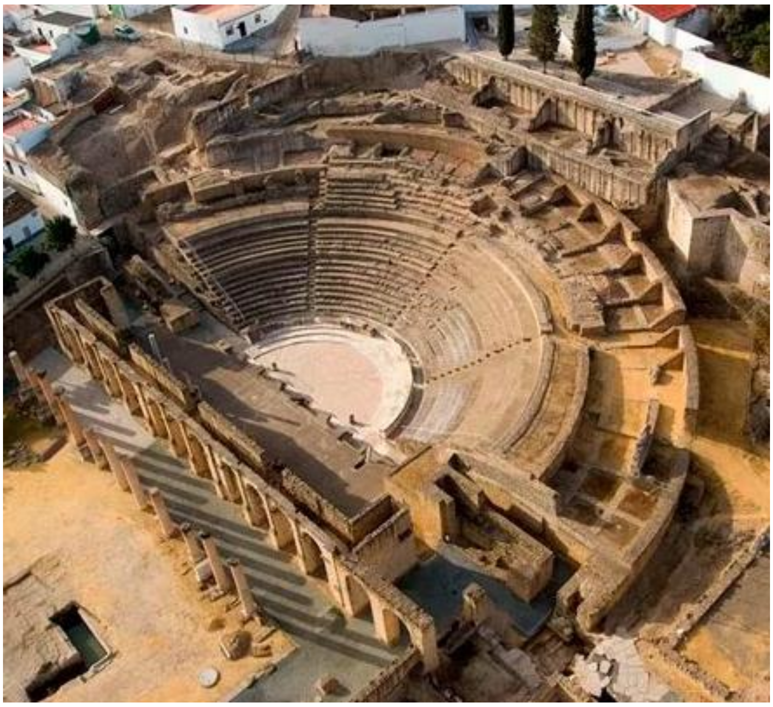


Figure 24. View of the Roman theatre of Benevento.

The construction element that makes a noticeable difference with the other two theatres is the presence of the scenic building, which remained with the first level completely erected. The importance of the *secnae fronts* is detectable from the impulse response.
Before proceeding with the acoustic parameters, Table 1 summarises the architectural features of the three theatres, as discussed.

Table 1. Characteristics' comparison between the Roman theatres of Benevento, Verona and Seville.

Description	Benevento	Verona	Seville
Diameter of the orchestra	20	29.6	15
Actual capacity (seats)	8000	2000	3000
Scenic building [L × W] (m)	44.2 × 3.5	72 × 6	42 × 5.6

The main acoustic parameters as defined by the international standards ISO 3382-1 [26] have been analysed, comparing the listening conditions existing inside the theatre of Benevento, Verona and Seville, as shown in Figure 24. The values found in Verona are obtained from the measurements undertaken by the authors, while the results related to Benevento, and Seville are provided by the literature [24, 25]. The results of the acoustic parameters are shown in the frequency range comprised between 125 Hz and 4 kHz, considered as the average results of all the measurement positions.

