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THE ACOUSTICS OF ANCIENT THEATRE OF HEPHAISTIA – LIMNOS ISLAND, GREECE

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Abstract
The ancient stone theatre of Hephaistia is located to the northeast of Limnos Island, Greece and is dated back to the end of the 5th- beginning of the 4th century BC with additions/modifications during the Hellenistic and Roman periods.

Works for the enhancement/restoration of the theatre were carried out during the period 2000 – 2004 by the K' Ephorate of Prehestoric and Classical Antiquities and after 2300 years, in the summer of 2010 hosted its first performance with the ancient Greek tragedy of Sophocles, "Oedipus Tyrant".

The evaluation process of the acoustics of the ancient stone theatre of Hephaistia includes:

- An objective assessment of its acoustics, based on the measurement and analysis of a number of acoustical parameters used for the evaluation of auditoriums.

- The development of an acoustic computer model of the theatre which is used to compare its simulated acoustic performance with measurement data obtained on site. The computer acoustic modeling of the theatre was also used to evaluate the effect of occupancy and various hypothetical treatment scenarios and geometry variations.

- A subjective assessment of its acoustics from a performer's point of view comparing their subjective experience during the performance of Oedipus Tyrant with that obtained from the performance of the same Greek tragedy in other ancient theatres such as the ancient theatre of Epidaurus.

Keywords
Stone Theatre Limnos Hephaistia Measurement

1. Introduction – Historical Data

Hephaistia, which is named after the smith-god Hephaistos is one of the two cities of Limnos Island in historical times, occupied the entire Palaiopoli Peninsula [1]. There is evidence of settlement at the site from the Early Bronze Age into the Post-Byzantine period and excavations have shown that the city enjoyed a sustained heyday from the seventh to the first century BC. The excavation of the ancient theatre of Hephaistia begun by Italian archaeologists in 1935, but it was cut short before the outbreak of Second World War. The theatre lay in ruins after its exposure in 1939 until 2002, with visible scars due to the removal of stones for building materials. The most important monument revealed so far is the theatre which is directly linked with the settlement of Athenian cleruchs on Limnos and their relations with the Athenian city-state in Classical times and of course, with the institutions of Democracy.

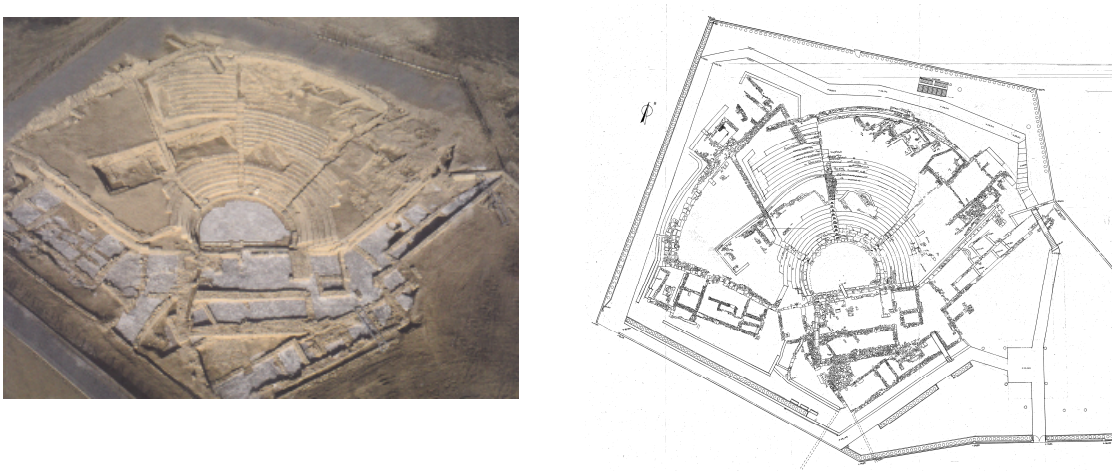

Figure 1 – Aerial photo and plan of the ancient theatre of Hephaistia after the rehabilitation works

2. Construction

The theatre was constructed in a locus sanctus (sacred location). The cavea of the auditorium was built upon the remains of earlier sanctuaries dated from the second half of the seventh to the sixth century BC. It is understood that due to the historical importance of the excavation findings, the theatre of Hephaistia was restored rather as monument, as opposed to that of a fully functional theatre, with a view to reveal its successive phases and features of its development over its 2500 years history. To understand better the geometry and the size of the monument, the proposed reconstruction of the theatre is presented on Figure 2.

