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ACOUSTIC STUDY OF A ROMAN THEATRE IN HISPANIA: COLONIA CLUNIA SULPICIA

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Abstract
This work presents the most excellent conclusions of the acoustic study made in the Theatre of Clunia, a Roman city (conventus iuridicus) situated near Coruña del Conde, in the province of Burgos (200 km North from Madrid, Spain).
The work is developed in several parts:
• General description of the theatre. Its dimensions and geometry have been compared with the construction guidelines bequeathed by the Roman Architect Vitruvius.
• Presentation of the simulation results using the CATT Acoustic software, which covers a geometrical analysis of the trajectories of the source-receiver sound rays and an evaluation of the parameters that define its acoustic quality. The software was used to analyze the acoustics as if it were an enclosed area and not an open area, which has been solved in the modelling closing the theatre with a ceiling of maximum absorption, as if it were an open window. Several ceilings have been tried with similar results.

Keywords
Roman theatre, Vitruvius, Hispania, modelling and acoustic simulation by computer.

1. The Theatre of Colonia Clunia Sulpicia [1]

During the first half of the 1st century AC a large theatre is built on the hillside of Clunia (Fig. 1). In the Roman Theater must have taken place plays and scenic games, shows where the spoken word, music and dance would take part. Its geometry is provided in a semicircle and is composed of three main parts: stage, *orchestra* and *cavea*. The grandstand was partly supported on the slope and partly carved on the rock; it is crowned by a portico which, taking account the characteristics of the implementation, was the entrance to it. The center is located in the front line of the pulpit, to which the line of the outer surfaces of the *paraescaene* converges, which is not parallel to the wall of the scene but perpendicular to the arches stands that excess of the semicircle.

Figure 1- Clunia Theatre in its current state

The *caveas* are arranged in three levels, *ima* (lower), *media* (middle) and *summa* (top). Between the *cavea summa* and the *cavea media* there is a leap of 6 feet and the stairs that supply with audience the two *caveas* below, from above, divide the *cavea summa* in 8 *cunei*, because the slope of which is higher than that of the stands, so it is not possible to establish a relation between these stairs and the *cavea* in which they are. Therefore, the *cunei* are independent, with one only possible superior access and no possibility of communication with the lower *caveas* due to the jump.

The audience watched a front stage composed of two floors of Corinthian columns, between which sculptures were located as well as the doors where the actors come and go. At the top an inclined wooden soundboard was placed. Between the acts, the view of the stage was hidden by a curtain that emerged from the floor through a complex system of poles that were lifted by a pulley mechanism. The stage area was constructed of large masses of concrete, covered with limestone ashlar, showing the outside of the city an architectural mole of a great height.

2. Dimensions, geometry and proportion: Vitruvius´ Writings [2]

The dimensions of the theater are very large. The capacity estimated [3] would be around 8000-9000 people. The distance from a speaker located at three meters from the edge of the stage to a hearer of the last row in the front direction is 56 m; the stage has a width of 50 m and a depth of 10 m. The *orchestra*, in semicircular shape, would be about 13 m radius and the height of the stage over it is 1.70 m. The height of the stands measured in the *cavea media* is 30 cm while its width is 60 cm.

