THE UNIVERSITY OF SHEFFIELD
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ANCIENT AND CONTEMPORARY USE OF OPEN-AIR THEATRES: EVOLUTION AND ACOUSTIC EFFECT OF SCENERY DESIGN

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Dissertation submitted for the Degree of PhD

VOLUME 2

JUNE 2007

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PART 3

ANALYSIS

CHAPTER 7

ACOUSTIC THEATRE EVOLUTION IN ANTIQUITY: ARCHITECTURAL LAYOUT AND MATERIAL PROPERTIES

7.1 INTRODUCTION

In this chapter the acoustic properties of ancient performance spaces used for Greek and Roman drama are studied, from the viewpoint of architectural layout and material properties. As indicated previously in Chapters 3 and 4, ancient theatres in Greece underwent a process that defined their architectural components and classified them into the Minoan, the Pre-Aeschylean, the Classic, the Hellenistic and the Roman types. The identifiable characteristics that enabled the typology of every theatre were either the result of new needs for the evolution of drama, new construction methods, in terms of materials and position of the theatre in the city or the country, or individual transformation of theatres. In particular, the same theatre could have evolved architecturally when the stage building gained a new shape, new components, or through changes in heights and relative positions between the actors, the chorus and the audience. This chapter is based on a recently published paper [Chourmouziadou and Kang, 2007a].

The transformations were always a determining factor for the acoustic environment of the theatrical space. This chapter examines the effectiveness of the architectural evolution on the acoustics. Hence, it examines the acoustic evolution of the theatres in their condition in antiquity. The stages the theatre went into through this process are only found in historical notes and in indications during the excavations, while the exact material properties are basically an assumption, based on contemporary data found in the literature. Since the material finishes in antiquity are not known, although the coefficients can be measured for their present condition, the chapter further investigates how the absorption and diffusion coefficients can affect the acoustics, by examining a coefficient range for every material, except for cases where the coefficient can be measured, as shown in Chapter 8. The hypothesis that, although changes in forms and materials during the theatre evolution may have improved acoustics, the architectural characteristics rather than the material properties determine the overall result is investigated.

The structure of this chapter is as follows: It first briefly reviews the theatre evolution in antiquity, as indicated in Chapter 3. It then presents the methodology and the results of a series of acoustic simulations in six typical theatre forms, using Raynoise, described in Chapter 2, according to Chapters 5 and 6. Early theatre forms, for which no previous acoustic analysis has been made, like the Minoan type, are examined. Later it presents the more focused analysis on the development of the Classic theatre type and the genesis of the Hellenistic, as these types are used today and will be of major concern in later chapters. Particular attention is paid to the comparison between Greek and Roman theatres, with representative examples the theatres of Epidaurus and Aspendus respectively. Moreover, it briefly discusses the simulation parameters, used for the evaluation of the theatre evolution and it divides the theatres into categories, according to the prevailing material they were built with. Consequently, stone, wood, earth as well as audience absorption and diffusion are examined by applying maximum and minimum values found in the literature. Finally, a discussion on the interdisciplinary nature of performance spaces and its relation to acoustics is presented and the results regarding the material testing are shown.

7.2 THEATRE EVOLUTION IN ANTIQUITY

7.2.1 PREVIOUS RESEARCH

As shown in Chapters 2-4, extensive research on ancient performance spaces in Greece started when the first historical excavations revealed evidence of the spaces used for performances. Previous works related to ancient performance spaces are found scattered in several fields, including drama, archaeology, architecture, philosophy and acoustics. Changes in performance styles led to innovations that altered the form of the theatre [Baldry, 1971; Cartledge, 1999; Chourmouziadou and Kang, 2002; Furneau-Jordan, 1969; Simpson, 1956]. Ancient Greek and Roman theatres have been discussed and compared in terms of architectural and construction trends [Cailler and Cailler, 1966; Dinsmoor, 1950; Dörpfeld, 1896; George, 1997; Izenour, 1977; Robertson, 1979; Vitruvius, 1st B.C.]. Still, it is not clear whether the Roman performance spaces were just a transformation or an advanced design of the Greek.

The acoustics in a number of theatres of antiquity have been examined in the past, based on general acoustic principles or on-site measurements [Barron, 1993; Beranek, 1962; Canac, 1967; Cremer, 1975; Egan, 1988; Shankland, 1973]. Although computer simulation has been used for studying the acoustics of ancient ritual spaces and theatres [Vassilantonopoulos and Mourjopoulos, 2001; 2003; 2004], as seen in Chapters 2 and 3, research regarding the influence of the architectural evolution and material use on the acoustic quality has been limited. Moreover, the relationship between the acoustic knowledge in antiquity [Chadwick, 1981; Guthrie, 1962; Hunt, 1978; O'Meara, 1989] and the design of these theatres have not been systematically investigated.

7.2.2 ARCHITECTURAL EVOLUTION

The Greeks were renovating their theatres, according to the need to accommodate a larger audience, the change in performance style and the use of new materials [Athanasopoulos, 1983; Chourmouziadou, 2002; Dinsmoor, 1950]. According to Chapter 3, the early forms were the Minoan (20th-15th B.C.) and the Pre-Aeschylean (15th-6th B.C.) in rectangular and trapezoid shapes respectively, with limited surviving examples [Athanasopoulos, 1983]. Figure 7.2.1 illustrates the plans and sections of these two types of performance space.

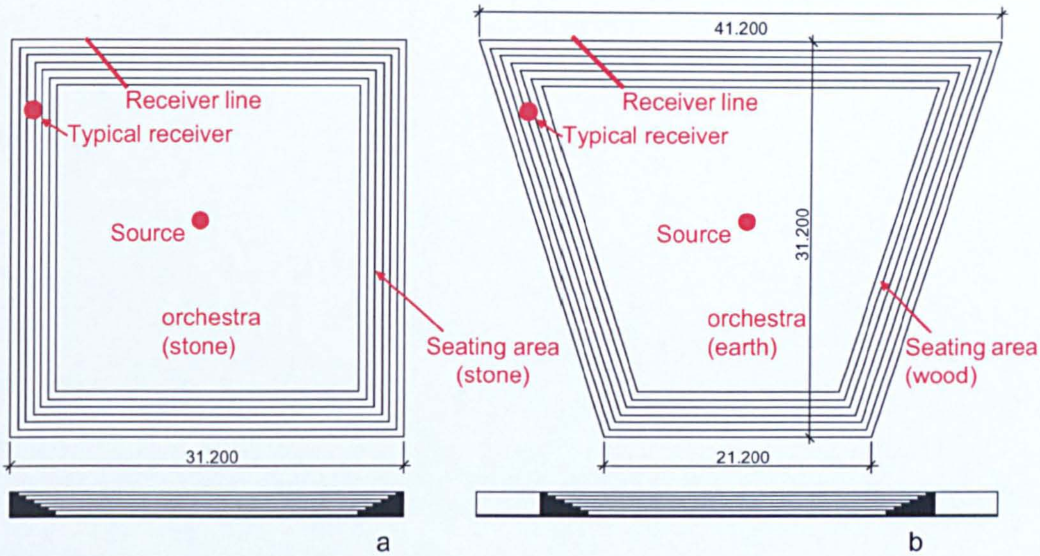


Figure 7.2.1. *Plans and sections of the early forms of performance space in Greece, with locations of typical receivers and receiver lines used in the simulation. a) Minoan and b) Pre-Aeschylean.*

The Classic Greek type was created in the 5th century B.C., comprising two basic elements: the orchestra and the koilon, namely the hill slope that provided ample amphitheatric space. Stepped tiers were hewn in the shape of concentric circular sections in the hillside around the orchestra to allow the audience a better view of the performers [Simpson, 1956]. They were then replaced by wooden benches. A stage building was constructed later. However, the definite form came with the use of stone and marble in the late 5th century B.C. The seats were laid out concentrically around the now circular orchestra in arcs exceeding 180^{o}, often extended around two-thirds of the orchestra circle. Figure 7.2.2a illustrates the Classic Greek theatre [Dinsmoor, 1950; Robertson, 1979; Simpson, 1956].

The descendant of the Classic theatre was the Hellenistic. Some characteristics can distinguish it from the previous form, such as the raised stage, and the stage building. These innovations were also connected with changes in the methods of playwriting at that period. For example, the introduction of the second and the third actor in tragedies moved the centre of the performance from the orchestra to the proscenium and the stage, which were therefore raised [Baldry, 1971]. In some cases the koilon was extended with more seating rows, like in the theatre of Epidaurus, or the orchestra was repositioned, like in the theatre of Dionysus in Athens. Figure 7.2.2b illustrates a typical Hellenistic theatre, based on the theatre of Epidaurus, although not including the high podium above the diazoma [Dinsmoor, 1950; Robertson, 1979; Simpson, 1956].

The Roman theatre, like Roman drama, was Greek in origin [Robertson, 1979], although it differed in several respects from all Greek theatres of Classic or Hellenistic times. The auditorium or cavea of the Roman theatre was semicircular and it was united as a single structure with the stage building, as illustrated in Figure 7.2.2c [Izenour, 1977; Robertson, 1979]. There were vaulted passages at the point where the orchestra was connected to the cavea, to make the orchestra accessible. The walls of the stage building were the same height as the cavea and the stage was wide but low in height, projecting much further than the proscenium and affecting the shape of the orchestra, which was reduced to a semicircle. Early Roman theatres, built from wood in unknown shapes, are not included in the simulation.

