ACOUSTIC RECONSTRUCTION OF THE ROMAN THEATRE OF CADIZ

PACS: 43.55. Ka

Álvarez-Corbacho, A.[1]; Bustamante, P.[2]; Girón, S.[1]; Zamarreño, T.[1]; Galindo, M.[1]
[1] Departamento de Física Aplicada II, Universidad de Sevilla.
Instituto Universitario de Arquitectura y Ciencias de la Construcción (IUACC).
Avda. Reina Mercedes 2. 41012 - Sevilla, España. Tel: +34 954556612, Fax: +34 954557892,
E-mails: arqangel@us.es; sgiron@us.es; teofilo@us.es; mgalindo@us.es
[2] Departamento de Construcciones Arquitectónicas I, Universidad de Sevilla.
Instituto Universitario de Arquitectura y Ciencias de la Construcción (IUACC).
Avda. Reina Mercedes 2, 41012 - Sevilla, España. Tel: +34 954559517, Fax: +34 954557018,
E-mail: bustamante@us.es

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 Tire, 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).

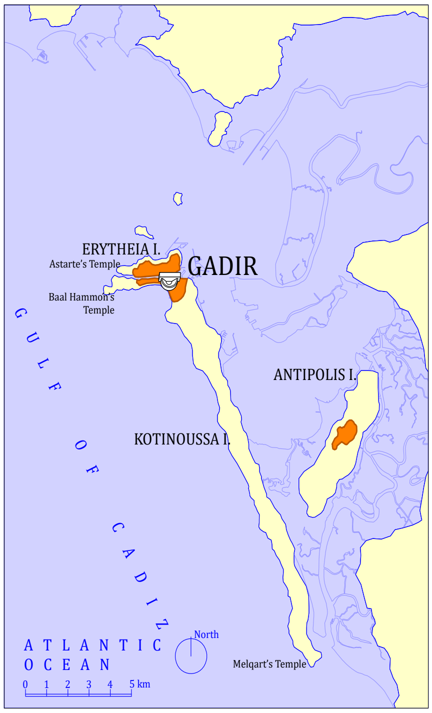

Figure 1. Location of the most significant Roman vestiges.

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 *Dípolis,* 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).

Figure 2. Current state of excavation of the *cavea*. Overhead view provided by *Dirección General de Bienes Culturales y Museos de la Consejería de Cultura de la Junta de Andalucía*.

Figure 3. Image of the gallery discovered, through which viewers accessed the *cavea*.

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].

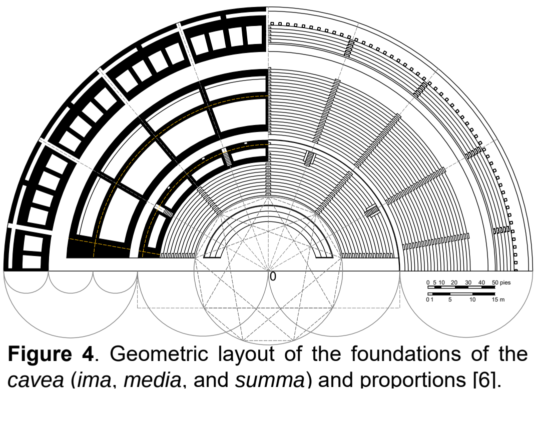

Figure 4. Geometric layout of the foundations of the *cavea* (*ima*, *media*, and *summa*) and proportions [6].

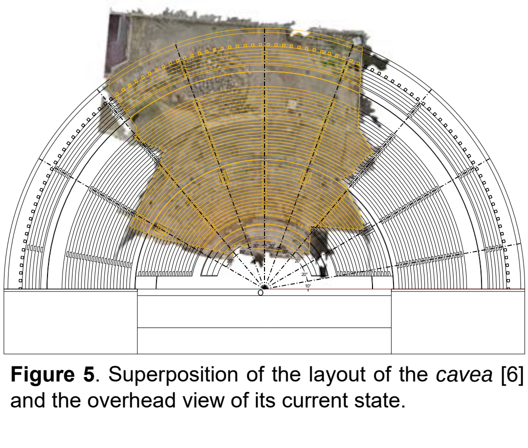

Figure 5. Superposition of the layout of the *cavea* [6] and the overhead view of its current state.

