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VIRTUAL ACOUSTICS OF THE ROMAN THEATRE OF MALACCA

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Resumen

En Hispania (actualmente España y Portugal), hay documentadas 25 estructuras de teatros clásicos romanos al aire libre, de las cuales 10 están el sur, en la Bética romana (Andalucía). La Bética se abrazó al progreso de las urbes en la época del emperador romano Augusto donde los teatros se construyeron en piedra como focos de entretenimiento, espectáculos y propaganda del imperio. El teatro romano de Málaga son los restos arqueológicos del principal vestigio de la Malaca romana. Está situado en el centro histórico de la ciudad, a los pies de la colina de la Alcazaba musulmana y fue descubierto en 1952. Se trata de un teatro de medianas dimensiones cuyo diseño corresponde a una construcción mixta que combina el aprovechamiento de la ladera del cerro para el graderío, al modo de los teatros griegos, con una importante construcción allí donde la roca es inexistente, creando el espacio necesario para las gradas. En este trabajo se analiza el proceso de producción, ajuste y validación del modelo 3D del teatro para la creación de un modelo numérico predictivo de su campo sonoro.

Palabras-clave: acústica virtual, simulación acústica, teatros romanos.

Abstract

In Hispania (present-day Spain and Portugal), there are 25 structures documented of classical Roman open-air theatres, of which 10 are in the south, in the Roman Baetica (Andalusia). The Baetica embraced the progress of urbanisation in the time of the Roman emperor Augustus, where theatres were built in stone as the foci of entertainment, performance, and propaganda of the empire. The Roman theatre in Malaga presents the archaeological remains of the main vestige of the Roman Malacca. It is located in the historical centre of the city, at the foot of the hill of the Muslim Alcazaba and was discovered in 1952. It is a medium-sized theatre whose design corresponds to a mixed construction that combines making use of the hillside for the terraces, in the manner of Greek theatres, with a major construction where rock is non-existent, thereby creating the necessary space for the stands. In this paper, the production process, adjustment, and validation of the 3D model of the theatre are analysed for the creation of a numerical predictive model of its sound field.

Keywords: virtual acoustics, acoustic simulation, Roman theatres.

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1 Introduction

Ancient Roman theatres form part of the acoustic and cultural heritage disseminated mostly in coastal countries along the Mediterranean shore and in other regions in the major cities of the ancient world of Europe, the Middle East, northern Africa, and beyond. According to Mourjopoulos and Fausti [1], to date, 741 structures of ancient theatres have been identified and documented, of which 425 theatres and 46 odeons belong to the Roman era. In many cases, only vestiges of these structures are present. In addition to the long-term interest by historians and archaeologists, increasing attention has been paid to the acoustics of ancient theatres in the last decade (acoustics is an immaterial aspect of the space; its acoustic heritage must be taken into account when reconstructing in accordance with the possible alternatives). The acoustics of classical open-air theatres and odeons impress not only visitors and spectators but also experts in the field.

Likewise, since 2000, interest has been renewed in the wide use of methods that use simulation software, since virtual acoustics and virtual reality enable the recreation of the original acoustics of the theatre and the comparison of various renovation proposals and refurbishments of acoustic conditioning, regardless of whether they be ephemeral or permanent for multiple purposes.

In this context, it is worth highlighting the European ERATO project, which responds to the acronym for Identification, Evaluation, and Revival of the Acoustical Heritage of Ancient Theatres and Odea [2]. Its objective was to investigate the acoustics of classical open-air theatres and odea using virtual reconstruction by means of computational models of the spaces, made in accordance with the archaeological information available. Musical instruments of the time and short musical pieces were reconstructed and recorded in an anechoic environment for their subsequent auralisation in these virtual environments.

Acoustic simulation, a powerful tool in these ancient performance buildings, has been implemented for various purposes, for instance, Chourmouziadou and Kang [3] research the evolution of the acoustic properties of classical theatres built in different eras from the viewpoint of material and design evolution. Their hypothesis proposes that changes in forms and materials during the evolution of the theatre have improved its acoustics. Furthermore, Gugliermetti *et al.* [4], based on historical data, records, and archaeological information, perform a thorough acoustic description of the spatial distribution of the sound field of the Roman theatre of ancient Ostia, for various virtual reconstructions ranging from its origin (Agrippa, at the beginning of the 1st century BC) to the present day. In the same approach, Iannace *et al.* [5] study, through simulation, the acoustic evolution during the Greek-Hellenistic, Roman period and later configurations of the large theatre of Pompeii, Iannace and Berardi [6] reconstruct, by means of a numerical model, the acoustics of the Roman theatre of Posillipo in Naples during the Imperial period, and Iannace and Trematerra [7] report the acoustic history of the Benevento Roman theatre from its origins in the Roman period to modern times.