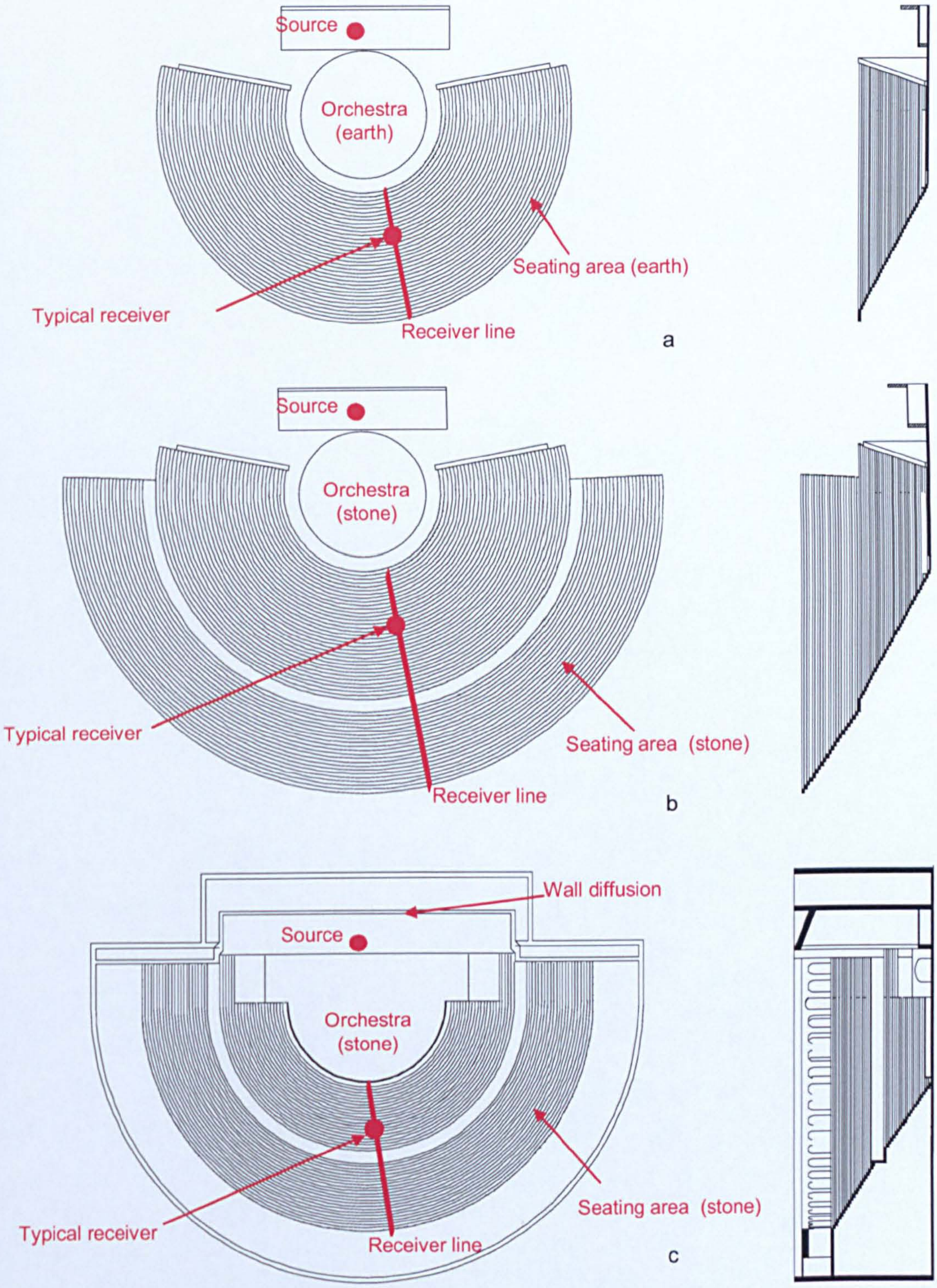


Figure 7.2.2. *Plans and sections of the performance spaces evolved after the 6th century B.C., with locations of typical receivers and receiver lines used in the simulation. a) Classic Greek theatre, b) Hellenistic theatre and c) Roman theatre.*

7.3 SIMULATION METHOD AND CONFIGURATIONS

Based on the above review, six configurations are simulated, as presented in Table 7.1. Two forms of Classic theatre are simulated, referred to as early Classic theatre and Classic theatre, considering different koilon conditions, one with earth koilon and one with wooden koilon.

Table 7.1. *Configurations used in the simulation.*

		Configurations					
		1	2	3	4	5	6
		Minoan	**Pre-Aeschylean**	**Early Classic**	**Classic**	**Hellenistic**	**Roman**
Characteristics	**Orchestra**	Stone	Earth	Earth	Earth	Stone	Stone
	Koilon	Stone	Wood	Earth	Wood	Stone	Stone
	Stage	No	No	Wood	Wood	Wood	Stone
	Stage height (m)	0	0	1.5	1.5	3	2

According to the comparison of room acoustics simulation software packages in Chapter 2, software Raynoise was used [LMS Numerical Technologies, 2001]. Regarding diffusion and diffraction from seat risers, which are important in outdoors theatres [Chourmouziadou and Kang, 2006b], and were examined in detail in Chapter 6, the flat panel diffusion coefficients, namely 0.3 at 125Hz, 0.2 at 250Hz, 0.15 at 500Hz, 0.01 at 1kHz, 0.09 at 2kHz and 0.07 at 4kHz are applied [LMS Numerical Technologies, 2001; Everest, 1994]. However, the stage wall in the Hellenistic and the Roman theatres, which had decorations, are simulated with increased diffusion, of 0.5, across the frequency range.

Table 7.2 illustrates the boundary absorption coefficients, which are based on typical values from the literature [Egan, 1988; LMS Numerical Technologies, 2001; Lord and Templeton, 1996], as shown in Table 7.2. Both unoccupied and occupied conditions are considered. The former is useful to study the basic acoustic characteristics of the theatres, and is also relevant to the acoustic conditions during rehearsals. For the occupied condition, audience absorption is applied to the stepped koilon of the theatres, with average absorption coefficient values for lightly upholstered seating.

Table 7.2. *Absorption and diffusion coefficients used in the simulation.*

	Frequency (Hz)	125	250	500	1k	2k	4k
Absorption	Stone	0.01	0.01	0.01	0.01	0.01	0.01
	Wood	0.15	0.11	0.10	0.07	0.06	0.07
	Earth	0.34	0.55	0.6	0.42	0.55	0.56
	Audience	0.28	0.40	0.78	0.98	0.96	0.87
Diffusion	Flat Panel	0.30	0.20	0.15	0.10	0.09	0.07

An omni-directional point source is positioned near the middle of the orchestra in the early theatre forms, and near the middle of the stage in the Classic, Hellenistic and Roman theatres, simulating a single actor. The sound power level of a performer's strong voice is determined by increasing the sound power level of conversational speech by 12 dB in each octave band [El-Zeky and Oldham, 1998]. The resulting sound power level is 84dB at 125Hz, 76dB at 250 and 500Hz, 72dB at 1kHz, 67dB at 2kHz, and 47dB at 4kHz. While the use of an omni-directional point source is conventionally adopted in the field of room acoustics and is useful for studying the basic characteristics of a theatre, effects of a directional source are also studied for a selected case, as previously seen in Chapter 5, Section 5.2.4.

For the sake of convenience, no background noise is applied in the simulation. As a result, the speech transmission index (STI) values in this paper represent the ideal conditions. If background noises are considered, such as wind in trees and others mentioned in Section 5.2.3, the reduction in STI can be easily obtained based on the method by Steeneken and Houtgast [1985].

The calculation parameters are carefully selected based on a pilot study [Chourmouziadou, 2002] and Chapter 5. The number of rays varies, depending on the complexity of the layout, from 20,000 to 100,000. The time window is 2-10s, and the dynamic range is 90dB. The maximum reflection order is 50, since high reflection order in outdoor spaces may produce long RT values, due to the expansion and overlapping of the beams after a large number of reflections. The triangular beam-tracing method is used, and no tail compensation is applied for such outdoor spaces [LMS Numerical Technologies, 2001]. As seen in Section 5.2.2.4, since Raynoise involves random distribution when calculating diffusion, repeated simulations were carried for a typical theatre type, and it was found that the variation was negligible.

The theatre models are first created using Archicad and 3D Studio, and then imported into Raynoise. Circular surfaces in the Classic, Hellenistic and Roman theatres are realistically represented and then divided by Raynoise into small triangles. A systematic comparison has been made between this method and the representation of the curved surfaces by various levels of polygons, as shown in Chapter 5, and it has been shown that this method provides good accuracy, although with the expense of a longer computation time [Chourmouziadou and Kang, 2004].

7.4 Acoustic evolution of Ancient Performance Spaces

This section presents a series of acoustic simulations of the aforementioned theatre types, investigating the general acoustic evolution. Particular attention is paid to the comparison between a Hellenistic and a Roman theatre. The main acoustic indices considered in the simulation are the SPL distribution, the RT30 and the STI. The RT30 is used in this research mainly for comparative studies, given that it is usually used for evaluating enclosed spaces.

7.4.1 Sound Distribution

Figure 7.4.1 compares the SPL between configurations 1-6 at 125 to 4kHz under unoccupied conditions. The receivers, as shown in Figures 7.2.1 and 7.2.2, represent middle/typical seats in each type of theatre.

