ACOUSTIC RECONSTRUCTION OF THE ROMAN THEATRE OF CADIZ

PACS: 43.55. Ka

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Keywords: Ancient theatres, virtual acoustic, virtual reconstruction, computer models.

ABSTRACT

The Roman Theatre of Cadiz, commissioned by Lucio Cornelio Balbo the Younger, was built in the 1st century BC. Since its discovery in 1980, excavations have enabled the recovery of a major part of the cavea (ima and media) and of the proedria, as well as the orchestra and an annular distribution gallery. Its construction date and its 120-metre diameter make it the oldest and the second-largest Roman theatre in the Iberian Peninsula, with an estimated capacity of more than 10,000 spectators. In this paper, the creation process, adjustment, and validation of the 3D model of the theatre is analysed to simulate its sound field.

RESUMEN

El Teatro Romano de Cádiz, mandado edificar por Lucio Cornelio Balbo el Menor, fue construido en el siglo I a. C. Desde su descubrimiento en 1980 las excavaciones han permitido recuperar parte importante de la cavea (ima y media) y de la proedria, así como de la orchestra y una galería anular de distribución. Su fecha de construcción y sus 120 metros de diámetro lo convierten en el más antiguo y en el segundo en tamaño de la Península Ibérica. Se le calcula una capacidad de más de 10000 espectadores. En esta comunicación se analiza el proceso de creación, ajuste y validación del modelo 3D del teatro para simular su campo sonoro.

THE CITY OF CADIZ

A. García Bellido [1] describes Gades (Roman name of Cadiz) as the possible Tartessos and the oldest city in the Western world, which was, in the golden age of Augustus, one of the richest, finest, and most populous cities of the Latin world. This was the city considered to be at the end of the world, finis terrae: towards the west of Cadiz only the Outer Sea was believed to exist, as the Greeks and Romans also called the Atlantic Ocean. Great historical personalities of the past,
such as Asdrúbal, Aníbal, and César visited this city, and the Balbus and Domitia Paulina, mother of the emperor Hadrian, were born there.

Geographer Strabo [2], in chapter V of Book III of his work Geography, relates an account of the founding of Gadir (Phoenician name of Cadiz, Gadeira for the Greeks) from the Greek historian Posidinio. It describes the founding ("enclosure") of the city of Gadir by the Phoenicians from Tyre, which, according to tradition, took place around 1104 BC, "eighty years after the fall of Troy." Gadir was a city of unique geography: it was, in fact, an archipelago formed by three islands known as The Gadeirai. The two most western islands, which we know by their Greek names of Erytheia and Kothinoussa, were joined by a tombolo, a sandy barrier formed by the sediments that the Guadalete river deposited when it was dumped into the sea. The third island, to the east, was that of Antipolis (Figure 1).

As an ally of Carthage during the Punic Wars, Gadir recognized Roman supremacy in the year 205 BC. It was then that it witnessed an increase in trade that led to growth in its population. In the time of Augustus, the larger Kothinoussa island, which was separated by a canal from the old Phoenician colony that had long been a zone of expansion of its necropolis, was where Balbo the Younger built a new city, the Neapolis, which, united with the old city, gave rise to a twin city, a Didyme or Dipolis, which signified the first planned expansion of Cadiz, as Estrabo relates [3].

Caesar granted full Roman citizenship to all citizens of Gadir in the year 49 BC; this was later ratified by the Senate in the year 19 BC. Cadiz received from Augustus, by Agrippa intervention, the status of Roman municipality. Hence, the municipality was named Augustum and the city was known as Urbs Iulia Gaditana. From the third century, the economic decline of the city began and its subsequent depopulation, which would not recover until the discovery of America.

THE ROMAN THEATRE OF CADIZ (THEATRUM BALBI)

The Roman theatre of Gades was rediscovered in 1980 when an old foundry in the city was being dismantled. This new theatre would replace that in Cadiz [4], probably a theatrum ligneum, rising in stone and occupying the southeast corner of the current neighbourhood of the Pópulo. The idea of giving the old Phoenician colony a theatre is due to Balbo the Younger [5], a friend of Caesar and Augustus, who, in the final moments of the confrontation between Pompeians and Caesarians, retired to his native city and dedicated himself to the construction of Neapolis in the Roman style to which correspond the monumental remains that extend along the old port channel from La Caleta to the San Juan de Dios square. The theatre was located, occupying a convenient place, on the edge of the channel and near the entrance to the city (Figure 1).