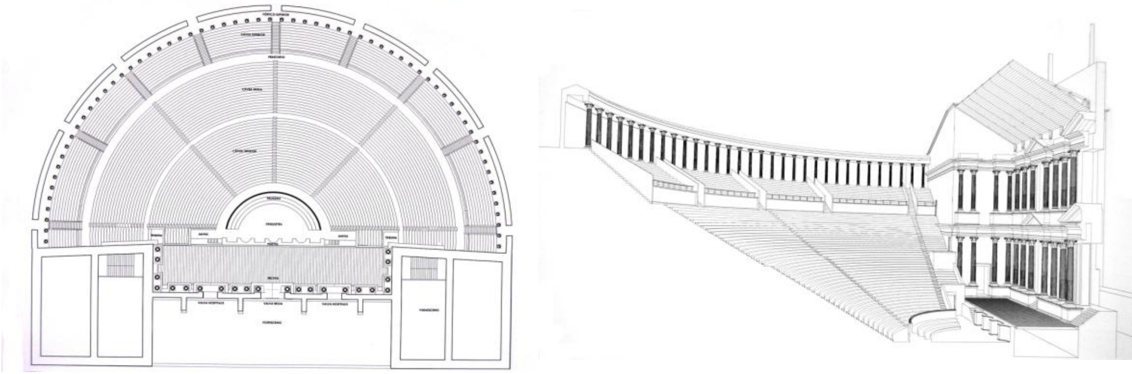


Figure 2 – Plans of Clunia Theatre: ground floor and longitudinal section

The *caveas ima*, *media* and *summa* have an inclination of 26.6º, 27.3º and 26.9º respectively, similar to those of the two *caveas* of Epidauro Theatre. These inclinations lead an optimum visibility, uninterrupted by the viewers placed in front. The corridors that separate the *caveas* have a width of 1.25 m (*ima* – *media*) and 2 m (*media* – *summa*). In this corridor the wall of separation from the *cavea summa* has 2 m height.
The design and dimensions of the theater respond to the classic pattern of these enclosures, but they have their peculiarities. It is interesting the comparison that has been made between the data obtained in Clunia Theater and the canons bequeathed by the Roman Architect Vitruvius in his Fifth Book about Architecture.

3. Modelling and materials [4]

For the simulation an acoustic model based on a drawing in 3D has been performed (Fig. 3). Clunia Theater is currently in ruins in a process of restoration, so the model has been made from an ideal reconstruction of it (Fig.2), based on the information obtained from the ruin as well as the construction practices in other Roman theaters.

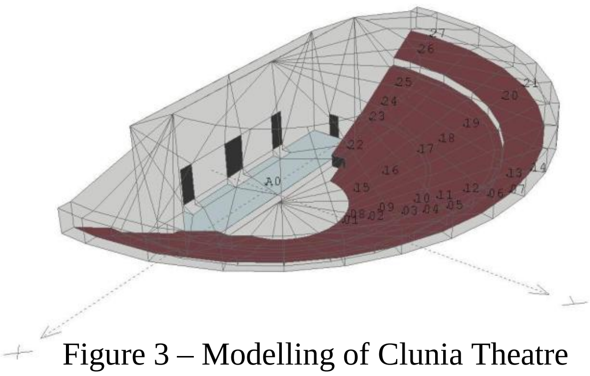


Figure 3 – Modelling of Clunia Theatre

The geometry is characterized using the AutoCAD software and then we have operated with the CATT Acoustic program [5]. We have obtained 265 3D faces and a 0% of lost rays. Taking into account the use of the theater, the chosen parameters characterize the enclosures used for the word and music. The software requires some adaptations:
a) The semicircular perimeter of the theatre was replaced by a polygonal line, because the program does not allow curved lines. The portico above the *cavea summa*, whose semicircle sweeps an angle of 186º, is modelled with a perimeter of 18 sides not equal, but keeping the same symmetry with respects to the plan yz.
b) Changing the circular plan of the columns by a polygonal one. At this point, two options were thought:
• Considering the columns of the *scenae frons* and the portico
• Removing the columns considering the surfaces near them as diffusers
Finally it was decided to remove the columns, because with their presence the results would not have been necessarily more accurate, not knowing the layout of each element of the *scenae frons*. However, we know that the behavior of the Roman *scenae frons* is strongly diffusing due to the many irregularities in their surfaces (columns, sculptures).
c) The software analyzes the acoustics of closed spaces and not in open air, as the Greek and Roman theaters are. It has been solved in the modelling closing the theatre with a ceiling of maximum absorption. This is based on the concept of absorption understood as no reflection that has an open area. Several ceilings with different shapes have been tried. In this model, the design of the ceiling begins in the soundboard and connects to the ceiling of the portico. The volume obtained by closing the theatre is 86800 m^3.