In another approach, Alfano *et al.* [8] perform acoustic simulation in three Roman theatres in order to understand whether *velaria* (awnings to provide shade for spectators) can affect the acoustics of the theatres. The use of numerical simulations to show the influence of the audience on the acoustics of theatres was carried out by Iannace and Trematerra [9]. For odea, numerical models are highly useful in the simulation of the influence of the roofed timber structures [10, 11] previous to their collapse.

Of the 25 documented theatrical structures built by the Romans during the almost seven centuries of their dominance in Hispania, 10 theatres, including that of Malacca, were built in the southern province, *Baetica*. In this paper, the production process, adjustment, and validation of the 3D model of the theatre is analysed for the creation of a numerical predictive model of its sound field.

2 The city of Malacca

The bay of present-day Malaga was converted at the end of the 9th century BC into one of the first places influenced by Phoenician culture in the southern peninsula. From the mouth of the Guadalhorce river to the west, passing through Malaka in the paleoestuary of the Guadalmedina river, and up to the today's Velez Malaga in the east, the presence of factories and urban settlements dotted the Mediterranean coast for more than fifty kilometres. For the most important settlement in this area, Malaka¸ the oldest remains date back to the beginning of the 6th century BC and in the surroundings of what was once the Roman theatre of the city. The initial Roman presence, at the end of the 3rd century BC, gave rise to a process of identity construction against the invader that relied on antiquity and generated, until the imposition of imperial forms, a "Phoenician way of being Roman" [12].

At the end of the 2nd century AD, Emperor Tito Flavio Domiciano granted the federated city of Malacca the title of municipality: *Municipium Flavium Malacitanum*. The new imperial political system meant that, at the beginning of the 1st century and with the creation of the Baetica province, the territories belonging to the city became the property of one of Rome's four legal convents. This also led to the building of major monuments in the city, for which the port was expanded and the construction of the theatre commenced.

In the republican era, spas were located in this space, of which part of an *opus spicatum* paved area is conserved. The theatre was built, in part, on the structures of these spas, which at that time were moved to a nearby site. Until the great urban work under Augustus, one main road stood out against the motley residential fabric, which organized the Phoenician colony and the republican city. As in other Semitic cities, such as Carthago Nova or Sexi, these main roads were paved and had pipes to conduct rainwater. Along with the remains of ceramic kilns that characterized a pottery area near Carretería street, there was a market area [13], which seems to belie evidence of the existence of a jetty in the vicinity.

2.1 The Roman theatre of Malacca

Located in the vicinity of the port, it is considered a mixed work since it takes advantage of part of the hillside to arrange the stands in the manner of Greek theatres, the rest standing on foundations of the aforementioned previous buildings (Figure 1). The theatre continued to be used for two centuries but by the end of the 2nd century it had dwindled to only very occasional usage. Its definitive abandonment can be verified as having occurred at the end of the 3rd century. The plundered and neglected theatre became the new area for the salting industry and a factory.

For centuries, the Roman theatre in Malaga remained hidden under the streets and buried beneath houses that existed on the slopes of the Alcazaba. In 1940, a building was constructed to house the Palace of Archives, Libraries, and Museums of Malaga, known as the House of Culture. During the landscaping work carried out in 1951 in front of the main entrance of the building, a monumental construction would come to light, which was originally interpreted as being one of the doors of the Roman wall. With the appearance of a series of tiered steps that were arranged behind the arch, it was found that it was in fact a Roman theatre. The rest of the theatre had been left under the foundations of the House of Culture. Over several decades, periods of excavation, consolidation, and constant debate would follow, which ended up with the demolition of the House of Culture and with the extensive excavation and enhancement of the entire archaeological site. Today this site is open to the public, and contains an interpretation centre.

Located adjacent to the highest point of the city, the theatre had suffered looting from the various people who had settled in the city, who took advantage of the stems and capitals for the construction and enrichment of the Alcazaba. Thanks to the legislation of the time, the 1950s triggered both the administrative recognition of the theatre as a monument and progress in the excavation and typological configuration of the stage [14].