The date of construction of the theatre, according to literary references of Roman authors such as Cicero and Strabo, lies between 46 BC-43 BC. The archaeological excavations that began after the discovery appear to show that the aspect offered by the excavated remains of the theatre comes from a major subsequent remodelling, already in the time of Augustus (29 BC-14 AD).
The excavation (Figures 2 and 3) has only laid bare the left part of the building (middle part of the cavea and the gallery that runs under it). The ima and media cavea settle on a natural rocky slope that fell in the direction of the old channel, whose diameter is estimated at 118 m. The section of the discovered gallery (Figure 3), through which the viewers accessed the cavea, is in an optimal condition of conservation, highlighting the barrel vault that covers it, the oyster stone rigging of the interior wall, the skylights that provided natural light, and the vomitoria that communicated directly with the cavea. However, the characteristics and state of conservation of the scaena remain unknown, although indirect references allow a certain architectonic wealth to be supposed.

GEOMETRICAL MODEL OF THE THEATRE

The geometrical model has been built based on the planimetry provided by Dr. J. D. Borrego de la Paz [6]. The cavea is preceded by a frithstool, or footrest, 20 cm high and 26 cm in tread, as in the Roman theatre of Regina Turdulorum [7]. Diametrically, between the edge of the frithstool and the line of the balteus, the first praecinctio of 1.83 m in width can now be outlined. Two rows of intact tiers and the foot of a flight of stairs have been preserved in situ. These rows measure 33 cm of riser and 77 cm of tread and are constituted by oyster stone ashlars. From these two first rows of the cavea, ashlars in situ are absent; only the foundation in opus caementicium remain [6].
By way of synthesis, the structure of the cavea can be traced through a circle centred at the focal point O of the theatre (Figure 4) and with a radius at the edge of the frithstool in which three equilateral triangles are inscribed whose vertices draw an enneagon. In the area of the cavea, the vertices and the centre of each side of this polygon determine radii spaced at 20° (Figure 5) that mark the situation of three alternate scalariae with four vomitoria.

The geometric reconstruction of the tiers is carried out by means of projecting circles centred at point O (Figure 5) and equidistant at 77 cm [6]. In section, (Figure 6), the cavea presents a slope of 25° and is slightly more pronounced for the media cavea, at 29°. The tiers are interrupted at a point at approximately 41 m of their radius, from where no trace of the theatre can be found. Nothing remains of the summa cavea, which has disappeared due to the continuous action of the sea, which is why the reconstruction has maintained the slope of the media cavea [6].

Regarding the materials, it should be taken into account that most of what is conserved corresponds to the foundations of the cavea, made in opus caementicium, and not with the terraces themselves. In fact, the terraces would have been formed entirely by oyster stone ashlars that were stolen after the abandonment of the building. The orchestra, proedria, the balteus and the surrounding praecinctio were finished in marble. From the stage front, although its position can be ascertained, neither its articulation nor its elevation in two or three orders is known. Being a large theatre, there was sufficient space for three orders. The theatre of Cadiz has dimensions comparable to those of Rome itself; until the discovery of the Roman Theatre of Cordoba in 1996, it was the largest in Hispania. The reconstruction carried out corresponds to the Vitruvian norms, which are merely hypothetical.

ACOUSTICAL MODEL AND SIMULATION

Along the same lines as the study developed on the virtual acoustic reconstruction of the Roman theatre of Palmira [8], the acoustic simulation was carried out in this work by using the CATT-Acoustic v9.1b programme (build 1.01) [9], based on geometric acoustics algorithms. For the geometric survey, a three-dimensional model generated by the SketchUp programme was then passed to the CATT-Acoustic through the SU²CATT v 1.3 plugin. The final model presents 8,267 plans, 107,508 m³ of approximate volume, and 5,132 m² of audience area.

Simulations were carried out considering the case of an open model with the source located in the proscaenium (S0); the height of the source was located at 1.50 m from the floor. The signal was recorded at 27 reception positions (R) distributed across the proedria (3), cavea (23) and tribulania (1), all of which were located at 1.20 m from the floor [10] (Figure 7).

Results were obtained with the TUCT v2.0b: 1.02 (The Universal Cone Tracer) calculation engine,
which calculates the acoustic parameters from the energy echograms (E) and/or the B-format and binaural impulse responses (h) based on the evaluation of sound pressure. In the simulation process, complete simulations were performed with 100,000 rays and an echogram duration of 7,100 ms using the TUCT algorithm 3.

Table 1 shows the absorption and dispersion coefficients assigned to the surfaces, together with the associated colours in Figure 8 and the bibliographical references that have served as the basis for the simulation. The meteorological conditions used for the simulation are shown in Table 2.