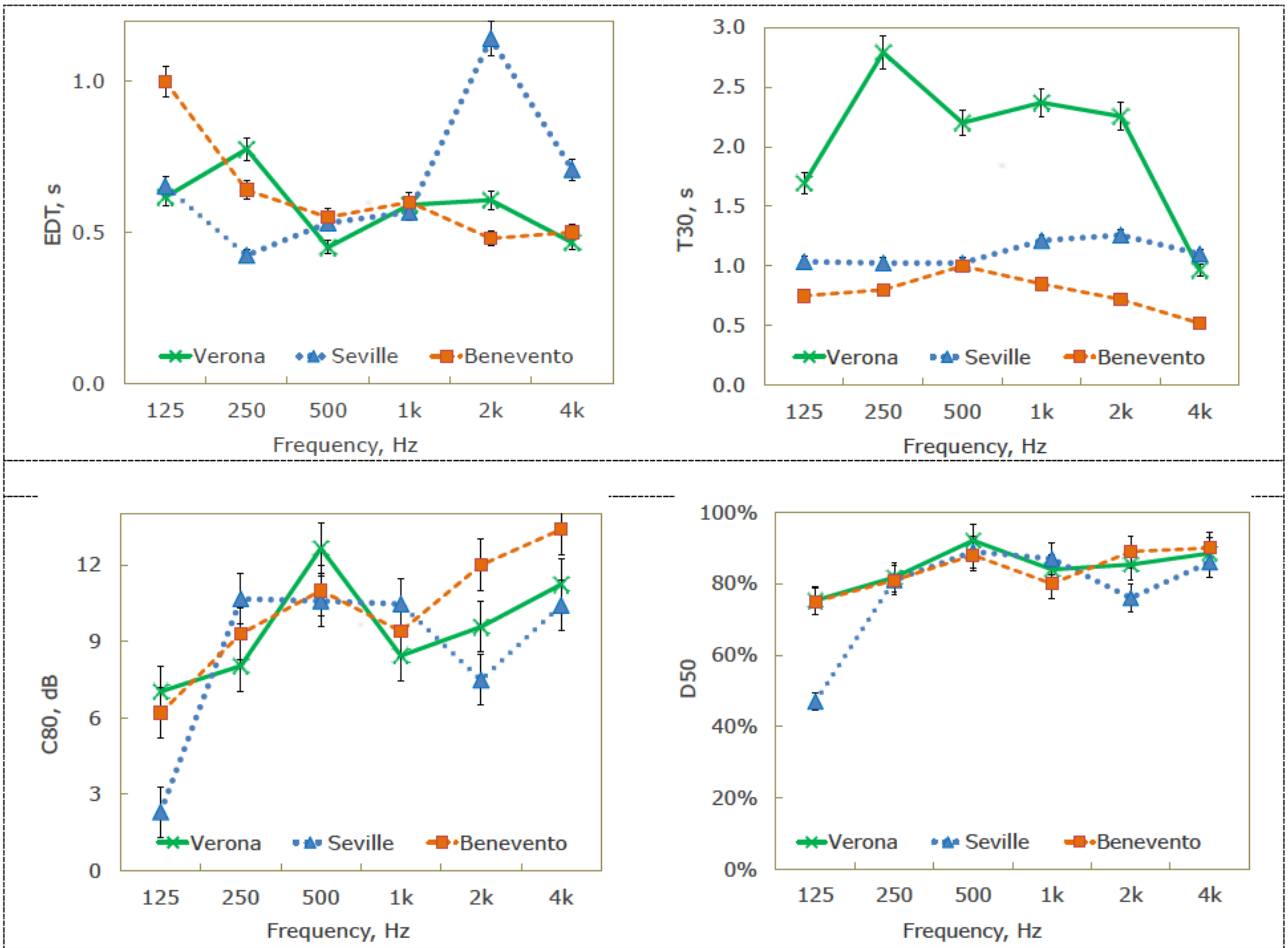


Figure 25. Measured results of the main acoustical parameters inside the Roman theatres of Verona, Seville and Benevento

Figure 25 shows that the EDT values related to all the three theatres are very similar, fluctuating around 0.6 s across all the frequency bands, with the exception at 2 kHz where the value related to the theatre of Seville is around 1.2 s, probably due to the presence of the stage walls that reflected the high frequency