2.1.1 The theatre. Typological characteristics

Various discoveries and excavations of the singular elements that remain today from the initial structure have provided an idea of the importance of both this performance space and of the city itself: The *cavea*, semi-circular in shape, whose flat side is almost parallel to the alignment of the current Alcazabilla street. This consists of a total of 14 stepped tiers, made of large stone ashlars. The central part of the *cavea*, the best-preserved part, shows Roman ashlars up to the 13th tier, while on the sides, these building elements fail to reach further than the 7th tier in places. The arrangement of the ashlars presents a radial exploded view towards the virtual centre of the *orchestra*. However, the ashlars do not rest directly on the stone, but instead on a concrete bed. To facilitate descent towards the lowest part of the *cavea*, there are three stairways or *scalaria* that maintain the radial orientation and subdivide the *cavea* into four sectors.

Vomitoria: In agreement with the alignment of the three interior stairways of the *cavea* and of those in the upper area, there are the remains of an equal number of entrances, whose function was to grant plebeians access to the stands. These consist of three staircases that converge on a landing, from which an uneven corridor leads to the stairways. Parapet and stairways are made of stone ashlars, while the paved floor of the corridor is made of live rock, although it is possible that it was originally stuccoed. On the outer side of the three *vomitoria*, an annular corridor would join them together, thereby facilitating the distribution of the public destined to the stands.

The *orchestra* has a semi-circular shape and only its left half is visible, since the rest was, until a few years ago, buried beneath the House of Culture building. The *orchestra* is framed on its flat side by a white marble slab with an inscription in capital letters. Low, white marble steps of low height connect the *orchestra* and the beginning of the *cavea*.

The *aditus maximus,* visible from the west side, consists of a masonry wall corridor, part of which retains a half-barrel vault, precisely in the area closest to the *orchestra*. The interior wall also fulfils the function of restraining the hill on which the *cavea* rests. A lintelled access opens onto the outer wall. From the arch at the entrance to the vault to the *orchestra*, the paved floor is made of marble slabs that have a complex moulding at its junction with the wall.

The *scaena* is the part of the theatre with the least monumental remains. In the line immediately behind the *orchestra*, several rows of ashlars are visible, which allows us to assimilate the shape of the *proscaenium.* The alternation of straight sections, a semi-circular exedra, and remains of a staircase can all be observed. From the exterior of the open tunnel under the foundations of the House of Culture, another major exedra is visible and what appears to be another identical staircase. Of the *frons scaenae* itself, nothing remains but loose ashlars, several column bases, and Ionic capitals. The *postscaena* are robust walls more than 4 metres long, whose function would be to counteract the thrust of the great scenographic machinery that would make up the *scaena*.

In addition to the original marble and cladding remains, the construction of a balcony over the *aditus* was arranged, made of steel and laminated wood, a material that is also used in the remains of the *scaena*. Travertine ashlars were placed in those sectors where the original stone was lacking (Figure 2).

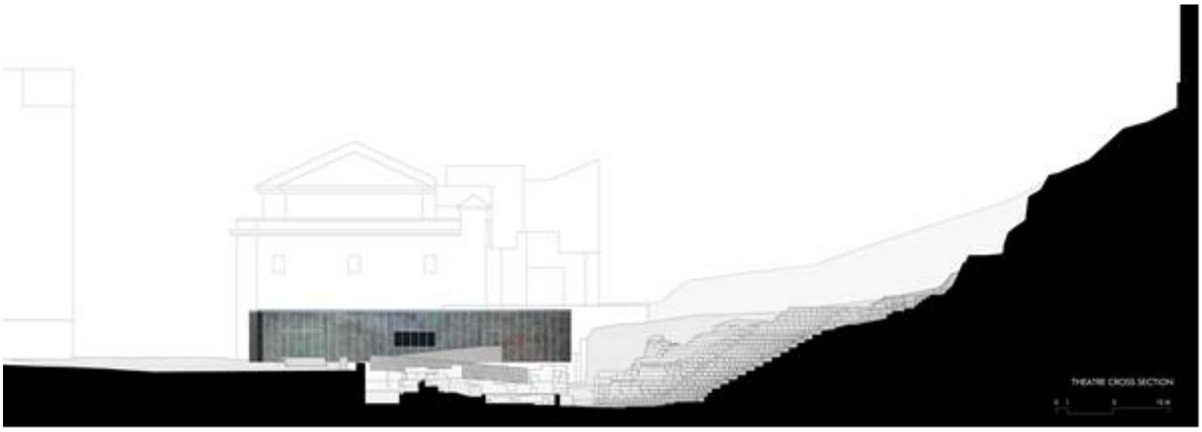

Figure 1 – Section of the theatre. Source: Tejedor and Linares architecture studio.