The theatre of Hephaistia was built on a steep, semi-rocky side of a hill. The rocky slope of the hill was used for its construction and was smoothed by filling the hollows with stone chips and earth boxed in by walls built of medium-size stones from the area in a radial arrangement. The orchestra is made of dry soil covered with crushed stones. It has a circular shape with 12.40m diameter. The first rows of seats belong to the earliest phase of the stone theatre of Hephaistia made of large rectangular slabs of local poros stones. In contrast, the seats of the epitheatre were built of cheaper materials, slabs of locals schists and limestone of various sizes. The angle of the cavea varies with the front rows at a steeper angle than the epitheatre which is estimated to be approximately

23 degrees. The most distance seat of the theatre, in direct line, is approximately 28m from the centre of the orchestra.

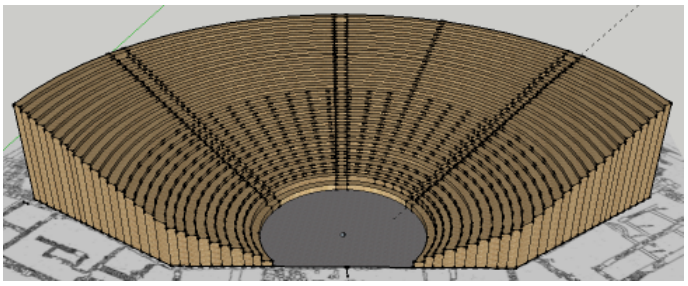

Figure 2 – The ancient theatre of Hephaistia – Proposed restoration (3D - computer acoustic model)

3. Acoustic Measurements

The acoustic measurements of the theatre were carried out on the 19th, 20th and 22nd of June 2011. Two different sets of measurements were carried out and two testing methodologies were used. In both testing procedures, room acoustic parameters used to describe objectively the quality of speech and music in auditoria were recorded at a number of receiver locations spread around the cavea of the theatre for various source positions. The use of various source positions was done in order to investigate possible variations in the acoustic performance of the theatre associated with the position of the source. They are described below.

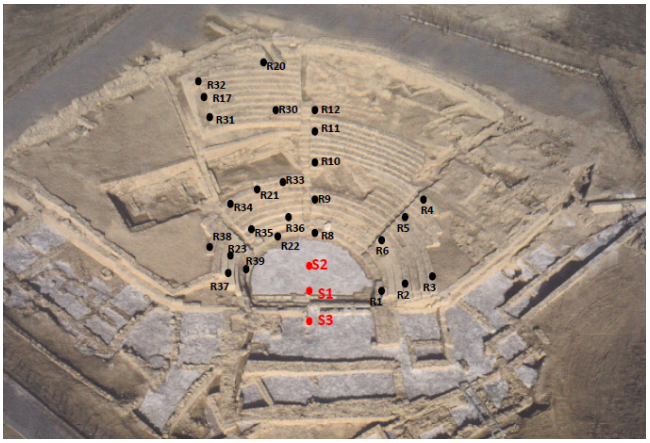

Figure 3 – Measurement positions

3.1 Measurement of room acoustics parameters using BS EN ISO 3382-1:2009. [2]

Three source positions, namely S1, S2 and S3, as shown in Fig. 3, located in the Orchestra (S1 and S2) and the stage (skene) (S3) of the theatre. S1 and S2 height was 1.70m and S3 height 2.10m. Source position S3 was selected to be located at the height of a person standing on a shallow stage, similar to the one which is currently used for performances.

A number of receiver locations were distributed around the cunea all at a seating person's height, as shown in Fig. 3.

Impulse response measurements were carried out with MLS excitation using an omni-directional loudspeaker as a source in accordance with BS EN ISO 3382-1:2009, "Acoustics - Measurement of Room Acoustic Parameters, Part 1, Performance Spaces".

3.2 Measurement of Speech Intelligibility STI and (%Alcons)

Two source positions were used, namely S1 and S3. Source heights and receiver positions as described above.

Impulse response measurements were carried out with an excitation signal of periodic speech noise, where STI and %Alcons parameters were estimated according to IEC-60268-16 "Sound system equipment - Objective rating of speech intelligibility by speech transmission index." [3]

The measurement of the STI was done using ARTA Software with the following procedure [4]: The microphone was initially set at 1m in front of a small loudspeaker, the size of which is close to the size of a human head. The loudspeaker was excited with the periodic speech noise signal. The power amplifier gain was set to obtain SPL = 70dBA. The generated spectrum was adjusted to have octave-band levels as given in Table 1 below.

Table 1 - Octave band levels of speech noise (ref. 1kHz level)

Octave band (Hz)	125	250	500	1000	2000	4000	8000
Speech noise of male speech (dB)	9.7	9.7	6.0	0.0	-6.0	-12.0	-18.0
Speech noise of female speech (dB)	-	14.4	7.2	0.0	-6.7	-7.6	-8.9

3.2.1 Measurement Results - Analysis

The ancient theatre of Hephaistia is located on a quiet site in a rural area away from industrial, traffic and urban noises with a typical background noise level of 35dB L_{A90} during daytime. Weather conditions during the measurement periods were dry, warm with little wind.