sound rays. Despite this small difference, the values of the EDT for these selected open-air theatres are considered good for both speech and music [27]. For this graph, the results show the 5% Just Noticeable Difference (JND) error bars. As such, the average error in JND is highest at 2 kHz related to the theatre of Seville with 0.15; the remaining octave bands have values less than 0.1.
In terms of reverberation time (T_{30}) the values in Verona result of up to 1.5 s compared to the other two theatres. This effect is mainly due to the presence of many buildings surrounding the *cavea*: the museum on one side of the scenic building, the St Siro and Libera's church, the convent of St Jerome that with its high wall at the back of the *cavea* contribute to building up the sound reflections, residential properties burdening the archaeological site of Verona. The facades of all these buildings are favourable to cause a longer reverberation tail, that in the other two sites is not so marked. In fact, in Benevento and Seville no important reflecting contribution has been given by the surrounding buildings, despite the partial presence of the *scenae fronts*. As such, in these latest sites the values of T_{30} float around 1 s. Specifically, the little variance between the values found in Benevento and Seville could be justified by the integrity of the vertical walls of the scenic buildings; this difference has been found to be up to 0.7 s, to be null at 500 Hz. In this graph, the average error in JND is highest for the results related to the theatre of Verona until up to 0.15; for the other theatres the average error in JND is almost null [28].
In terms of clarity index (C_{80}) the response is very similar for all three theatres. An averaged value could be approximated to 11 dB across all the frequency bands, considered a good target for listening to music inside open-air theatres. The highest spikes of C_{80} have been found at 500 Hz in Verona and at 4 kHz in Benevento, which could be due to the materials (i.e. stone in Verona and bricks in Benevento) currently installed on the seats of the *cavea* as a result of recent restoration works [24] which reflect the sound at different frequencies. In Seville probably the roughness of the original stone of the seats attenuated this effect, resulting in more uniformity across all the frequency bands. In this graph, lines denoting ± 1 JND are represented and for the given results no values larger than 1 JND are seen for C_{80}.
Although the field is not completely diffuse to be open-air theatres, the definition of all the cases is very similar, around 0.85 (85%), considered a good value for good listening and speech comprehension. Overall, the values are above 0.5 (50%), with the exception at 125 Hz for Seville, having a small shortfall but still an acceptable value [28].

12. Model calibration

Before proceeding with the reconstruction of the theatre as it was originally, a calibration of a digital model has been made in order to define the absorbing coefficients applied to the materials.
In Figure 22(B) it is possible to see that all the element surfaces have been drawn as flat planes, providing a simplification to the complex architectural decorations that, otherwise, cannot be handled by the ray-tracing software [29]. The AutoCAD layers were grouped to consider the existing finish materials.
After the existing conditions have been modelled digitally by using AutoCAD, they were exported in dxf format in order to compute the acoustical calibrations with Ramsete [30], a software that calculates the ray-tracing reflections following a triangular-base pyramidal (instead of conical) spreading [31]. The source and the microphone positions were reproduced at the same location of the real measurements.
Table 2 reports the absorption and scattering coefficients for all the materials considered in the calibrations. The scattering coefficients were obtained from the literature [29, 32], while the absorption coefficients are the results of both the calibration process and previous experience on similar studies of ancient theatres.

Table 2. Surface, absorption and scattering coefficients for all the materials considered in the calibrations.

Materials	Area (m^2)	125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz	Scattering
Terrain and grass	2623	0.6	0.6	0.6	0.5	0.6	0.75	0.05
Brick masonry - walls	14190	0.02	0.09	0.10	0.04	0.10	0.10	0.05
Tuff stone - *cavea*	2690	0.01	0.09	0.10	0.02	0.10	0.15	0.05
Sand/gravel - orchestra	1000	0.45	0.50	0.45	0.50	0.55	0.70	0.50

On this basis, the results obtained by the model calibration and the measurement survey have been compared. The main acoustical parameters are shown in Figure 26.