Figure 2 – View of the Alcazaba and the Roman theatre of Malacca. Source: http://www.autosbahiasol.es/index.php/es/articulos/8-conjunto-castillo-gibralfaro-alcazaba-teatro-romano.

3. Acoustical model and simulation

The geometrical model has been built from a basic planimetry from urbanism maps [15]. Along the same lines as the study developed on the virtual acoustic reconstruction of other Roman theatres [16, 17], the acoustic simulation has been carried out in this work by using the ODEON software (version 15.12) [18], based on geometric acoustics algorithms. For the geometric survey, a three-dimensional model has been generated by the SketchUp software, and finally imported through the SU^2CATT v 1.3 plugin. The final model presents 1730 plans and 1037 m^2 of audience surface with a *cavea* diameter of

45.6 m (Figure 3). The final model reflects the current environment of the theatre, with the Alcazaba standing out at the top of the slope.

Simulations have been carried out considering the case of an open model with the source located in the centre of the *proscaenium*; the height of the source was located at 1.50 m from the floor, and the signal was obtained in 38 reception positions distributed across the *scaena* (2), *proedria* (6), *cavea* (29), and *orchestra* (1), all of which were located 1.20 m from the floor (Figure 4). A symmetry of receivers was placed around the X axis (see Figure 4) in order to verify whether this symmetry also existed acoustically.

Air conditions correspond to a temperature of 20 ºC and a relative humidity of 50 %. Due to the location of the theatre, in the historic centre and with a high density of people, the values of the NC-50 curve have been chosen as background noise, which corresponds to a value of 53.4 dBA. The calculation is based on the survey pre-set with an impulse response length of 2 s and 10,000 late rays. Angular absorption is considered for all materials.

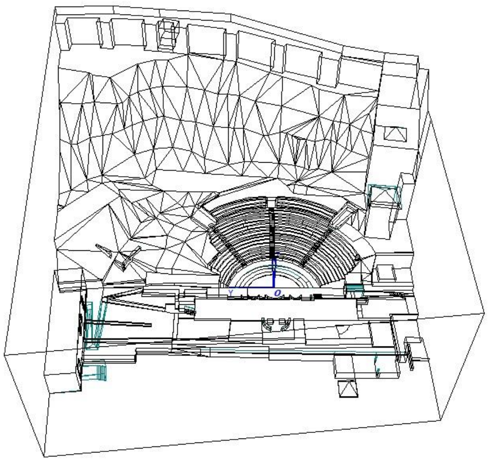
Figure 3 – Section of the final geometric model of the theatre.

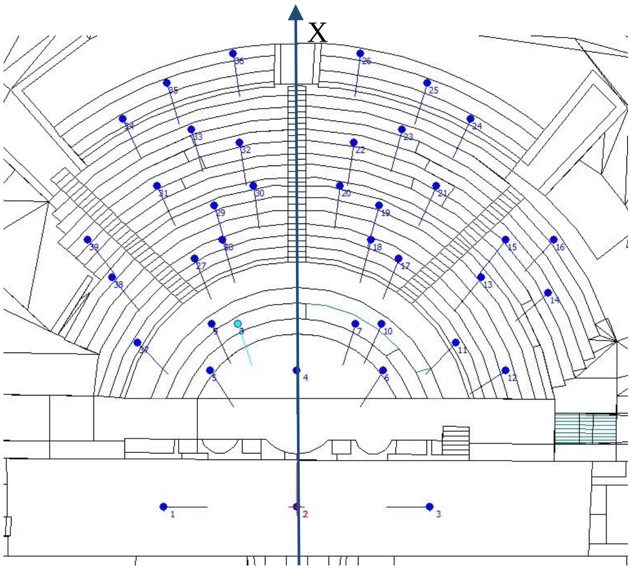

Figure 4 – Floor plan of the Roman Theatre of Malacca with source (red) and receiver (blue)

In Table 1, the main materials correspond to the original stone of the theatre, which in some parts has been replaced by 2 other types of stone, one of which has a different finishing and characteristics. It also highlights the wood of the *scaena* and the marble of the *orchestra*.

Table 1 –Absorption coefficients at octave bands of the materials for the simulation.