<u>EDT (125Hz - 4kHz)</u>
Measured EDT (which is correlated with the subjective impression of reverberance) across all receiver positions, show that on average, there is an increase in EDT as the source gets further away from the audience (on stage). On average, the EDT varies from 0.23sec (S1 and S2) to 0.32sec (S3). Variation on the EDT was also observed with receiver position. The lowest EDT values were observed in the middle part of the cavea when the source is located behind the middle of the orchestra with the highest EDT values occurring on left and right edges of the cavea. When the source is located in front of the middle of the orchestra, the highest EDT values occur in the upper part of the central part of the cavea.

<u>T30 (125Hz - 4kHz)</u>
Measured T30 are found to be fairly consistent across the cavea at approximately 0.28 sec. A slight increase on the T30 values was observed with the source located further away on the left and right edges of the cavea.

D50 (125Hz - 4kHz)
Measured D50 values are found to vary, on average, between 89% and 93%. They tend to slightly decrease as the source gets further away from the audience (on stage) but they remain within acceptable limits. Variation on the D50 values was also observed with receiver position. Remotely located seats, on the upper part of the audience tend to score lower D50 values than receiver positions closer to the source. This variation lies between D50 values of 73% and 99%.

Ts Centre Time (125Hz - 4kHz)
Centre Time (Ts) values are found to vary significantly. They show that on average, there is an increase in Ts as the source gets further away from the audience (on stage). However, significant variation was observed with receiver position. Similarly to D50, remotely located seats, on the upper part of the audience tend to score higher Ts values than receiver positions closer to the source. This variation lies between 15ms to 180ms. The extreme values of the Ts range were observed on the closer and most distant receivers with the majority of the receiver position to remain within acceptable limits (below 60ms).

C80 (125Hz - 4kHz)
Measured C80 values are found to vary, on average, between 12 and 14 dB. Similarly to D50 values, they tend to slightly decrease as the source gets further away from the audience (on stage) but they remain within acceptable limits. Variation on the C80 values was also observed with receiver position. Remotely located seats, on the upper part of the audience tend to score lower C80 values than receiver positions closer to the source. This variation lies between C80 values of 6 and 18dB.

STI and (%Alcons)
Measurements of speech intelligibility (STI and %Alcons) across all receivers indicate that speech intelligibility varies from Fair to Excellent with the majority of the receivers scoring from Fair to Good ratings. %Alcons at the most distant positions were found to be Poor, but these specific measurements may have been affected by wind.

Similar results were obtained with the source on stage. STI rating was found to lie between Fair and Good.

The effect of the orientation of the speaker's head was also investigated, indicating as anticipated, a significant improvement on the STI rating when the speaker faces the receiver.

The subjective impression of the author as well as many of the spectators, during a play that took place on 3rd September, confirmed the findings obtained from measurements as described above. The view of the orchestra from a listener in the most distant seats of the audience was partially obstructed probably due to the lower seating angle of the epitheater. In those positions it was observed that speech clarity was improved when the listener was on a standing position. .

4. Computer Acoustic Modelling

The ancient theatre of Hephaistia which has a capacity of approximately 500 spectators, even in its current not fully developed theatrical form, presents a challenge, purely from an acoustics point of view because it offers the opportunity to evaluate in an "abstractive way" the contribution of the missing parts of the cavea to the overall acoustic performance of the theatre. Computer acoustic modelling offered an easy way of further investigation. A computer acoustic model of the theatre was built in order to evaluate various hypothetical treatment scenarios such as, the effect of occupancy, the effect of a fully absorbent Orchestra and variations in the geometry of the auditorium. The acoustic model of the theatre was made using ODEON. The various treatment and configuration scenarios investigated are described below:

1. Simulation of the existing theatre (with/without occupation)
2. Simulation of the proposed restoration (with/without occupation)
3. Simulation of a fully absorbent Orchestra

The results obtained from the computer acoustic modelling are presented and discussed in the following sections.

4.1 Simulation of the existing theatre (with/without occupation)

As a generic observation, computer acoustic modelling results tend to overestimate to some extent the values of the room acoustic parameters used, compared to the values obtained from site measurements. Nevertheless, for the purpose of a qualitative comparison between the proposed and existing configurations, it is considered appropriate.

4.2 Simulation of the proposed restoration (with/without occupation)

<u>Reverberance</u>
The acoustic modelling results indicate that on average, the subjective perception of reverberance (EDT) on the proposed restoration is predicted to be higher by a factor of approximately 60%. In absolute terms, it is expected that the EDT would increase from 0.22sec to 0.37sec. T30 is also anticipated to increase by a factor of approximately 35%.