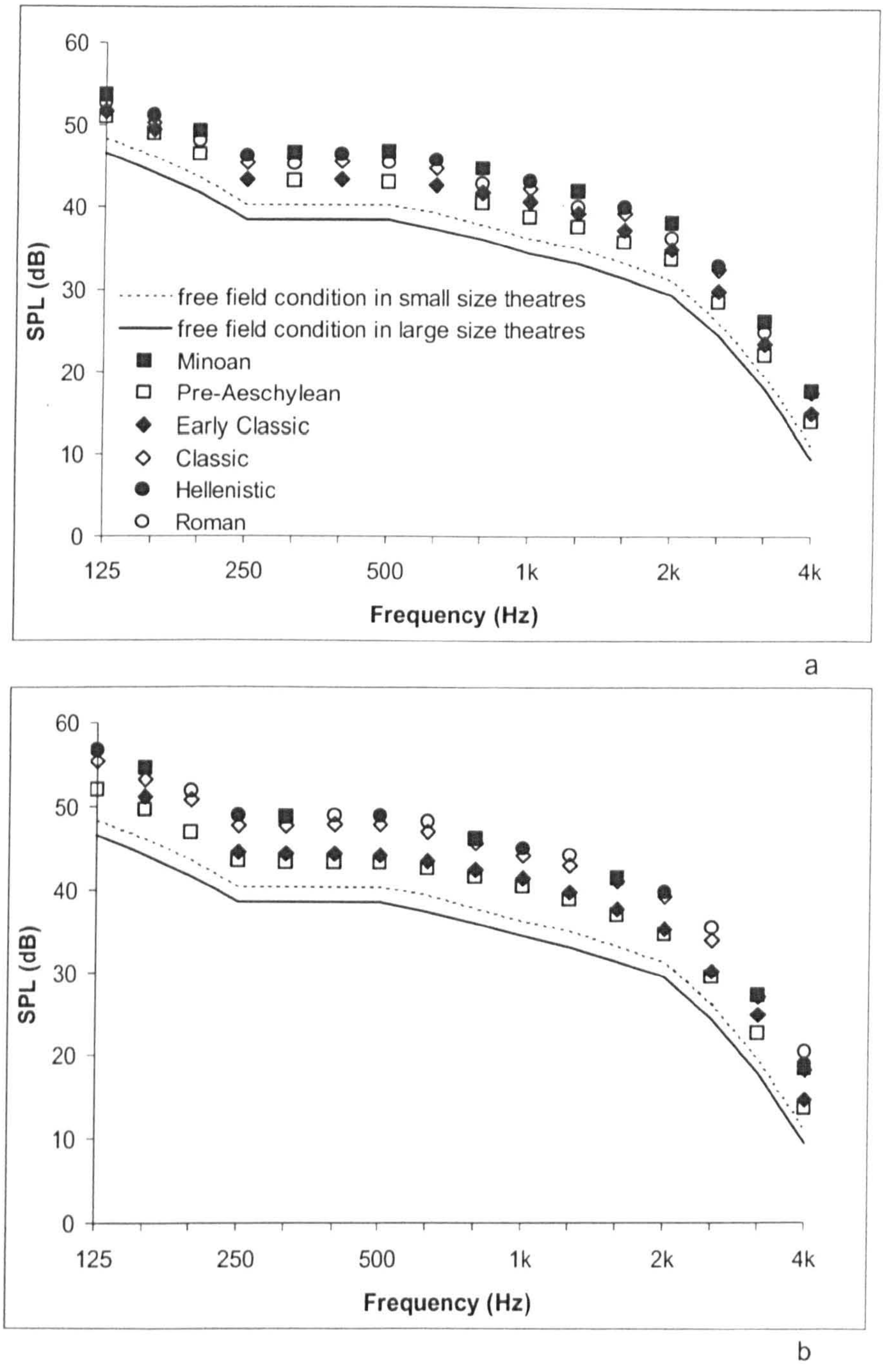


Figure 7.4.1. *Comparison of the SPL (dB) between configurations 1-6 at the typical receivers under unoccupied conditions. a) With flat panel diffusion, b) Specular reflections only.*

The highest values are found in the Minoan type, caused by the proximity to the sound source, and in the Roman and Hellenistic theatres, caused by strong early reflections. In Figure 7.4.1a the SPL of the free field condition at two source-receiver distances corresponding to the above middle/typical seats is also shown, which is about 6-8dB lower than those of other configurations, when flat panel diffusion is applied, demonstrating the usefulness of boundary reflections. It is interesting to note that, from the Pre-Aeschylean theatre, to the early Classic, the Classic, and then the Hellenistic, there is an increase in SPL up to 5dB. This is mainly caused by the use of harder materials, as can be seen in Table 7.1. Additionally, Figure 7.4.1b illustrates the SPL with no diffusion calculations, which indicates greater differences between the configurations as well as with the free field condition. However, with geometrical reflections only the results would be unrealistic, especially for reverberation and consequently for speech intelligibility. Calculations have also been made along typical receiver lines (see Figures 7.2.1 and 7.2.2), and the results at 500Hz for the Hellenistic and the Roman theatres are shown in Figure 7.4.2, for both occupied and unoccupied conditions. For comparison, results without boundary diffusion/diffraction, namely with geometrically reflecting boundaries, are also shown.

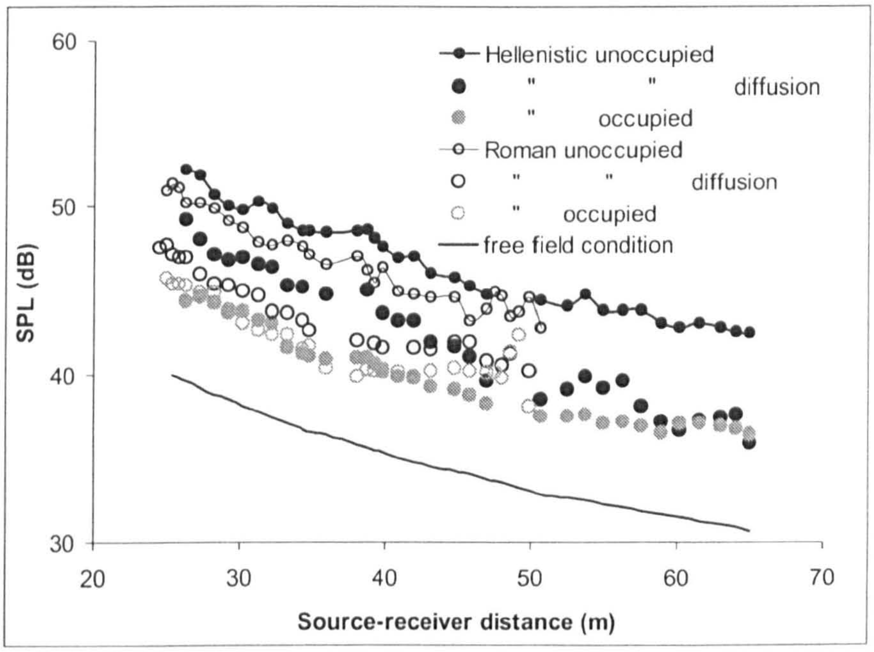
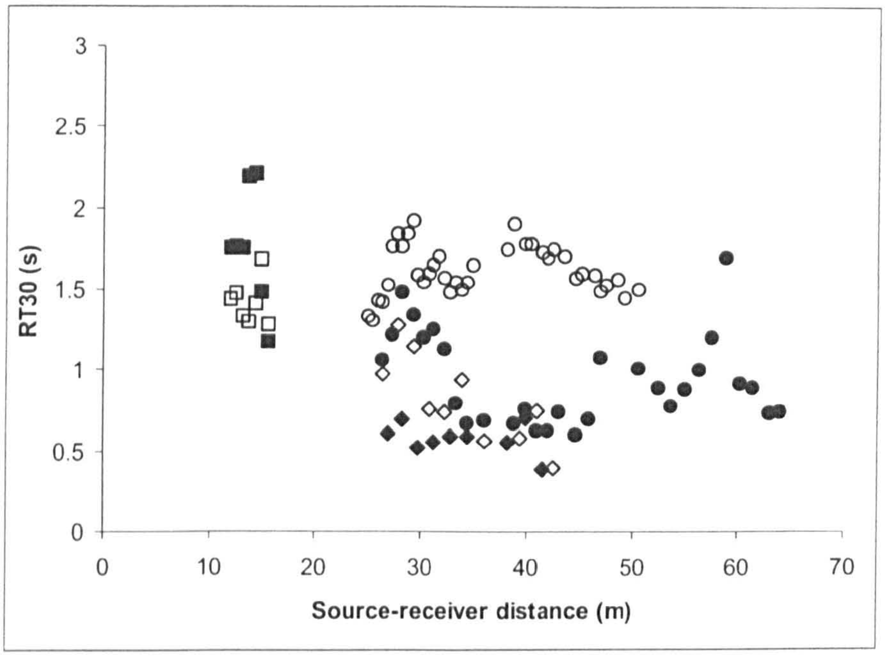


Figure 7.4.2. *SPL(dB) at 500Hz in the Hellenistic and Roman theatres along the typical receiver line.*

From Figure 7.4.2 it can be seen that diffusion reduces SPL values considerably, by about 3dB in the relatively near field and 6dB in the far field. Under the occupied condition, the SPL is further reduced by 2-5dB in the Hellenistic theatre and by 1-2dB in the Roman theatre. Compared to the direct sound only, namely the free field condition, the theatre spaces provide an increase of about 4-6dB under occupied conditions and 7-8dB under unoccupied conditions when boundary diffusion is considered. This reveals the importance of factors like materials and reflection patterns, in addition to the distance from the stage. Further analyses of the reflection patterns show that, apart from the reflections off the risers of the koilon which significantly enhance sound in the unoccupied condition, the early reflections off the orchestra and the stage building are also of great importance.

7.4.2 REVERBERATION

Figures 7.4.3a and b compare the RT30 between configurations 1-6 under unoccupied conditions along the receiver lines at 500Hz and at the typical receivers from 125 to 4kHz.