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 20º (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 25º and is slightly more pronounced for the *media cavea*, at 29º.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 SU^{2}CATT v 1.3 plugin. The final model presents 8,267 plans, 107,508 m^3 of approximate volume, and 5,132 m^2 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,

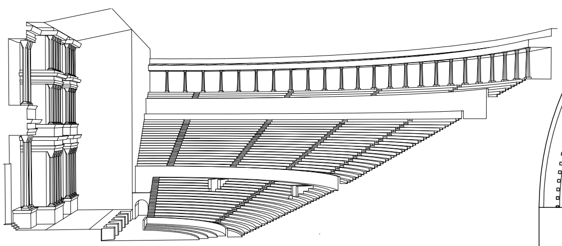

Figure 6. Section of the final geometric model of the theatre.

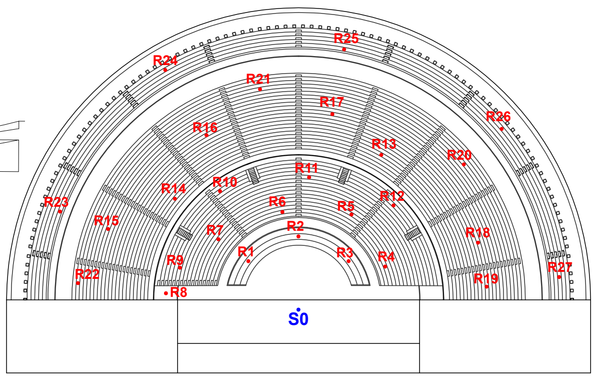

Figure 7. Floor plan of the Roman Theatre of Cadiz with source (S, in blue) and receivers (R, in red) positions.

Tabla 1. Absorption (upper row) and dispersion (lower row) coefficients at octave bands of the materials for the simulation.

Surfaces, [reference]	Colour (Fig. 9)	Absorption and dispersion coefficients					
		125	250	500	1k	2k	4k
Marble columns, [11]		0.01 0.35	0.01 0.35	0.01 0.45	0.02 0.45	0.02 0.50	0.02 0.50
Marble stairs, [11]		0.01 0.05	0.01 0.45	0.01 0.75	0.02 0.90	0.02 0.90	0.02 0.90
Flat marble surfaces, [11]		0.01 0.10	0.01 0.10	0.01 0.15	0.02 0.15	0.02 0.20	0.02 0.20
Curved marble surfaces, [11]		0.01 0.10	0.01 0.15	0.01 0.20	0.02 0.25	0.02 0.30	0.02 0.35
Stone stairs, [12]		0.05 0.05	0.05 0.45	0.05 0.75	0.08 0.90	0.14 0.90	0.20 0.90
Flat stone surfaces, [12]		0.05 0.10	0.05 0.10	0.05 0.15	0.08 0.15	0.14 0.20	0.20 0.20
Curved stone surfaces, [12]		0.05 0.10	0.05 0.15	0.05 0.20	0.08 0.25	0.14 0.30	0.20 0.35
Stone *cavea*, [12]		0.05 0.05	0.05 0.45	0.05 0.75	0.08 0.90	0.14 0.90	0.20 0.90
Roof tiles, [11]		0.03 0.20	0.03 0.30	0.03 0.40	0.04 0.50	0.05 0.60	0.07 0.70
Wooden platform, [11]		0.10 0.10	0.07 0.10	0.06 0.15	0.06 0.15	0.06 0.20	0.06 0.20
Wooden roof, [13]		0.16 0.10	0.16 0.10	0.13 0.15	0.01 0.15	0.06 0.20	0.05 0.20
Occupied *cavea*, [14]		0.19 0.05	0.54 0.45	0.75 0.75	0.89 0.90	0.86 0.90	0.97 0.90

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*".

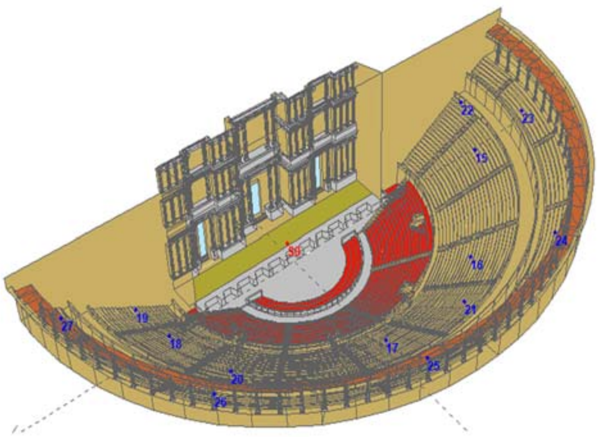

Figure 8. Computer model used for the acoustic simulation.