Table 1 shows the materials with their absorption and diffusion (in percentage) at the octave bands of 125 Hz, 250 Hz, 500 Hz, 1 kHz, 2 kHz and 4 kHz:

Table 1 – Coating surfaces: absorption and diffusion at the octave bands

MATERIALS	ABSORPTION	DIFFUSION
Reflective marble for the *orchestra*, the wall of separation between the *cavea media* and *cavea summa*, and the side walls flanking the stage	1 1 1 1 2 2	10 10 10 10 10 10
Moderately diffusing marble for the floor, walls and ceiling of the perimetral portico after the *cavea summa*	1 1 1 1 2 2	15 20 25 30 35 35
Diffusing marble for the stairs and the front and side walls of the *scenae frons*	1 1 1 1 2 2	30 40 50 60 70 70
Window for the closing ceiling of the theatre, the central and lateral doors of the *scenae frons* and the side doors of the *orchestra*	99.9 99.9 99.9 99.9 99.9 99.9	10 10 10 10 10 10
Wood on battens for the stage floor	19 14 9 6 6 5	
Diffusing wood on battens for the soundboard	19 14 9 6 6 5	30 40 50 60 70 70
Audience area with high density of public for the *caveas ima, media* and *summa*, including corridors and stairs between them	52 68 85 97 93 85	30 40 50 60 70 70

4. Acoustic study

We consider an omnidirectional source A0 centered on the width of the stage, to 3 m from the edge and 1.5 m height, which emits a sound pressure level of 90 dB at 1m distance in all the octave bands (125 Hz, 250 Hz, 500 Hz, 1k Hz, 2 kHz and 4 kHz). There are 27 receivers placed in one side of the plan of symmetry yz distributed in four axial directions along the three *caveas* (Fig. 3). Data provided by the simulation are classified in two sections:

- Geometrical analysis: sound ray trajectories source-receptor
- Results of acoustic parameters: SPL, RT, D_{50}, LF and RASTI

4.1 Geometrical analysis

We have analyzed the trajectories of the issuing rays from the source to the receivers, considering the reflections of order less or equal to three (echogram). It has been studied for each receiver the number of the reflections, where they come from, their temporal distribution and the sequence of intensities. The conclusions are:

- The surfaces most involved in the reflections are the soundboard, the stage floor and *orchestra*; the receptors located in the back rows of the *cavea summa* get reflections from the walls and ceiling of the perimetral portico.

The importance of the *orchestra* in the reflections depends on the position of the speaker on the scene; if he is near the edge the *orchestra* gets more reflections, if he is behind, the sound reflected by the *orchestra* would be reflected by the stage floor [6].

- The soundboard was modelled with an inclination of 26º, the same as Orange Theatre (France). With this inclination, it gives reflections to the *cavea ima* and the lower half of the *cavea media*.

This is important because some references consider the perimeter of the *orchestra* with stands occupied by authorities, which would intercept the reflections that would go to these front rows. Even considering the authorities in the *orchestra*, the combined action of the *orchestra* and the soundboard would ensure a direct reflection on all the stands; the soundboard would cover the front and the *orchestra* the rear part of the theater.

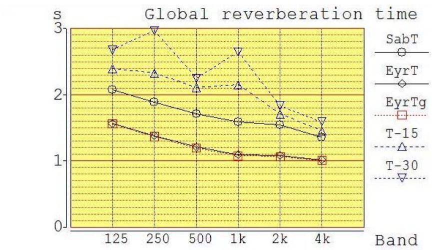
4.2 Results of the acoustic parameters

• Sound pressure level SPL

The sound pressure level SPL obtained for the receivers in the different frequency bands ranges between **58-70dB**. The global SPL is relatively low in the back rows, which is logical considering the size of the theatre (> 50 m distance from the speaker); however, it would be sufficient for the listening in these locations due to the reflections, being equivalent to that obtained at 32m in the open air. The loss of SPL, global and for each band, between the first and the last rows along each axial direction is about 7-8 dB.

• Reverberation time

Figure 4 shows table and graphs of the different values of the reverberation time, some of them obtained through its corresponding formula (Sabine and Eyring), other calculated from the geometry of the room with their coating surfaces, as T-15 and T-30.