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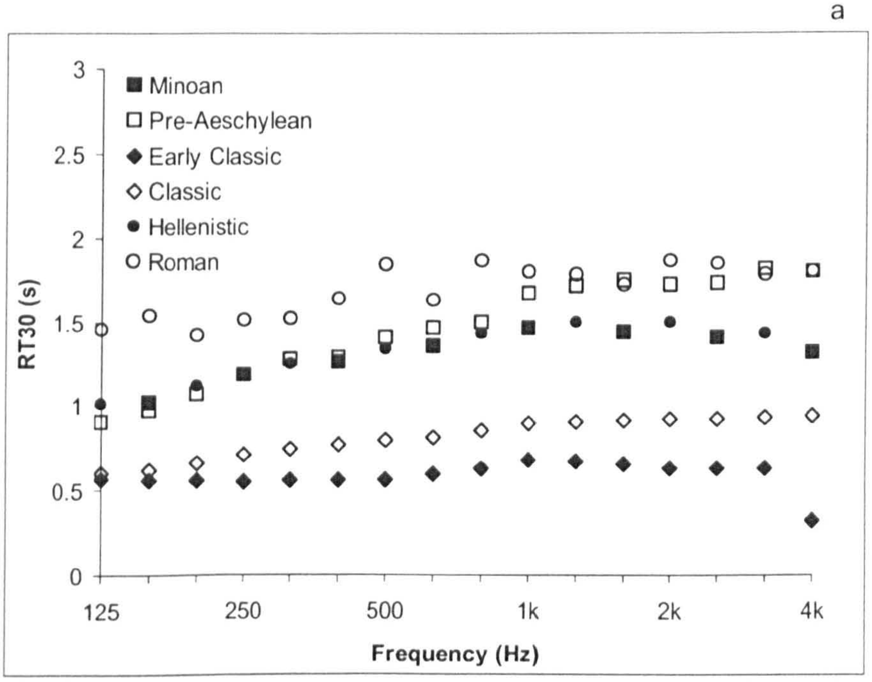


b

Figure 7.4.3. *RT30 (s) in unoccupied theatres. a) Along the typical receiver lines at 500Hz and b) At the typical receivers from 125 to 4kHz.*

It can be seen that in the Minoan theatre the RT30 varies between about 1.20 and 2.20s at different receivers. The long reverberation as well as the large variation between receivers in this rather open layout is mainly due to the rectangular shape, which causes multiple geometrical reflections and flutter echo effects. In the Pre-Aeschylean theatre, due to the trapezium shape, combined with relatively softer materials, the reverberation is considerably reduced. In the early Classic and Classic theatres, since the boundaries are comparatively soft, reverberation is relatively short, around 0.40-1.20s. In the Hellenistic theatre, due to its stone surfaces, RT30 becomes longer compared with Classic theatres. The RT30 varies considerably, from 0.60 to 1.50s at different seats. A possible reason, based on more detailed analysis on the reflection patterns in the Hellenistic theatre of Epidaurus, is that the koilon below the diazoma receives significant early reflections from the risers of the seating area, as well as some late reflections, whereas the upper part of the koilon receives only the reflections from the orchestra and the short stage wall [Chourmouziadou and Kang, 2002]. In the Roman theatre the reverberation is much longer than that in the Greek theatres, and the variation along the source-receiver distance is generally not as significant. The longest reverberation occurs near the diazoma, about 1.90s, whereas in the lower part the RT30 fluctuates between 1.30 and 1.90s. The long reverberation is mainly caused by the reflections between the stage wall, the unoccupied audience area and the peripheral corridor. Compared with the Hellenistic theatre, the back wall of the stage in the Roman theatre has increased height, equal to the height of the auditorium [Chourmouziadou, 2002]. This creates a more enclosed space, enabling multiple reflections between opposite surfaces, while with boundary diffusion a relatively even reverberant field is created.

The energy responses at the typical receivers in the Hellenistic and Roman theatres are shown in Figure 7.4.4, where the dark lines relate to reflections from boundary diffraction/diffusion. It can be seen that the Hellenistic theatre, although with extended koilon and raised stage, has distinct gaps between reflections, whereas the Roman theatre, due to the enclosed layout, has an echogram with features of indoor spaces. Similarly, the relatively long reverberation in the early forms of Greek theatres, as shown in Figure 7.4.3, is associated with distinct gaps between reflections. As a result, such reverberation times may not be perceived as equivalent to the same values in indoor spaces.

It is also noted that the reverberation of the unoccupied condition in Figures 7.4.3 and 7.4.4 is generally longer than the measured values, presented in Section 8.4 for representative examples of the Hellenistic theatre type. This is mainly because the simulations are based on the theatre forms with the original stage buildings, whereas on-site measurements can only be carried out with current theatre situations, where the stage buildings have been demolished or temporary sceneries are placed for performances [Chourmouziadou and Kang, 2006a; Gade *et al*, 2004].

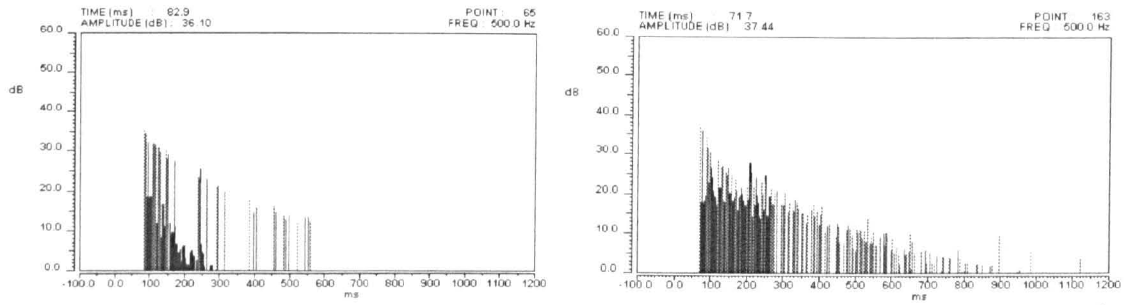


Figure 7.4.4. *Energy responses at 500Hz at the typical receivers in the unoccupied condition. a) Hellenistic theatre and b) Roman theatre. The dark lines associate with diffuse and high order reflections.*

The RT30 under occupied conditions is shown in Figure 7.4.5. As expected, reverberation becomes shorter with the presence of the audience. It needs to be noted that no audience diffusion has been applied to the simulations. The Minoan, the Pre-Aeschylean and the two forms of Classic theatre have RT30 of around 0.30-0.60s. A measurement of the theatre of Knossos, which applies to the Minoan type, is presented in Section 8.4.2, corresponding to the results of this section. The Hellenistic theatre has relatively shorter RT30 at some receivers at the upper part of the auditorium, around 0.40s, whereas in the relatively near field the RT30 is 0.60-1.30s. The Roman theatre, conversely, has longer RT30 at the upper part, up to around 1.50s. As a general tendency, the evolution from the Classic to the Hellenistic, and then to the Roman theatre is associated with an increase in reverberation.

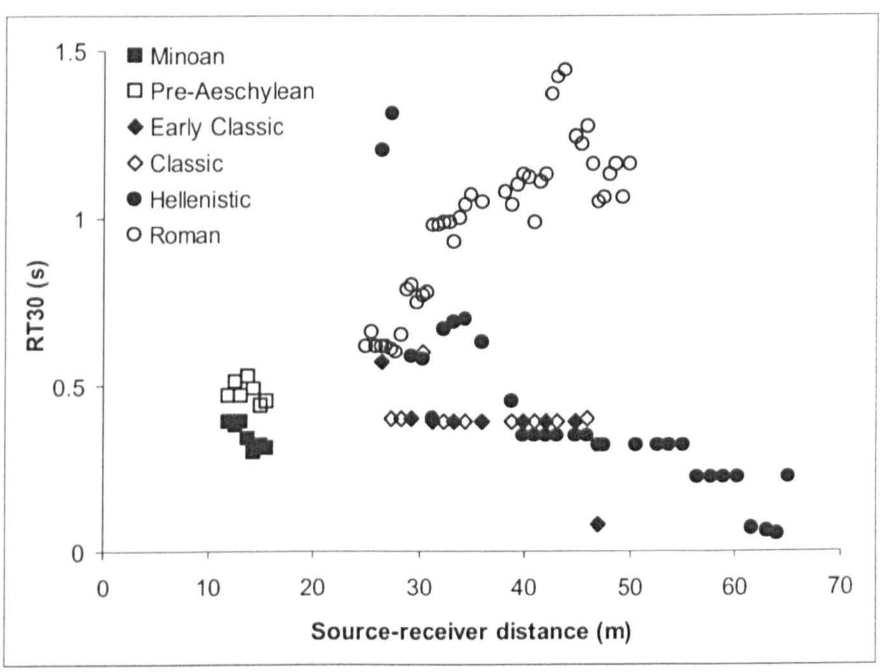
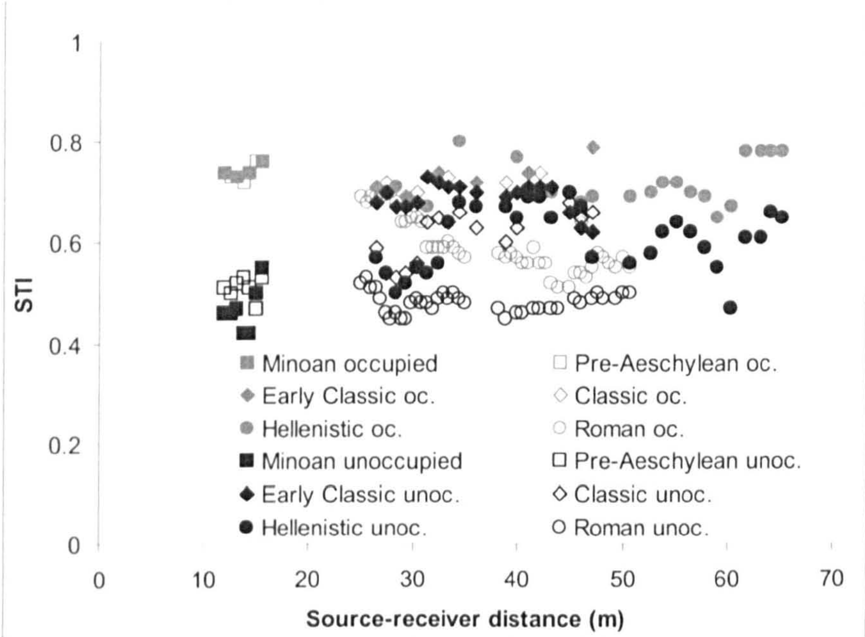


Figure 7.4.5. *RT30 at 500Hz along the typical receiver lines in the occupied theatres.*

7.4.3 SPEECH INTELLIGIBILITY

The STI in the six ancient theatre types are compared in Figure 7.4.6a, along the typical receiver lines at 500Hz. Both occupied and unoccupied conditions are considered, and the effect of background noise is not taken into account, as mentioned previously. Under the unoccupied condition, the STI is around 0.42-0.55 in the Minoan, 0.47-0.53 in the Pre-Aeschylean, 0.62-0.73 in the early Classic, 0.53-0.71 in the Classic, 0.47-0.70 in the Hellenistic, and 0.45-0.53 in the Roman theatre.