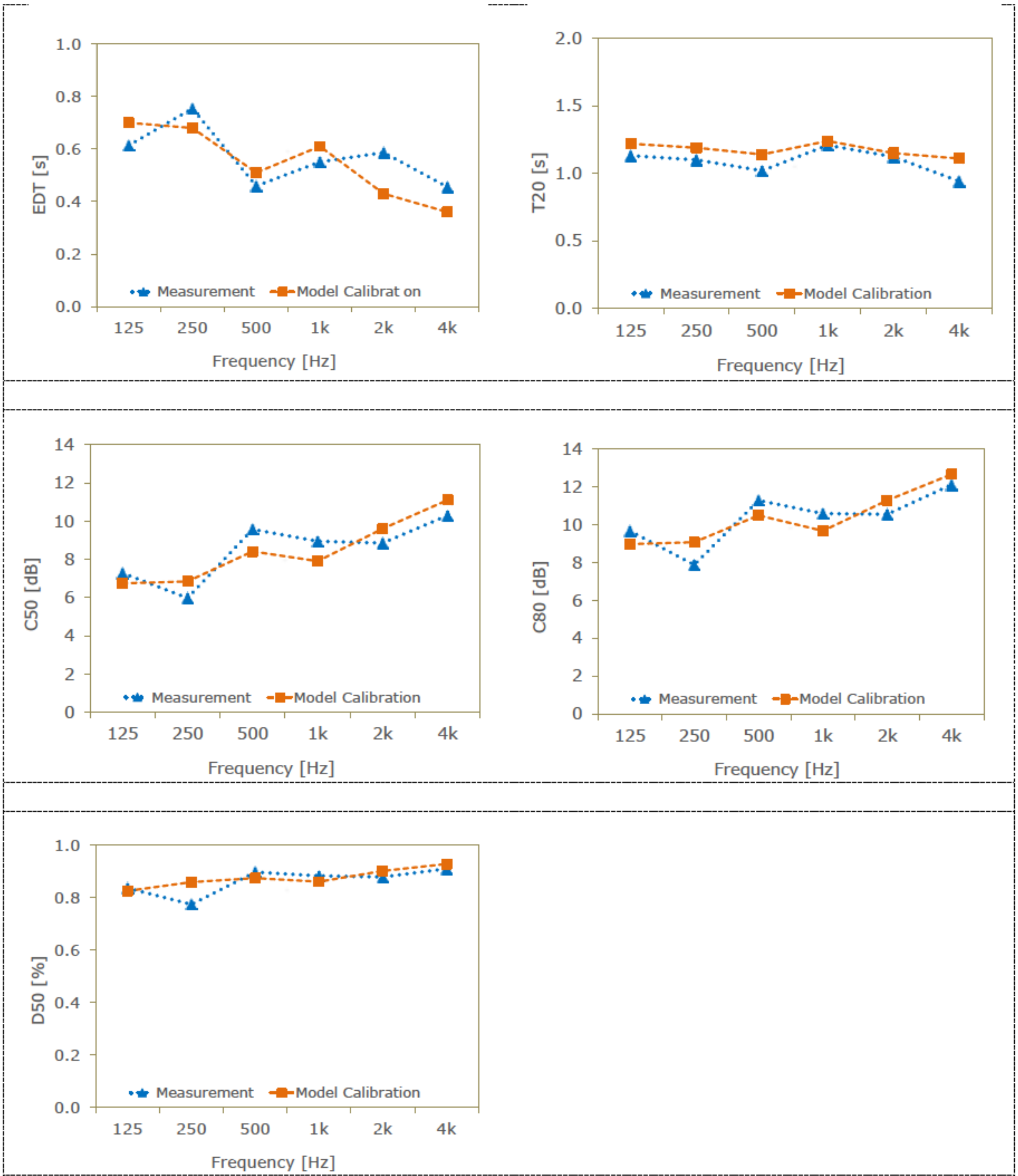


Figure 26. Average values of measured and calibrated acoustical parameters.

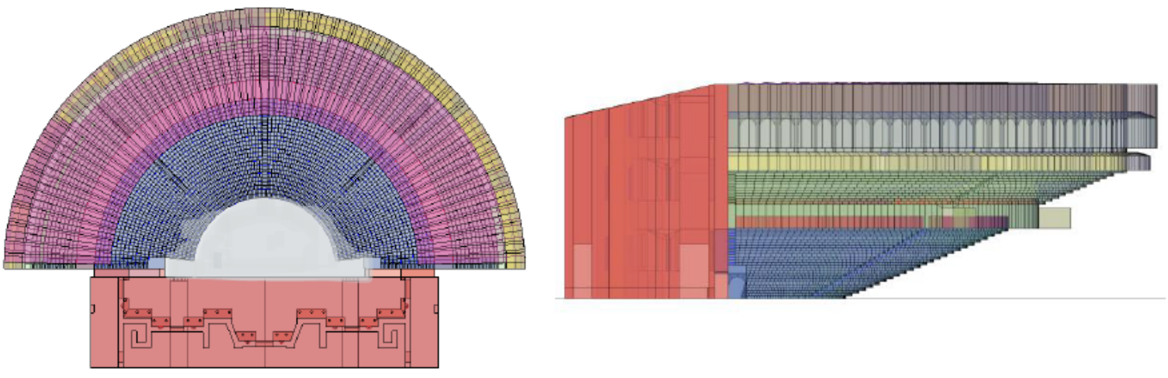
The Roman theatre of Verona is not provided anymore with a scenic front, a structure considered very important for its vertical surface in directing the sound towards the audience [33]. Although this inconvenience, the T_{20} above 1 s across all the frequency bands is a good result to be an unroofed theatre. These outcomes are suitable for both speech and musical performance. The T_{20} results are due to the presence of posthumous buildings at and around the *cavea* that contribute to reinforce the late reflections [34].