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_{30m} 1.95 s, theatre diameter 85 m), and in the Roman theatre of Siracusa of similar dimensions (T_{30m} 1.81 s, *cavea* diameter 135.5 m) [15]. The results of the T_{30m} parameter as a function of

Table 2. Meteorological conditions of the simulation.

Temperature (ºC)	Relative humidity (%)	Pressure (Pa)	Air density (kg/m^3) [10]
18.2 ºC	72	102,650	1.13

Table 3. T_{30} in seconds spatially averaged in the empty theatre at the various octave bands and their standard deviation.

125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz
6.46	5.46	4.07	3.31	2.57	2.04
0.07	0.10	0.06	0.05	0.03	0.01

Table 4. T_{30m} in seconds spatially averaged at the various occupation levels and their standard deviation.

Empty	P+T+I	P+T+I+M	Occupied
3.69	3.79	3.82	3.79
0.06	0.07	0.10	0.10

P *Proedria*, T *Tribunalia*, I *Ima Cavea*, M *Media Cavea*

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 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

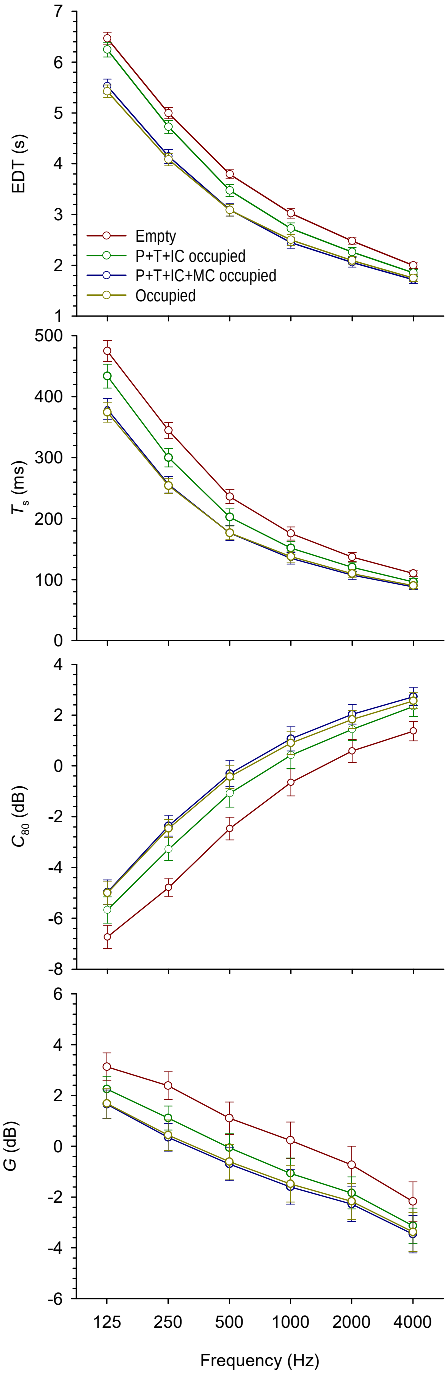

Figure 9. Spatially averaged simulated results of the acoustic parameters for each octave band and degree of occupation. The vertical bars indicate the spatial dispersion of the parameters.