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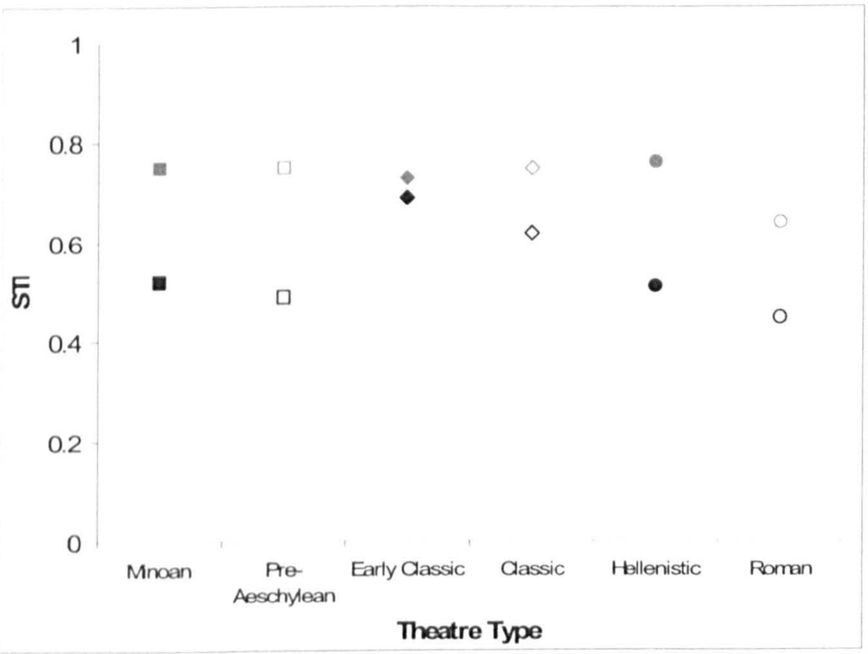


b

Figure 7.4.6. *STI in the six configurations. a) Along the typical receiver lines at 500Hz and b) At the typical receivers from 125 to 4k Hz (Black symbols, unoccupied conditions; grey symbols, occupied conditions).*

Under the occupied condition, the STI becomes systematically higher, which corresponds to the decrease in reverberation. As Cremer [1975] pointed out, the occupied theatres lacked delayed reflections, which helped intelligibility. In the Minoan and Pre-Aeschylean theatres the STI is 0.72-0.76, in the two forms of Classic theatre 0.64-0.79, in the Hellenistic theatre 0.65-0.80 and in the Roman theatre 0.51-0.70. The results concerning the Hellenistic theatre, especially under the occupied condition, are at the same range as the study carried out in Epidaurus by Shankland [1973] for speech intelligibility. The STI for the frequency range at the typical receivers is shown in Figure 7.4.6b. According to Steeneken and Houtgast [1985], the STI values correspond to 'good' speech intelligibility in terms of subjective evaluation. If the level of ambient noise is high, from the audience for example, the above STI values will be decreased.

7.5 Further Investigation on Theatre Types used Today

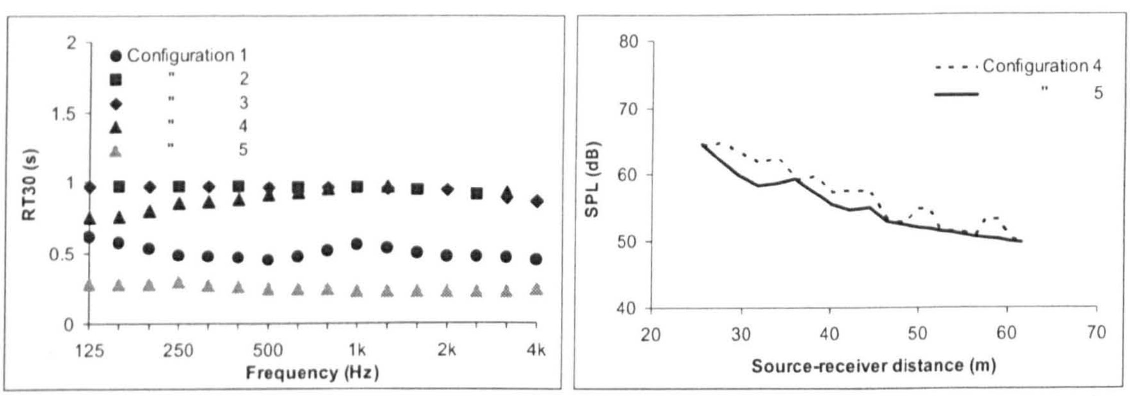
This section describes a systematic investigation on the acoustic environment of the Classic and Hellenistic theatre types [Chourmouziadou, 2002; Chourmouziadou and Kang, 2002]. Several examples of these theatre types were excavated in the last two centuries in Greece and are currently extensively used for ancient drama performances during the summer period. The investigation particularly involves simulations of the theatre types as these evolved from their initial form, namely the early Classic theatre type, to the final form, namely the Hellenistic type, in terms of material changes, stage height, surface diffusion, according to the literature review presented in Section 3.3.2. For example, the theatre of Dionysus in Athens underwent major transformations. Wooden benches were the first addition to the original form of the early Classic theatre type, with earth koilon, while a wooden shed called skene appeared later. Then, stone replaced the wood of the koilon, and the stage building was added. In the Hellenistic times the koilon was extended and the stage was raised. The result of the raised stage, sometimes by 2-2.5m, like in the case of Epidaurus and Priene, was an increased angle of incidence for the direct sound relative to the seating plane. However, the reflection off the orchestra, according to Canac's measurements, reduced its angle to the audience plane [Canac, 1967] with a minimum of 5°. This could have caused an increased attenuation by the seating audience.

The simulation of this section is carried out for five configurations, representing different layout and material characteristics, as shown in Table 7.3. The koilon is considered in its later version with detailed simulation with both vertical and horizontal reflective surfaces. Raised stage is considered, with two heights above the orchestra, 1.5m and 3m. Two cases are examined for the surfaces, geometrically and diffusely reflective, with the flat panel diffusion coefficients, as indicated in Chapter 6. In Configuration 5 each person in the audience is simulated with an absorbent box, to investigate the effect of their reflections. Conventional data for audience absorption are used, which is clearly an approximation [Egan, 1988; Davies *et al*, 1994; Bradley, 1991] partly because there is no chair and the seating inclination is very high. More investigation on audience absorption is presented in Section 7.7.4. Still, the simulated reflection pattern should be meaningful. The source is an actor, with a height of 1.8m above the stage, corresponding to a male actor wearing *cothornous*, the shoes with thick soles). The calculation parameters used are the same as in Section 7.3. The absorption and diffusion coefficients are as shown in Table 7.2.

Table 7.3. *Configurations for the evolution from the Classic to the Hellenistic type.*

	Configurations				
	1	2	3	4	5
Orchestra	Earth	Stone	Stone	Stone	Stone
Koilon	Earth	Stone	Stone	Stone	Stone
Stage	Wood	Wood	Wood	Wood	Wood
Stage height (m)	1.5	1.5	1.5	3	3
Audience Absorption	No	No	No	No	Yes
Surface Diffusion	No	No	Yes	Yes	Yes

In general, the SPL has increased with stone surfaces, while the effect of surface diffusion is negligible. Figure 7.5.1a illustrates the RT30 for Configurations 1, 2 and 3. RT30 is increased almost by 0.5s with stone surfaces, which is significant, even for outdoor performance spaces. With audience reverberation is generally longer for the upper parts of the koilon, which is very useful for outdoor performance spaces, although the concept of indoor and outdoor reverberation might be different. However, for the lower part of the koilon, the RT has decreased, due to the audience absorption. With audience as diffusers the unevenness in the SPL curve, as shown in Figure 7.5.1b, is smoothed, corresponding to Shankland [1973] who indicated that the upper part of the diazoma can receive little reflected sound from the lower seating area but this can be partly overcome by the steeper angle.



a b

Figure 7.5.1. *Comparing RT30 (s) and SPL (dB) for Configurations 1-5. a) RT30 for the range of frequencies and b) SPL at 500Hz.*

Another interesting finding from the simulation is that for the lower part of the marble koilon, the first reflection comes from the vertical surfaces behind the audience [Chourmouziadou, 2002], namely the risers of the koilon, before the reflections from the orchestra and the stage house. Figure 7.5.2 shows the paths of such reflections. For the first row, for example, the direct sound reaches a listener at 90ms with amplitude of 51dB, whereas a reflection from the vertical surface behind him arrives at 94ms, although with a reduced amplitude (44dB) due to the audience absorption. Raised stages, which were developed during the Hellenistic renovations, would have been advantageous, due to relative source-reflection surface-receiver positions, which would consequently increase the number of rows that are benefited by such specular reflections. Nevertheless, this applies to specular reflections only; sound is also diffused towards all directions. At the upper part of the koilon sound would be reflected to the sky, because of the large reflection angle. In addition to that, a raised stage is useful for avoiding grazing incidence [Canac, 1967]. It has been indicated that by changing the vertical angle of incidence of sound, the seat dip effect can be tuned to a lower frequency [Bradley, 1991]. Other studies that compared the stage and the roof of the stage building, as conventional positions of the protagonists and the gods respectively, have suggested that the overall sound in the second occasion was less intense, since there was no boundary in the background, similar to the stage wall, to reflect sound [Mparkas, 2006].