Occupancy does not seem to affect the overall subjective impression of reverberance (EDT) in either configuration, compared to their "empty" counterparts. Similar conclusions apply to T30. T30 values on the proposed configuration remain unchanged or slightly lower.

<u>Speech definition and music clarity (C80, D50 and Ts)</u>
D50 values on the proposed restoration is predicted to decrease by a factor of approximately 5%, compared to the existing. Similar conclusions apply to the values of Centre Time (Ts) and C80. It should be noted however that although the predicted values of the proposed restoration are expected to decrease, they would still be within acceptable limits.

The effect of occupancy is considered to be negligible although there is a tendency to improve speech and music clarity on average.

4.3 Simulation of a fully absorbent Orchestra

In order to investigate the effect of the off-the orchestra reflection, the orchestra was modelled as fully absorbent to remove completely the off-the orchestra reflection. The "fully absorbent orchestra" was applied on the occupied configurations and the results are compared with its "reflective" equivalent. They indicate the following:

Reverberance
The effect of removing the off-the orchestra reflection seems to increase, on average, the subjective perception of reverberance as well as the reverberation time. This effect was maximised for source positions located further away from the audience i.e. on stage). A possible explanation for that could be that in the absence of 1st order reflections off- the orchestra, all other reflected sound arrives later in time contributing to the reverberant field. The presence of fully absorbent orchestra an additional absorbing surface does not seem to affect the reverberberation in a way that it would in an enclosed space because it is small compared to the total absorption surrounding the theatre (sky etc). Its presence, only affects the distribution of reflections.

Speech definition and music clarity (C80, D50 and Ts)
The effect of removing the off-the orchestra reflection seems to decrease, on average, the speech definition and music clarity. This effect was maximised for source positions located further away from the audience i.e. on stage). It was observed however, that for distant receivers, Speech definition and music clarity were marginally increased.

It was attempted to investigate the effect of the off-the orchestra reflection with actual measurements on site. The only practical means available was to place a strip of 20mm plexiglass panels on the orchestra between the source and the cavea along the line of the source-receiver direction. This was an indicative set of measurements and it was carried out for source position (S1) and receivers along the center of the cavea. The orchestra ground consisted of dry soil covered with crushed stones. This is considered as a fairly reflective surface but certainly not as reflective as the plexiglass. Ideally, this test should have been done by applying 100mm low density mineral wool as opposed to plexiglass but given the opportunity it was considered that it worth a try.

The fully reflective orchestra indicate, as expected, a marginal improvement on speech definition and music clarity for the receivers closer to the source but interestingly, their values were decreased for the most distant receivers. This change was mainly attributed to the frequency octave bands of 4kHz and 8kHz. This finding is in line with that obtained from the acoustic modelling with a fully absorbent orchestra, where the speech definition and music clarity were found to increase for distant receivers and it is subject to further investigation. Reverberance parameters remained unchanged.

5. Conclusion

In conclusion, the acoustics of the Ancient Theatre of Hephaistia as it is currently restored were found to be satisfactory. Speech intelligibility ratings vary from Fair to

Good and energy ratios such as Definition and Clarity index were found to be good and suitable for theatrical and music performances.

Computer acoustic modelling of the theatre in its current and proposed fully developed restoration indicates that on average, the subjective perception of reverberance on the proposed restoration is predicted to increase. Speech definition and music clarity are predicted to decrease compared to the existing but to remain within acceptable limits.

Occupancy does not seem to affect the overall subjective impression of reverberance (EDT) in either configuration, compared to their "empty" counterparts. Similar conclusions apply to T30. The effect of occupancy on speech definition and music clarity is considered to be negligible although there is a tendency to improve speech and music clarity on average.

The effect of removing the off-the orchestra reflection seems to increase, on average, the subjective perception of reverberance as well as the reverberation time. This effect was maximised for source positions located further away from the audience i.e. on stage). Speech definition and music clarity seems to decrease, on average. It was observed however, that for distant receivers, speech definition and music clarity were marginally increased. This is subject to further investigation work and site measurements.

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[1] The ancient theatre of Hephaistia, K' Ephorate of Prehistoric & Classical Antiquities, Lemnos 2004.
[2] BS EN ISO 3382-1:2009, "Acoustics - Measurement of Room Acoustic Parameters, Part 1, Performance Spaces".
[3] IEC-60268-16 "Sound system equipment - Objective rating of speech intelligibility by speech transmission index."
[4] ARTA software, User Manual " Program for Impulse Response Measurement and Real Time Analysis of Spectrum and Frequency Response", version 1.7.0, 125 - 128 (2010).