Surfaces [reference]	Absorption coefficients					
	125	250	500	1k	2k	4k
Stone [19]	0.02	0.02	0.03	0.04	0.05	0.05
Replaced stone [20]	0.05	0.05	0.05	0.08	0.14	0.20
Wood *scaena* [19]	0.10	0.07	0.06	0.06	0.06	0.06
Marble [21]	0.01	0.01	0.01	0.01	0.02	0.02
Hillside [22]	0.15	0.35	0.40	0.50	0.55	0.80

Three scattering coefficients have been established: 0.02, 0.20, and 0.80 depending on the degrees of roughness. The value presented by the ODEON software corresponds to 707 Hz but it gives a different weighting for the remaining frequencies [18]. The 0.02 value is for smooth surfaces, 0.20 is assigned to the hillside, and 0.80 corresponds to the audience area.

4 Results and discussion

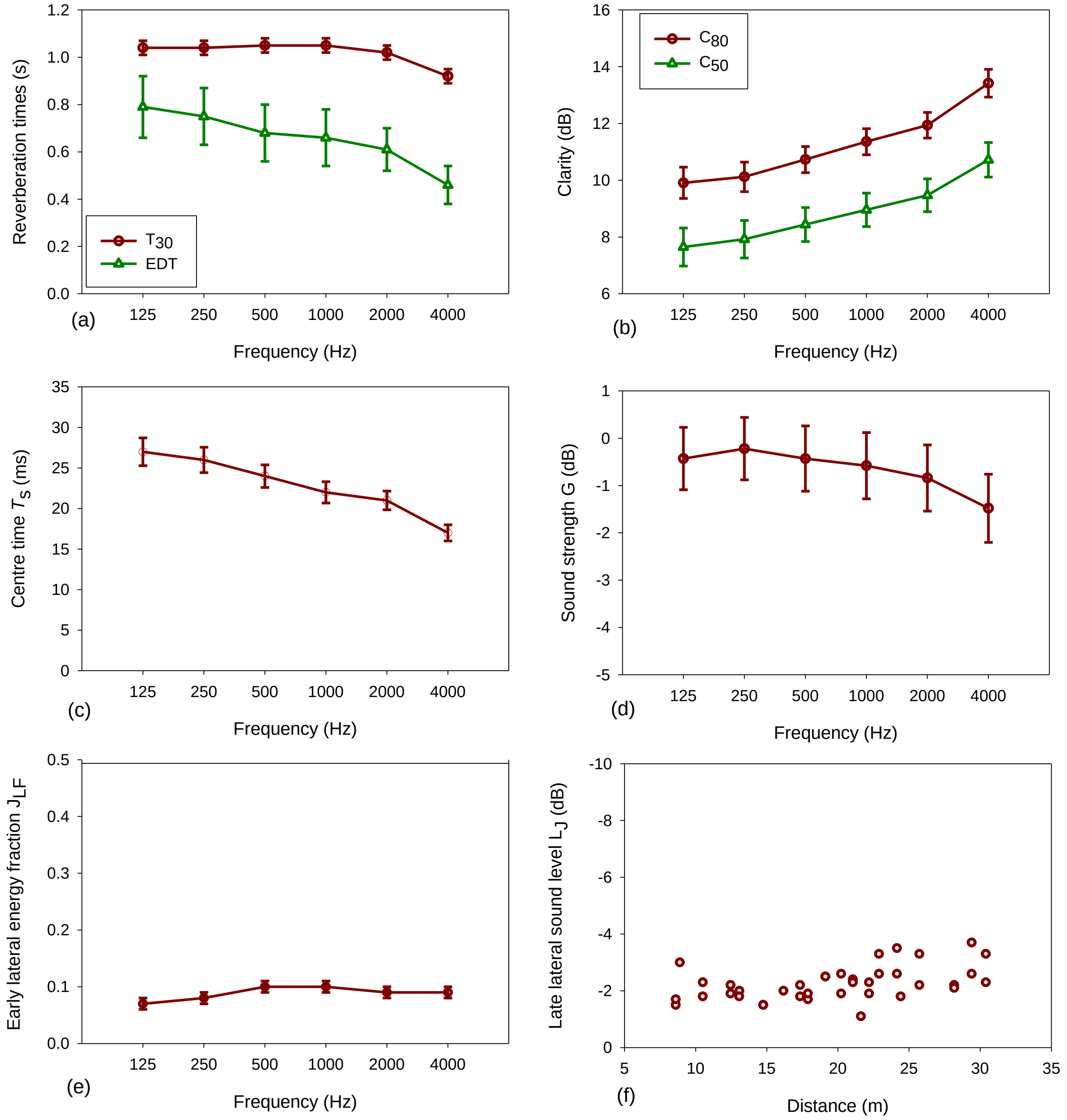

Figure 5 ─ Simulated monaural acoustic parameters in the Roman theatre of Malacca: (a) Reverberation time parameters, T_{30} and EDT; (b) Clarity parameters, C_{80} and C_{50}; (c) Centre time, T_S; (d) Sound strength, *G;* and (e) Early lateral energy fraction, J_{LF}, all as a function of frequency. (f) Late lateral sound level, L_J, energy averaged as a function of source-receiver distance.

The aim of the simulation is to predict the current sound behaviour of the Roman Theatre in Malaga. This will serve as a basis for the evaluation of future performances as well as for other possible configurations and virtual rehabilitations or reconstructions.

Various subjective aspects of hearing can be derived from simulated impulse responses: perceived reverberance, perceived clarity of sound, subjective level of sound, apparent source width, and listener envelopment.

The acoustic quantities analysed herein and related to the subjective aspects include: Early decay time (EDT) for the subjective reverberance; Clarity for music (C_{80}) and Clarity for speech (C_{50}) for the clarity of sound; Sound strength (G) for the subjective level of sound; and for the two aspects of spatial impression there is the Early lateral energy fraction (J_{LF}) for the apparent source width, and Late lateral sound level (L_J) for listener envelopment, respectively (see Figure 5).