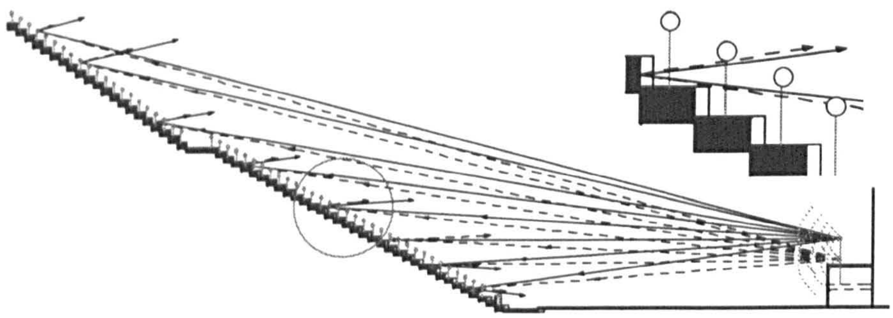


Figure 7.5.2. *Section of the theatre of Epidaurus showing the 1st reflection from the vertical surfaces behind the audience. The solid lines represent the ray paths with a stage height of 3m and the dashed lines represent the ray paths with a stage height of 1.5m.*

Moreover, in Greek theatres the mass-produced seating system involved a relief cut into the riser face to allow retraction of the feet by the seated people, for comfort, and other people to approach their seats. Additionally, because the seats could be decreased in width, it enabled the greatest number of people to seat as close to the orchestra as possible. In the theatre of Dionysus the riser was cut into a concave shape, as shown in Figure 7.5.3. The concave shape of the riser could have contributed and directed sound to the audience. Further work should consider investigating these reflection paths.

Overall, the above results suggest that the developments in the Classic and Hellenistic theatres show a clear improvement in acoustics, both in terms of sound level and reverberation. The steeper seating area, the harder materials and the higher stage in the evolution process had all been useful for improving acoustics.

a

b

Figure 7.5.3. *Detail of the seating system of the theatre of Dionysus. a) Archons' seats and b) Typical seats.*

7.6 COMPARISON BETWEEN THE GREEK THEATRE OF EPIDAURUS AND THE ROMAN THEATRE OF ASPENDUS

As mentioned before, the Hellenistic was the last type of the Greek theatre development, before the influence of the Greco-Roman period, which brought many renovations to existing theatres. This section compares the acoustic attributes of the Hellenistic theatre of Epidaurus with the Roman theatre of Aspendus. The differences between these types, from an architectural and functional point of view, have been distinctive. Based on the development of theatres in antiquity, it appears that Roman theatres had better acoustics. This is supported by some discussions about the acoustics of these theatres [Vitruvius, 1st century A.D.; George, 1997; Izenour, 1977].

Comparison between the acoustics of the theatre of Epidaurus and some Roman theatres has been carried out both theoretically [George, 1997], and based on computer simulation [Chourmouziadou, 2002]. Also, the two theatres have been extensively examined separately [Chourmouziadou and Kang, 2006a; Vassilantonopoulos *et al*, 2004; Gade *et al*, 2004; Lisa *et al*, 2004], but no comparison has been carried out between them. They are both representative examples of two eras in theatre construction. In this study the compared indices include SPL distribution along a receiver line, reverberation time, speech intelligibility and the impulse responses of typical receivers.

7.6.1 HISTORICAL INFORMATION AND SIMULATION PARAMETERS

The models of the theatres were created in Archicad. The Greek theatre had the hillside construction of the koilon separately from the stage building, whereas in the Roman the vaultsupported auditorium was tightened up with the coupled towering stage house [Izenour, 1977]. Moreover, the vertical sightline in Epidaurus was less steep than in Aspendus. The similarities or differences of the two theatres, in terms of size, height and layout, are shown in Figure 7.6.1.

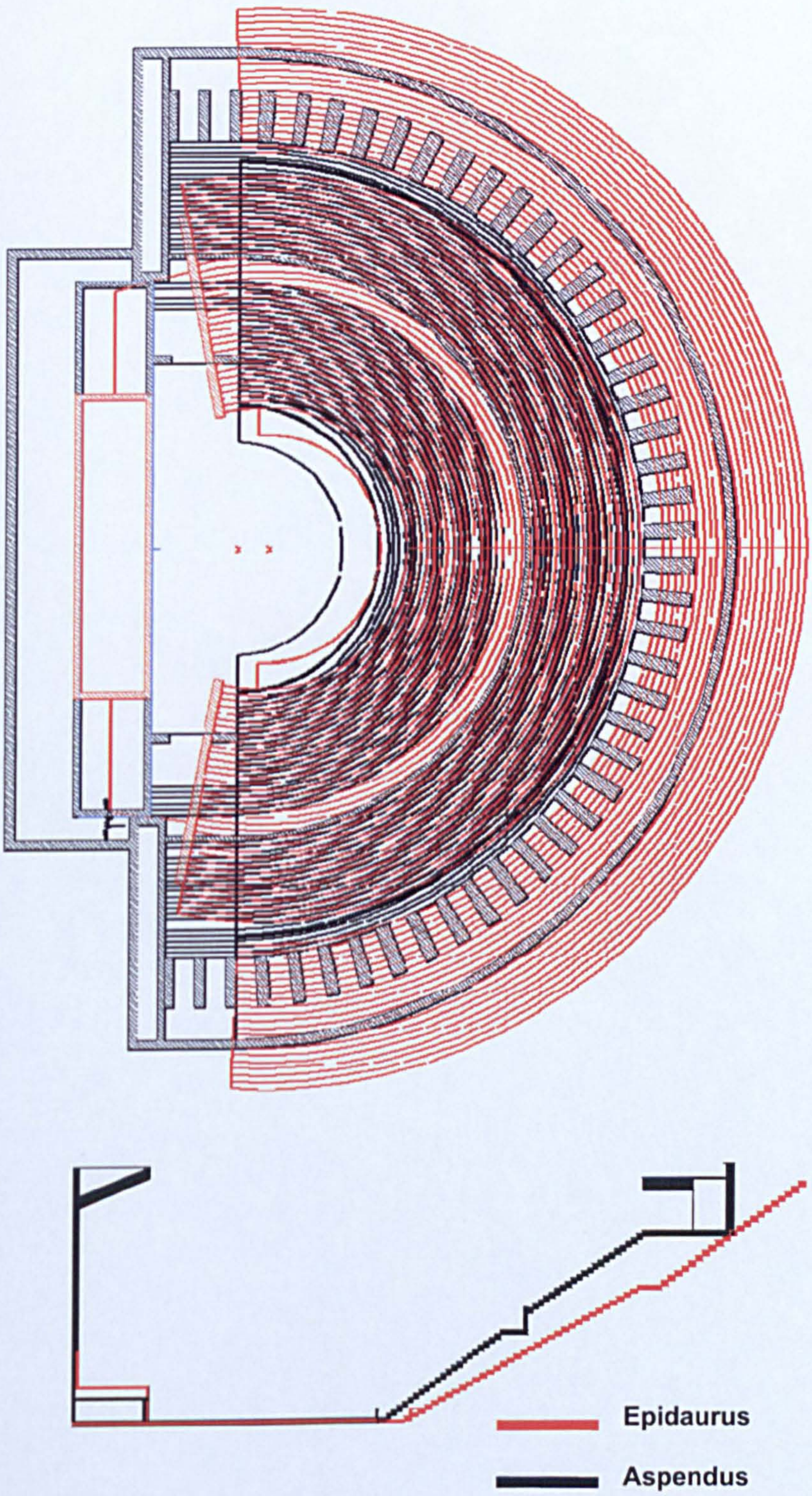


Figure 7.6.1. *Plans and longitudinal sections of the theatres of Epidaurus and Aspendus.*

The seating areas and most of the stage building in both theatres were constructed with stone, while the stage floors were made of wood. The total diameter of the theatre of Aspendus used in the calculations is 90m, which is an approximation. Compared to the Greek theatre, a major difference in Aspendus was the peripheral corridor on the top of the cavea. This had arches leading to the seating area, acting as a reflector. Moreover, in some cases the Roman theatres were covered by the velarium, described in Section 3.3.6. Furthermore, the height of the stage in Aspendus was around 2m, whereas in Epidaurus it was around 3m. The stone surfaces had adornments in some places (stage building), thus these surfaces are considered as diffusely reflective in the simulation. The absorption coefficients and simulation parameters used are the same as in Sections 7.3 and 7.5. For the velarium the absorption coefficients are 0.05 at 125Hz, 0.03 at 250Hz, 0.35 at 500Hz, 0.40 at 1kHz and 0.50 at 2-4kHz. Flat panel diffusion is applied to the surfaces, as indicated in the methodology in Chapter 6.

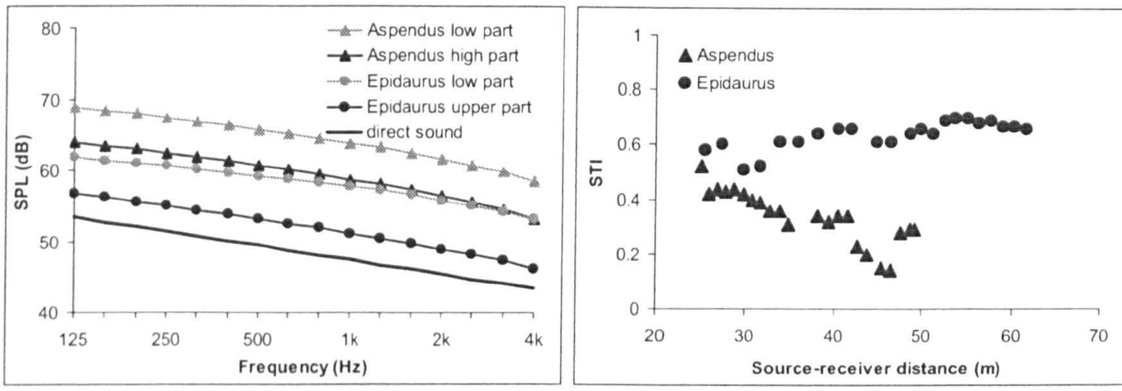
Five configurations have been considered for the simulation, as shown in Table 7.4. They include occupied and unoccupied conditions, and the presence of the velarium. The receiver lines used for the calculations were off the theatre axis by about 3°, similar to those illustrated in Figure 7.2.2 b and c.