	125	250	500	1k	2k	4k	
EyrT	1,56	1,38	1,21	1,10	1,08	1,02	s
EyrTg	1,56	1,37	1,19	1,08	1,07	1,01	s
SabT	2,08	1,89	1,71	1,59	1,54	1,36	s
T-15	2,39	2,32	2,11	2,15	1,71	1,45	s
T-30	2,68	2,97	2,25	2,65	1,83	1,59	s
AbsC	46,67	50,69	55,09	58,19	57,34	55,03	%
AbsCg	46,82	51,05	55,56	58,79	57,95	55,55	%
MFP	24,53	24,50	24,48	24,45	24,44	24,44	m
Diffs	20,20	25,43	30,66	35,91	41,19	41,14	%

Figure 4 – Graphs and table of the reverberation time values

We will choose the graphic of T-15 because it is the most balanced at the different frequencies and presents intermediate values between those provided by Sabine's formula and T-30. It is obtained a value for mid frequencies **RT_{mid} = 2.13seg**, which is **higher than the suitable values for spoken word**, despite having considered a very absorbent ceiling. This is logical because Clunia Theater has a capacity and closing volume at least five times that of the great closed theaters today. The most important question is to know if these results affect to the intelligibility of speech, what will be discussed with the parameters early energy fraction D_{50} and especially with the RASTI.

• Early energy fraction (Deutlichkeit) D_{50}

For all the frequency bands, the percentage values in nearly all the receivers is $D_{50} > 50$, being the average **$D_{50} > 63$**. Therefore, the early energy fraction has results that **contribute to reinforce the strength and the intelligibility of speech**.

• Lateral energy fraction LF

The average is **LF (4) = 3.5%**, extraordinarily low value, that is justified because the reflections coming from the *orchestra*, stage floor or soundboard are not lateral, but frontal or zenithal. It shows that **spatial impression of sound is not created** in this type of enclosures, which helps to identify the actors on the stage and to clarify the speech.

• RASTI

The values of RASTI exceed in most of the receivers the percentage value of 60. The average is **62.5**, which classifies the intelligibility of the theater as "good". It can be considered surprising, thinking in the high value of the reverberation time. It proves that **high values of the reverberation time may be compatible with a good intelligibility**.

5. Study of the theatre with different ceilings

Clunia Theater has been studied with four different ceilings; the other three are shown in Figure 5 (left: V=113123 m^3; centre: V= 127253m^3; right: V= 187409m^3). The results obtained in the different simulations have been very close for the parameters studied here, with differences less than 1 jnd (just noticeable difference).

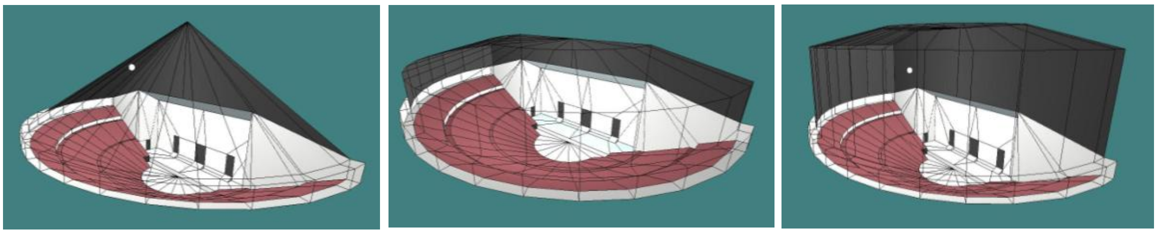


Figure 5 - Different shapes of virtual ceilings for Clunia Theatre

6. Conclusions

1. It can be seen in Table 2 the results of the simulation with the CATT Acoustic software put in relation with the acoustic characteristics of the theatre.

Table 2 – Results of the acoustic parameters and subjective evaluation

ACOUSTIC PARAMETER	SIMULATION VALUE	SUBJECTIVE EVALUATION
Sound pressure level SPL	58-70 dB	Sufficient in the last rows
Reverberation time RT_{mid}	2.13 seg	Rather high for spoken word
Early energy fraction D_{50} (%)	> 63 dB	Contribution to the clarity and intelligibility
Lateral energy fraction LF (%)	3.5	No spatial impression, actor identified on the stage
RASTI (%)	62.5	Intelligibility classified as “good”

2. The calculated values of the parameters with different absorbent ceilings are practically independent of the shape of the ceiling taken in each case, which supports the study methodology used with these virtual ceilings.

References

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