In addition, reverberation time (T_{30}), the main descriptor parameter of a room, related to reverberation, and the STI index, related to speech intelligibility, have been included. The reason for the inclusion of the latter parameter is that although it also evaluates the clarity of the sound, as C_{80} and C_{50}, this parameter is better related to speech intelligibility. Therefore, the behaviour of the theatre can be evaluated for events regardless of whether the priority is musical or oral clarity.

The set of graphs in Figure 5 shows all the parameters, spatially averaged, as a function of frequency in octave bands, except for the L_J parameter, which is presented as energy averaged versus source-receiver distance, since this is the way in which the ODEON software provides this spatial parameter. The spatial dispersion is valued in terms of the standard error.

Analysing reverberation, Figure 5(a), T_{30} shows homogeneous behaviour with an overall value of 1.05 s, with a drop to 0.92 s at 4000 Hz due to the effect of air absorption. EDT values, which are more subjectively related to reverberation, give an overall value of less than 0.67 s and also show the effect of air absorption at high frequencies. However, the spatial dispersion is much greater in EDT since this parameter is highly sensitive to the location of source and receiver.

In this type of venue, the number of early reflections is low, with the main contribution of reflection in the orchestra after the arrival of direct sound: see the pattern of the binaural impulse response of Figure 6. This gives rise to non-linear energy fall curves, with different slopes or steps (energy decay curve of Figure 6). This results in the EDT parameter being questionable in its role of rating the subjective sensation of reverberation in outdoor venues.

As expected, both the musical clarity and speech clarity is high (see Figure 5(b)), and their spectral behaviour is very similar: they grow with frequency and with a fairly homogeneous spatial distribution for all frequencies, whereby C_{50} is more sensitive to seat-to-seat variations. There are no recommended values for the analysed parameters, but by considering the STI index rating scale as a function of distance (Figure 7(b)), the intelligibility of speech is between *good* and *excellent* depending on the location. The C_{80} spatial dispersion is high, exceeding one decibel in all the octave bands, which reinforces the importance of the location of the source and the receivers and implies a jump in the Just Noticeable Difference (JND) for a human.