Table 7.4. *Configurations used in the simulation of the theatres of Epidaurus and Aspendus.*

	Configurations				
	1	2	3	4	5
Theatre	Epidaurus	Epidaurus	Aspendus	Aspendus	Aspendus
Stage height (m)	3	3	2	2	2
Surface Diffusion	Yes	No	No	Yes	Yes
Audience Absorption	No	Yes	No	Yes	No
Velarium	No	No	No	No	Yes

7.6.2 Comparison of Results and Discussion

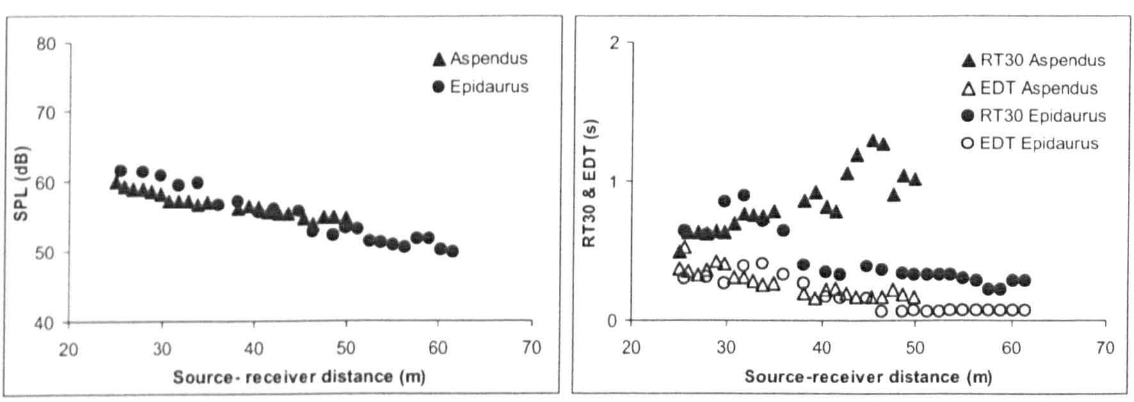
For the unoccupied conditions of the theatres of Epidaurus and Aspendus, namely Configurations 1 and 3, Figure 7.6.2a illustrates the sound distribution at two points on the receiver lines, at the lower and upper part of the diazoma. The SPL is considerably increased for both receivers in the theatre of Aspendus, by 5-7dB. In terms of amplitude the SPL of Aspendus is higher. However, because of different source-receiver distances, further comparison shows that the theatre of Aspendus has higher values of SPL, by about 2dB, which result from the uniformity of its shape. Overall, the SPL are above 50dB in both theatres. The boundaries have considerably increased the sound level, when compared to a semi-free field, calculated based on the following equation: $SPL=L_w-20logr-11$ [Beranek, 1971]. Figure 7.6.2b presents the simulation results for the STI. Corresponding to the long RT, discussed later, the STI for the theatre of Aspendus has lower values than that for Epidaurus, for the two receiver points, with most noticeable differences at large distances from the source. Previous research on the theatre of Epidaurus has revealed values at the same ranges [Shankland, 1973; Vassilantonopoulos at al, 2004; Chourmouziadou and Kang, 2006a], but no intelligibility values have been found in the literature concerning the theatre of Aspendus for comparison.



a b

Figure 7.6.2. *Comparison between the theatres of Epidaurus and Aspendus. a) SPL (dB) at two typical receivers and b) STI at 500Hz for the receiver lines.*

The reverberation for the two theatre types has already been presented in Figure 7.4.5. For Aspendus in particular the RT30 is longer, especially at the receiver high at the auditorium, at 1.7-2.0s, caused by the reflections from the peripheral corridor. However, in Epidaurus, RT30 is around 0.5-1s, depending on the seat. In general, the layout of the theatre of Epidaurus encouraged reflections that are beneficial for the lower part, whereas in the theatre of Aspendus reflections were helpful at the upper parts. Figure 7.6.3 illustrates the RT30 for the two occupied theatres, namely Configurations 2 and 4. The occupied conditions have considerably shorter RT30 and EDT, as expected. The maximum value of the decrease appears in the theatre of Aspendus, at around 1-1.20dB. Hence, the audience can reduce RT substantially, and consequently influence the acoustic environment of the space.



a b

Figure 7.6.3. *SPL (dB), RT30 (s) and EDT (s) in the occupied theatres of Epidaurus and Aspendus. a) SPL at 500Hz and b) RT30 and EDT at 500Hz.*

For good speech intelligibility high early energy and low late energy are necessary [El-Zeky and Odham, 1998]. According to Houtgast and Steeneken [1985], the STI values of Aspendus, shown in Figure 7.6.4a correspond to 'fair' to 'good' intelligibility. On the other hand, Epidaurus has increased STI at the upper part of the diazoma, probably because there are no delayed reflections there, with good intelligibility. Definition at the low part of the seating area is illustrated in Figure 7.6.4b. It is between 60-97% for Aspendus and between 80-95% for Epidaurus. This reveals that, unlike Aspendus, the theatre of Epidaurus has a steady value in D50, without many fluctuations.

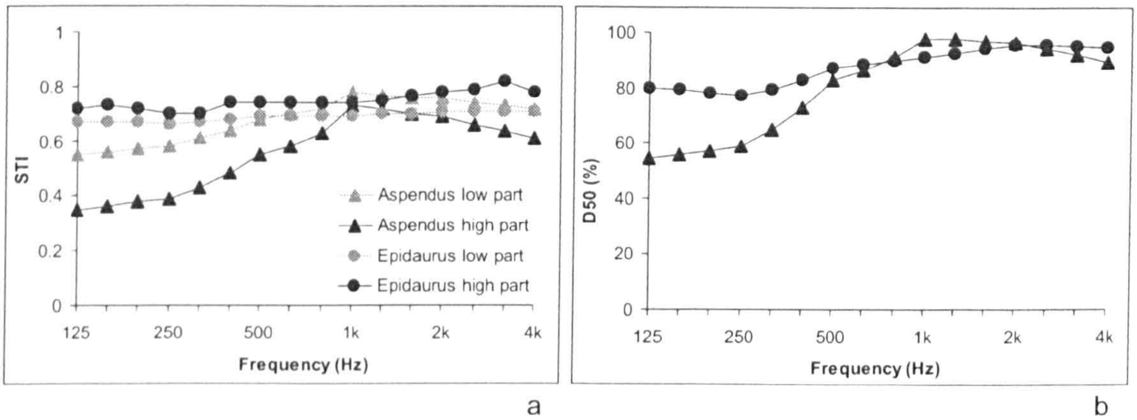


Figure 7.6.4. *STI and D50 (%) for the occupied theatres. a) STI at two typical receivers and b) D50 (%) at a typical receiver.*

From the impulse responses it is suggested that for the unoccupied conditions the layout of the theatre of Aspendus has generally provided many reflections, due to the better-accomplished enclosure of the space. Conversely to that, the reflections in the theatre of Epidaurus, like in any theatre of the Classic or the Hellenistic type, are less in number and, for this reason, they are very important for the distribution of sound. Moreover, there are delays in the reflection patterns, caused by the circular shape and the distribution patterns it creates, and have an impact on the performance in terms of clarity. Figure 7.6.5 presents the reflection paths for the typical receiver points.

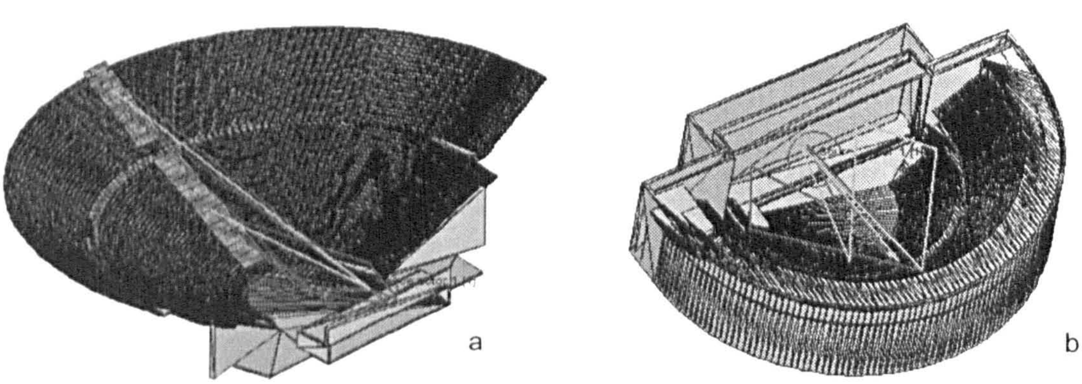


Figure 7.6.5. *Reflection patterns. a) Epidaurus and b) Aspendus.*

For the influence of the velarium on the indices of the theatre of Aspendus it is noted that SPL increased by 6-7dB for both receivers and RT30 became more uniform. Therefore, the velarium reduces RT fluctuations throughout the theatre.