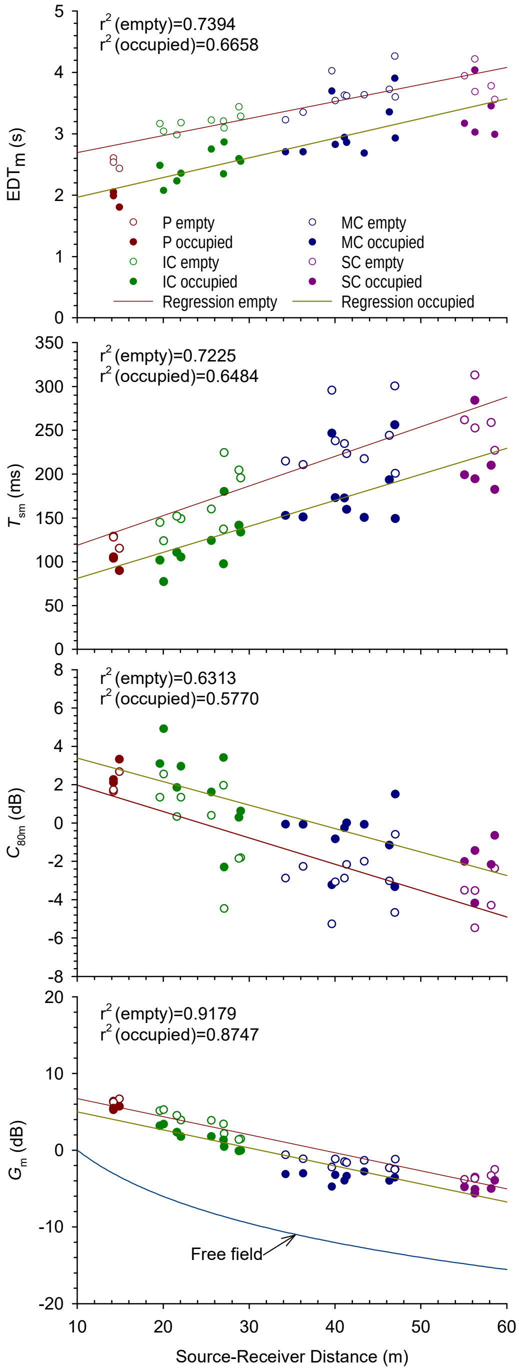

Figure 10. Mid-frequency averaged values of the acoustic parameters as a function of source-receiver distance for empty and completely occupied theatre. Solid lines show the linear regressions and *G* in free field.

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 kindly 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.

REFERENCES

[1] A. García Bellido. Iocosae Gades. Pinceladas para un cuadro sobre Cádiz en la antigüedad. Madrid (1951).

[2] Estrabón. Geografía. Libro III.5.5.

[3] Estrabón. Geografía. Libro III.5.3.

[4] M. T. Cicerón. Epistulæ ad familiares. Libro X. XXXI.

[5] R. Corzo Sánchez. El Teatro Romano de Cádiz. Teatros Romanos de Hispania. Cuadernos de Arquitectura Romana. Vol. 2 (1993).

[6] J. D. Borrego de la Paz. La configuración arquitectónica del Teatro Romano de Cádiz. Nuevas perspectivas. El Theatrum Balbi de Gades. Cádiz (2011).

[7] A. Álvarez-Corbacho, T. Zamarreño, M. Galindo, S. Girón. Acústica Virtual del teatro romano de Regina Turdulorum. Proceedings of Tecniacustica. Valencia, pp 1515-1522, (2015).

[8] A. Álvarez-Corbacho, P. Bustamante, T. Zamarreño, M. Galindo, S. Girón. Reconstrucción Acústica Virtual del Teatro Romano de Palmira. Proceedings of Tecniacustica, A Coruña, pp 1173-1180, (2017).

[9] B. I. L. Dalenbäck. CATT-Acoustic v9 powered by TUCT user manuals. Computer Aided Theatre Technique, Gothenburg (Sweden), (2011).

[10] ISO 3382-1:2009(E), Acoustics-Measurement of room acoustic parameters, part 1: Performance rooms, International Organisation for Standardisation, Geneva, Switzerland 2009.

[11] M. Vorländer. Auralization, fundamentals of acoustics, modelling, simulation, algorithms and acoustic virtual reality. Springer-Verlag, Berlín (2008).

[12] A. Colomo-Gragera, D. Espinosa-Corbellini, T. Zamarreño-García, S. Girón-Borrero. Acústica de la Cripta de la Catedral de Cádiz. VIII Congreso Ibero-americano de Acústica. Évora. Portugal, (2012).

[13] https://www.bunker-audio.com/bunker-audio-portal-sonido-documentos.php?id=3, (visited 30 July 2018).

[14] D. J. Oldham, A. Elkhateeb. The absorption characteristics of Muslim worshippers. Building Acoustics, 15(4), 335-348, (2008).

[15] J. H. Rindel. Roman theatres and revival of their acoustics in the ERATO Project. Acta Acustica United with Acustica, 99, 21-29, (2013).