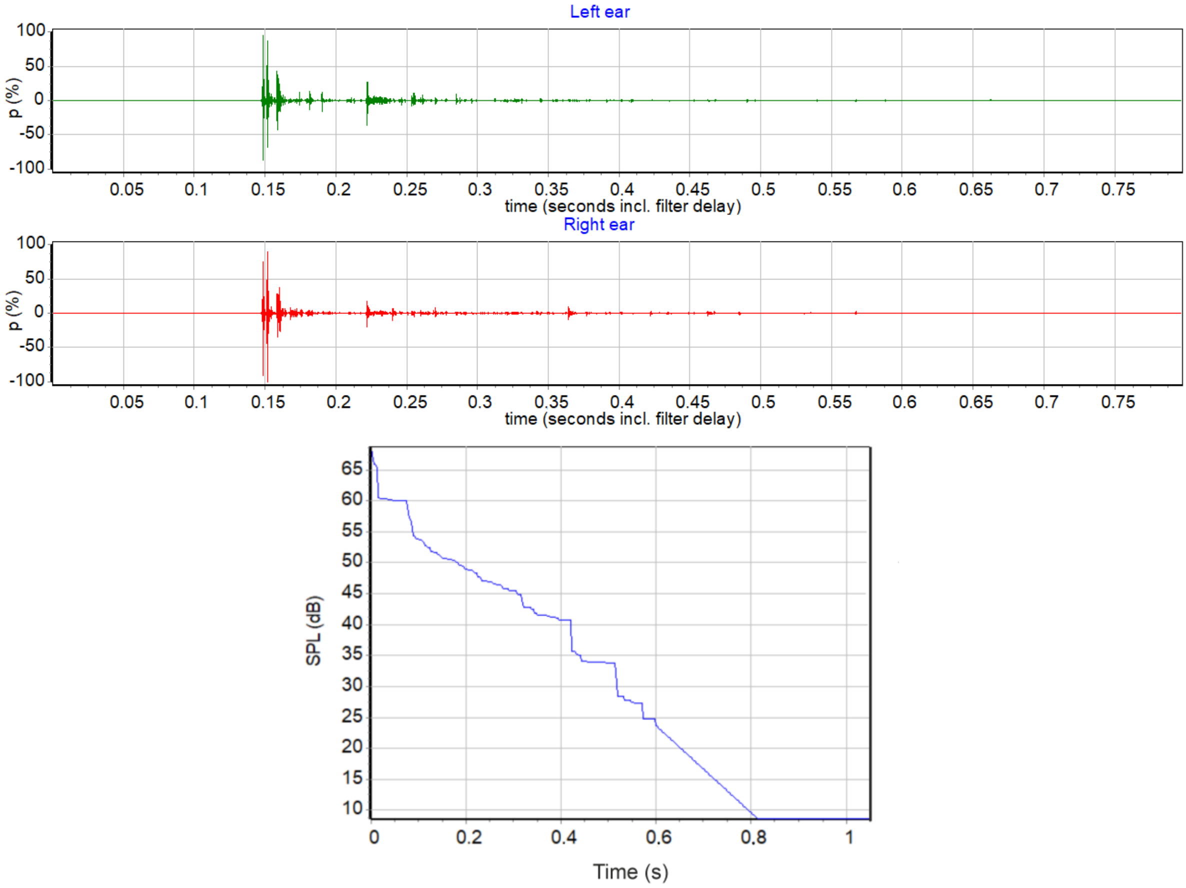

Figure 6 ─ Binaural room impulse response and decay curve (1 kHz) for receiver 19.

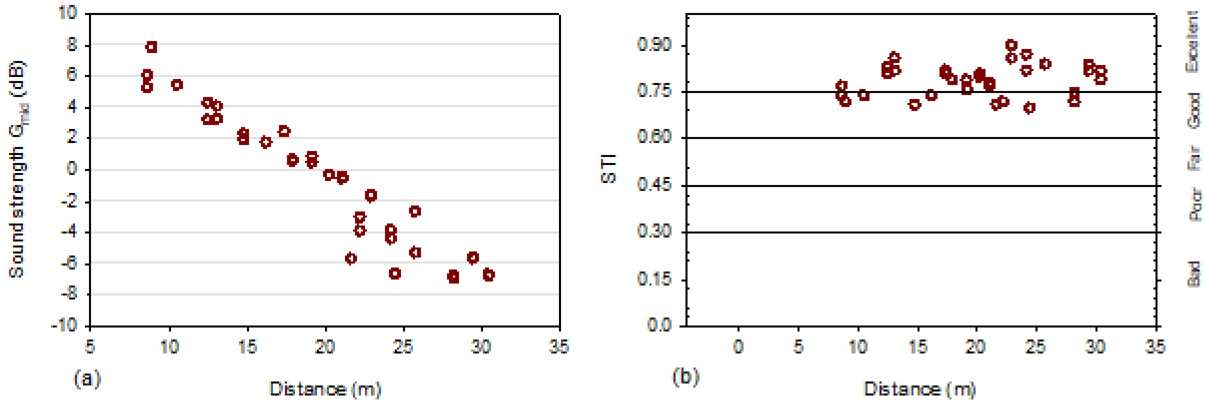

Figure 7 ─ (a) Sound strength G_{mid}, and (b) STI parameters versus source-receiver distance.