A similar concept could be applied to EDT, having an average value of 0.5 s mainly due to the absence of the *scenae* front of the scenic building, which should not be considered as a short time fall for its

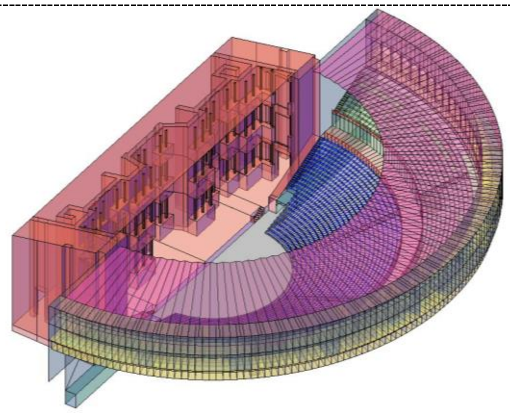
condition. The sound perception inside such environment, in terms of a subjective evaluation, could be defined as slightly “dry” or “deaf” [35].
The clarity indexes for speech (C_{50}) were found to be in line with the literature (i.e. > 3 dB as per Reichardt). In terms of music (C_{80}) the clarity index results to be higher than the upper range limits (i.e. +2 dB) especially at high frequencies, meaning that an excess of clarity for music performance characterizes the listening conditions.
A good speech definition is achieved for values higher than 0.5 (i.e. 50%), while the optimum values for music definition are lower than 0.5 (i.e. 50%) [36]. On this basis, the result indicated in Figure 25 shows that the values of definition around 0.9 are considered more favourable for speech across all the frequency bands.

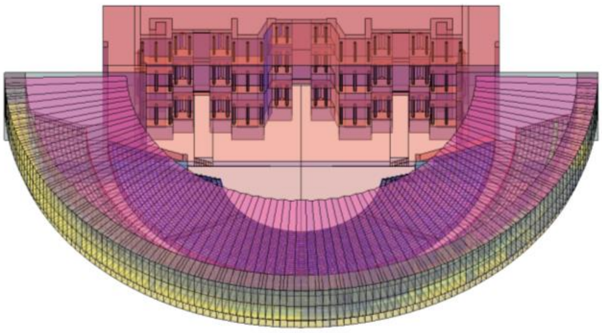
Overall, the graphs in Figure 25 show that the acoustics of the Roman theatre of Verona is found to be similar to other Roman and Greek theatres having comparable conditions (e.g. destruction of *summa cavea*, lack of scenic building, absence of ambulatory and/or upper gallery crowning and bounding the entire volume), and therefore influenced by atmospheric conditions [37].
A small drift between the measured values and the model calibration is due to physical factors that influenced the measurements, such as the wind direction or the presence of buildings away from site. Although the reproduced model tries to be as the most faithful as possible a slight difference remains to be attributed to the absorption coefficient related to different surface areas.

13. Acoustical revival of the Roman theatre of Verona at its original shape.
Based on the archaeological discoveries and on publications that took place during the centuries, the Roman theatre of Verona has been rebuild with the characteristics that evoke the original shape and the volume of such monument.
The model has been realized with the same methodology described above, consisting of drawing flat planes in AutoCAD and simplifying the decorations. The model has been exported in dxf format to be used in Ramsete [28] in order to compute the acoustical simulations. Figure 27 shows the geometric and architectural features in different views.



(A) (B)





(C) (D)

Figure 27. Digital reconstruction of the Roman theatre of Verona at its original shape. The four pictures include a plan layout (A), a side elevation (B), and perspectival views (C, D) of the entire complex.

Table 3 reports the absorption and scattering coefficients for all the materials considered for the simulations. The acoustical simulations have been undertaken by placing an omnidirectional sound source in the orchestra, in the same position of where it was placed during the measurements, at a height of 2.5 m from the finish floor, while the 12 microphones were distributed across the whole *cavea*, in order to cover all the sitting areas, located at 1.3 m from the relative finish floor.