Various simulations have been carried out, which consider the empty theatre and three situations of occupation: proedria, tribunalia and ima cavea; proedria, tribunalia, ima cavea and media cavea; and total occupation. In the cases of partial and total occupation, the surfaces "Stone cavea" are changed into "Occupied cavea".

RESULTS AND DISCUSSION

The simulation results of the $T_{30}$ parameter indicate according to Tables 3 and 4 that the reverberation time of this theatre is very long in comparison with other Roman theatres, such as that calculated in the Roman theatre of Aspendos, ($T_{30}$m 1.95 s, theatre diameter 85 m), and in the Roman theatre of Siracusa of similar dimensions ($T_{30}$m 1.81 s, cavea diameter 135.5 m) [15]. The results of the $T_{30}$ parameter as a function of...
occupancy reveal that the increase in absorption due to the audience bears no influence on this parameter, and likewise for $T_{30}$ at medium and high frequencies, while at low frequencies there are only slight changes with occupancy at the frequency of 250 Hz (graphs not shown due to space limitations).

The set of plotted graphs in Figures 9 and 10 show the results of the computational simulation of the monaural parameters: EDT, $T_s$, $C_{80}$, and $G$. The results averaged over all source-receiver positions as a function of frequency and degree of occupation are shown in Figure 9, whereby their error bars, which are also plotted, take into account the spatial dispersion of the different receivers by the standard deviation, for each octave band. Results, averaged over mid-frequencies 500-1000 Hz as a function of source-receiver distance for empty and complete occupation and their regression lines, are shown in Figure 10, whereby the location of the receiver in the different zones of the theatre are also specified in terms of the colour of the point on the graph.

The spectral results of Figure 9 show a marked dependence on frequency, especially EDT, which decreases as frequency increases, mainly from 2 kHz, where the air absorption is notorious; this is similar to that which occurs in large enclosed spaces. It should also be noted that both the spectral values and the mean values as a function of source-receiver distance show a moderate and gradual decrease of the EDT, $T_s$, and $G$ parameters, and a moderate and gradual increase of the $C_{80}$ parameter with the increase in the audience. In all cases, no acoustically significant difference is observed in any of the acoustic parameters studied when the theatre is completely occupied, nor when it is almost full with only the summa cavea unoccupied.

Figure 10 also displays the lines of linear regression of the results obtained for the empty theatre and total occupation for the acoustic parameters. Correlations present coefficients of the determination $r^2 > 0.5$ in all cases. The plotted graph of the results for the $G$ parameter shows that there is a difference of approximately 10 dB for the completely occupied theatre and of 12 dB for the empty theatre with the values of $G$ in free-field conditions.

CONCLUSIONS

The Roman Theatre of Cadiz, commissioned by L. C. Balbo the Younger, was built in the 1st century BC. Since its discovery in 1980, excavations have enabled the recovery of a major part of the cavea (ima and media) and of the proedria, as well as the orchestra and an annular distribution gallery in optimal conditions of conservation. Its construction date and its 120-metre diameter make it the oldest and second-largest Roman theatre in the Iberian Peninsula, with an estimated capacity of more than 10,000 spectators. In this paper, a 3D geometric and acoustic computer model has been created. Simulations have been undertaken with the sound source in the centre of the scaenae frons, and omnidirectional impulse responses have been obtained at 27 reception points under various scenarios of audience occupation. The simulated results of the $T_{30}$, EDT, $T_s$, $G$, and $C_{80}$ parameters show that the theatre is highly reverberant due to its large size.
dimensions and the oyster finishing stone despite being a semi-open space. In this respect, the comparison of the values of $G$ in free-field conditions and in the empty and completely occupied theatre is therefore decisive.

The results of the acoustic parameters both in their spectral behaviour and in their dependence on source-receiver distance show a moderate and gradual dependence with the change of...
absorption due to the degree of occupation of the audience, there being no acoustically significant
difference in the acoustic parameters when the theatre presents complete occupation with respect
to when it is full except for the unoccupied summa cavea.

ACKNOWLEDGEMENTS

The authors would like to express their gratitude: to la Dirección General de Bienes Culturales y
Museos de la Consejería de Cultura de la Junta de Andalucía and to Pedro Lobato Vida, who so
dkindly provided us with the graphic documentation essential for the development of this work; and
to Phd. Juan de Dios Borrego de la Paz for all the archaeological and planimetric information
provided and for his selfless collaboration. This work is funded by ERDF funds and the Spanish
MINECO with ref. BIA2017-85301-P.

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