As for T_s, the values of this parameter are in the optimal range for auditoriums with a low and very uniform spatial dispersion at all frequencies.

G average values follow the same trend as the T_{30} with a global value of -0.5 dB, close to the value obtained in free field at 10 m distance from the sound source. However, the spatial dispersion values exceed 4 times the JND. The behaviour of the G_{mid} parameter as a function of distance is also worth noting, where changes of more than 12 dB in the parameter according to the receptor can be present (Figure 7(a)).

For the spatial parameters, J_{LF} presents low average values, although these lie within the typical range in non-occupied concert and multi-purpose halls of up to 25,000 m^3. Again, spatial dispersion is very high, and the apparent source width can improve markedly for certain receivers. For the assessment of the amount of listener envelopment in the theatre, the L_J parameter suggested by Bradley and Soulodre [23] has been displayed in Figure 5(f), where the parameter is energy averaged in the 125 to 1000 Hz octave band versus source-receiver distance. Although the preferred values for this parameter in performance halls are missing, according to an experimental campaign in British concert halls, values greater than -5 dB correspond to a stronger sense of listener envelopment [24], as is the case in this Roman theatre.

Despite the particularities of the environment and location of the theatre, the energy parameters largely maintain symmetry around the X axis. As an example, the average values of C_{80mid} in the *scaena*, *proedria*, *cavea,* and *orchestra* are shown in the map of Figure 8.

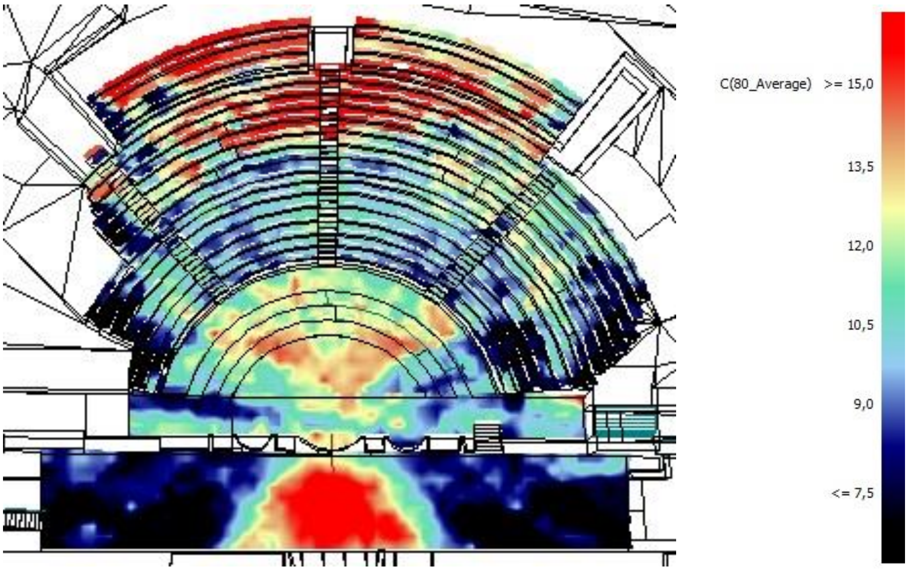

Figure 8 – Map of C_{80mid} values for the *scaena*, *proedria*, *cavea,* and *orchestra* of the Roman theatre of Malacca.

5 Conclusions

The environmental conditions of this theatre have prevented the on-site acoustic measurements from being carried out. However, the acoustic simulation accomplished in this work, based on data of absorption and dispersion coefficients of the stone and marble of the *cavea* from other Roman theatres and other bibliographic sources, has enabled results to be obtained that are highly consistent for these outdoor theatre structures of Roman Hispania. The reverberation times lie within the optimal range for the size of the theatre, and although it lacks a stage front, there are urban buildings close to the *scaena*. It is worth noting the high values of musical clarity in accordance with the values of T_s and C_{80} and of the intelligibility for speech corresponding to the results of the STI index versus source-receiver distance. The results also show the seat-to-seat variations that occur in EDT and the subjective noise level *G* in the theatre, and reveal high values for the feeling of listener envelopment. Likewise, the computational simulation shows the symmetry of the energy parameters around the symmetry axis of the theatre. The data shown here corresponds to the study of the sound field of the theatre with a single position of the source. However, it is intended to continue this work by studying the sound field for other positions of the source, and to investigate the effect of the Alcazaba hillside on its acoustics.

Acknowledgements

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