Table 3. Surface, absorption and scattering coefficients for all the materials considered in the simulations.

Materials	Area (m^2)	125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz	Scattering
Tuff stone – orchestra	1413	0.01	0.09	0.10	0.02	0.10	0.15	0.05
Brick masonry – vomitoria	119	0.02	0.09	0.10	0.04	0.10	0.10	0.05
Tuff stone – *cavea,* ambulatory and top gallery	12196	0.01	0.09	0.10	0.02	0.10	0.15	0.05
Marble – scenic building	7316	0.01	0.01	0.02	0.03	0.04	0.05	0.05
Fabric/cloth - *velarium*	2971	0.95	0.95	0.95	0.95	0.95	0.95	0.2
Audience	856	0.65	0.65	0.65	0.65	0.65	0.65	0.4

The acoustical parameters obtained by the simulations are shown in Figure 26, in comparison with the values measured with the existing conditions. Values shown in the graphs of Figure 28 are the average results of all the receivers' positions.

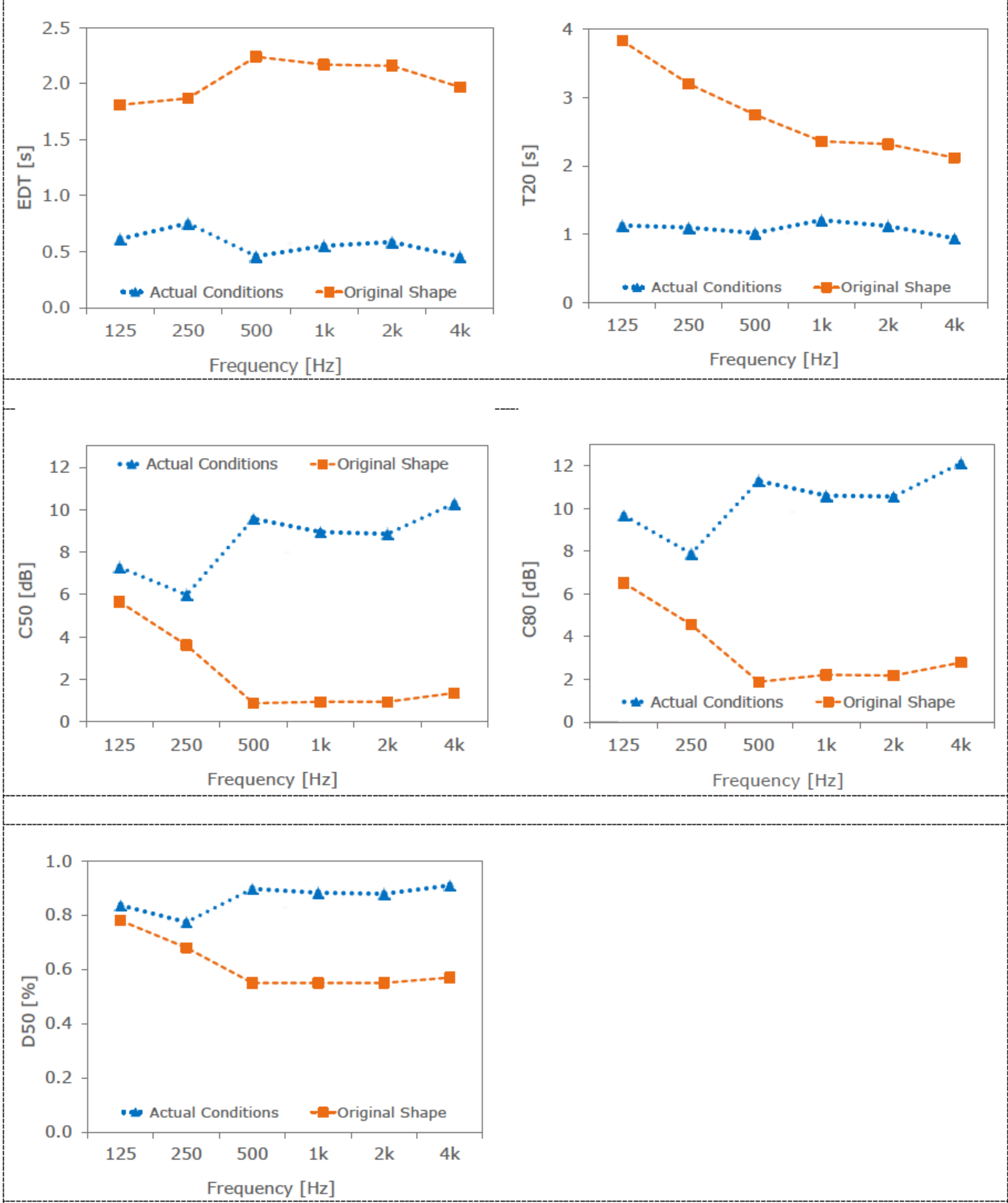


Figure 28. Average values of the simulated acoustical parameters.

By the graphs of Figure 28 it is visible how the results of EDT related to the open-air theatre of Verona at its original shape are found to be very close to the optimal values of an enclosed space, ranging between 1.8 s and 2.6 s as defined by Jordan [32]. As such, the analysis of the overall characteristics digs the comparison to the importance of the *summa cavea*, the ambulatory and the top gallery, construction elements that are missing from the existing conditions and that are considered essential in increasing the reverberation tail [38].

In a similar way, the values of T_{20} obtained by simulating the reconstruction model are up to 3 s more than the existing conditions for low-mid frequencies and almost 1 s for the high frequencies (i.e. 1 kHz to 4 kHz). The reflecting absorption coefficients applied to almost the whole surface area of the digital model and the volume size resulting in higher than the actual site conditions are considered the two main factors that contribute to release this noticeable difference.
Regarding the clarity index, by definition, this parameter relates the transparency of the voice/music to the sound energy [39]. In particular, the speech clarity index (C_{50}) with the existing conditions has been found to be around 10 dB from 500 Hz onwards, 9 dB more than the simulated conditions. The results of the actual conditions indicate that some difficulties in speech understanding might be existing at this frequency range, because of a lack of energy supporting the voice. In terms of music (C_{80}) the values obtained by simulations indicate a good result, being within the optimum range (i.e. -2 dB / +2 dB) for the frequency bands comprised between 250 Hz and 4 kHz. The exception at 125 Hz, with a slightly high value, do not compromise the overall outcome. On this basis, it can be observed that the C_{80} is now worsened by listening to music in the actual theatre [40], and the intelligibility even worse if considering the effects of mask protection due to the pandemic of COVID_19 [41].
In terms of definition (D_{50}) results indicate that the existing conditions are more suitable for speech performance, while the original shape of the theatre was suitable for both speech and music, by having values around 0.5 (i.e. 50%).

14. Conclusions

The analysis of all the documents related to the Roman theatre of Verona was never deeply undertaken under an acoustic perspective in line with the dimensional, structural, architectonic, and historical background. This paper deals with the comparison of different hypotheses sustained by prominent architects and scholars of the past centuries, trying to reconstruct the original environment of such cultural heritage. Acoustic simulations have been performed on a digital 3D model unveiling the parameters related to the listening conditions of the theatre at the period of its flourishing activity. The results highlight worsening conditions of the acoustics of the existing conditions, mainly due to the absence of the *summa cavea*, ambulatory and upper gallery that, by coronating the entire volume, represented the construction elements to be responsible for a good listening condition, for both speech and music performance. Although the presence of the convent of St Jerome and the existence of private properties nearby the theatre contribute to building the reverberation tail, the actual listening conditions result drier than the past conditions, because of the lack of reflecting surfaces (e.g. scenic building) that can support the early reflections and direct the sound towards the audience area.
Further studies will be focused on the acoustics reconstruction of the environment existing at the Roman age, including the scenography and the presence of audience at difference percentage of occupancy. These factors would be determining further changes to the acoustic perception standing inside the theatre.

Author Contributions

Conceptualization, A.B. and L.T.; methodology, A.B. and L.T; software, A.B. and L.T; validation, A.B.; formal analysis, L.T.; investigation, A.B.; resources, L.T.; data curation, A.B. and L.T.; writing original draft preparation, A.B.; visualization, A.B and L.T. Supervision: L.T.. All authors have read and agreed to the published version of the manuscript.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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