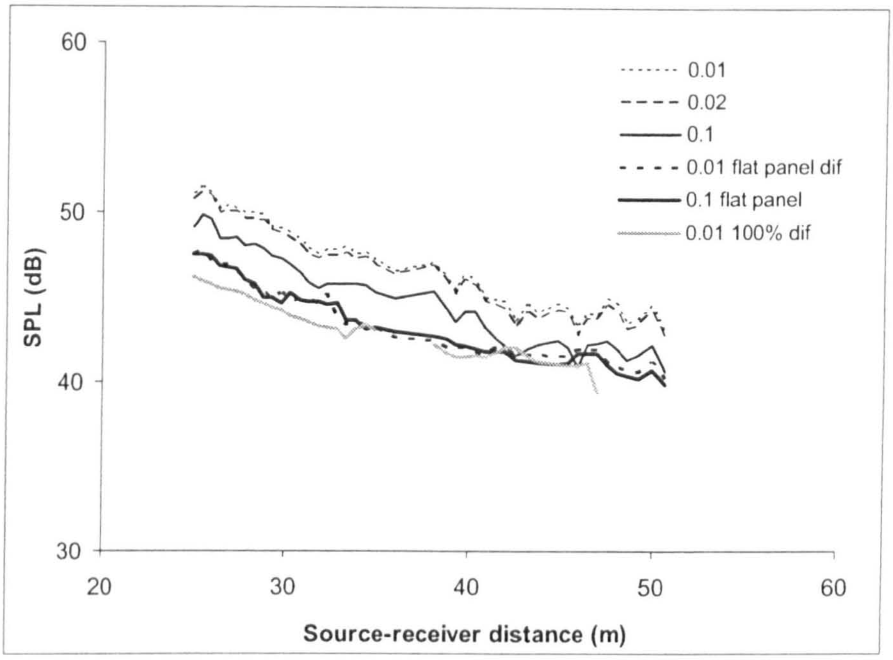
7.7 Examination of the Effect of Material Properties on the Acoustic Evolution

Ancient theatres were usually built from local materials and it is difficult to obtain exact acoustic properties for all of them [Chourmouziadou and Kang, 2003]. This section investigates the effect of absorption and diffusion coefficients on the sound field of ancient theatres. For each major surface material, comparisons are made with a range of absorption coefficients α found from the literature, including the possible minimum and maximum, while the other conditions are the same as in Section 7.4. Various diffusion/diffraction coefficients are also compared, including purely geometrically reflective, flat panel diffusion [Everest, 1994; LMS Numerical Technologies, 2001] and high diffusion coefficients, up to 1, namely diffusely reflecting boundaries.

7.7.1 Stone

Stone was the main material in the Minoan, the Hellenistic and the Roman theatres (as seen in Table 7.1). Marble was probably the most common, but acoustically softer materials like limestone, porous stone or brick were also used. Hence three α values are considered, 0.01, 0.02 and 0.1, across 125 to 4k Hz [Egan, 1988; LMS Numerical Technologies, 2001; Lord and Templeton, 1996].

For the Roman theatre, the SPL distribution along the receiver line between α=0.01, 0.02 and 0.1 is compared in Figure 7.7.1a. The SPL variation with different α is generally insignificant. For calculations that consider only geometrical reflections, SPL is reduced by 0.2dB when α is changed from 0.01 to 0.02, and by 1-2dB when α is changed from 0.02 to 0.1. With the flat panel diffusion the difference between different absorption coefficients becomes much less, around 0.5dB between α=0.01 and 0.1. In the mean time, the SPL is systematically lower than that with geometrically reflecting boundaries, by about 2-3dB. If the boundaries are totally diffusely reflecting, the SPL further decreases, but the difference between diffuse boundaries and flat panel diffusion is much smaller than that between geometrical boundaries and flat panel diffusion. Similar phenomenon exists in urban streets and squares, where if the boundary diffusion coefficient is increased from 0 to about 0.2, the SPL decreases significantly, whereas when the diffusion coefficient is further increased, the decrease in SPL is rather small [Kang, 2007]. From Table 7.5 it can be seen that the SPL is reduced by 0.2dB when α is changed from 0.01 to 0.02, and by less than 1.5dB when α is changed from 0.02 to 0.1.



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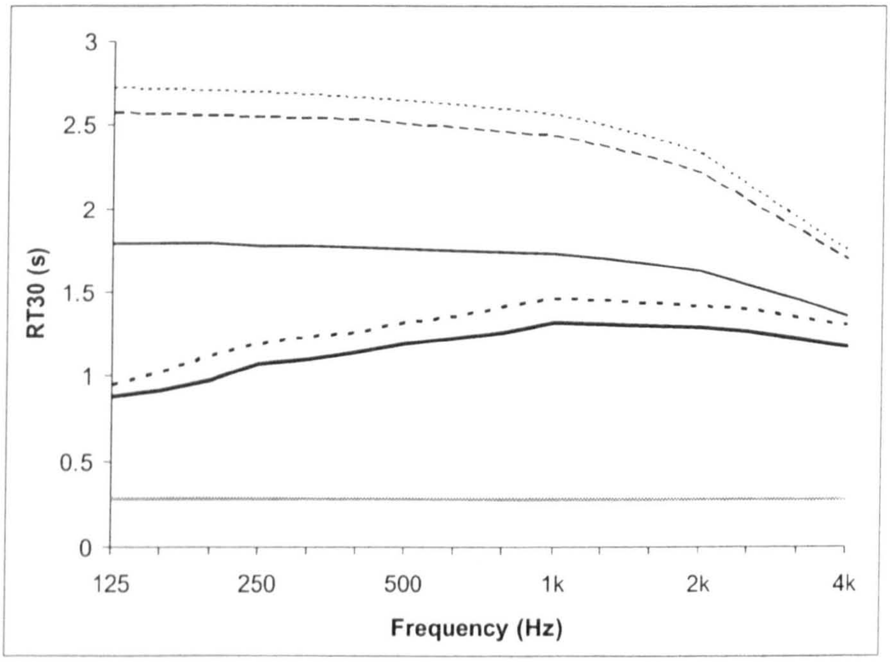


b

Figure 7.7.1. *Comparison between various absorption and diffusion coefficients for stone. a) SPL (dB) along the typical receiver line at 500Hz in the Roman theatre and b) RT30 (s) at the typical receiver in the Minoan theatre.*

For reverberation, the effect of α is generally greater than that for the SPL, since the latter is mainly determined by the direct sound and early reflections, whereas the RT depends on multiple reflections. Figure 7.7.1b compares the RT30 with various absorption and diffusion conditions at the typical receiver in the Minoan theatre. In the case of geometrically reflecting boundaries, it can be seen that changing from α=0.01 to 0.02 the RT30 decreases by about 3-5%, and from α=0.02 to 0.1 the RT30 reduces by about 20-30%. When the flat panel diffusion is applied, the RT30 is systematically lower, by 25-65% with α=0.01, and 13-50% with α=0.1. The difference increases with decreasing frequency, mainly due to the increase in diffusion coefficient. The difference between α=0.01 and 0.1 also becomes much smaller, only around 10%. Unlike SPL, with further increase in boundary diffusion, the decrease in RT30 is significant.

Table 7.5. *Effects of surface absorption coefficients on the acoustic indices at 500Hz with no diffusion applied. The calculation is based on the typical receiver positions in the unoccupied condition.*

Type	Absorption coefficients								Acoustic indices		
	Stone			Wood			Earth				
	0.01	0.02	0.10	0.04	0.20	0.40	0.20	0.40	SPL	RT30	STI
Minoan	•								48.7	2.64	0.38
		•							48.5	2.5	0.39
			•						47.3	1.76	0.46
Pre-Aeschylean				•					46.4	2.7	0.38
					•				44.6	1.5	0.5
						•			43.3	0.97	0.6
Early Classic				•					43.8	0.55	0.72
					•				43.5	0.52	0.73
						•			43	0.47	0.75
							•		47.9	0.82	0.63
								•	45.4	0.73	0.66
Classic				•					52.2	1.11	0.56
					•				47.7	0.78	0.64
						•			44.7	0.61	0.69
Hellenistic	•								48.9	1.22	0.54
		•							48.7	1.19	0.55
			•						47.2	1.02	0.58
Roman	•								49.1	2.63	0.38
		•							48.9	2.50	0.39
			•						47.4	1.87	0.45

Further calculations show that the Hellenistic theatre has relatively less fluctuations in reverberation with changing α compared to the Roman theatre, because of its less enclosed feature, as indicated in Section 7.4. The RT30 in the Roman theatre fluctuates between 1.80 and 2.60s with geometrical boundaries and between 1.30 and 1.90s when flat panel diffusion is considered, which approximately corresponds to the recently published measurements of 1.70-1.80s in the Roman theatre of Aspendus [Gade *et al*, 2004]. It is noted that RT30 values under contemporary conditions should be shorter than those in the simulation, due to the large diffusion of the partly destroyed koilon.

The STI increases with increasing α, since no background noise is considered and therefore the STI corresponds to reverberation only. With geometrically reflecting boundaries, from α=0.01 to 0.02 the STI increase is less than 0.1, and from α=0.02 to 0.1 the STI increase is 0.03-0.07, as also shown in Table 7.5.

7.7.2 Wood

Three absorption values are considered for wood, from 0.04, corresponding to wooden parquet laid on concrete (from 125 to 4k Hz: 0.04, 0.04, 0.07, 0.06, 0.06, 0.07), to 0.4, a wooden panelling with airspace behind (from 125 to 4k Hz: 0.42, 0.21, 0.1, 0.08, 0.06, 0.06) [Egan, 1988]. Three theatre types with sizeable wooden areas are considered: the Pre-Aeschylean, the early Classic, and the Classic. The Classic theatres are simulated without the extended koilon (see Figure 7.2.2).

In Figure 7.7.2a the SPL at 500Hz along the typical receiver line in the Classic theatre is shown, with α=0.04, 0.2 and 0.4, for geometrically reflecting boundaries and flat panel diffusion, respectively. It can be seen that, having most of its structure wooden, in the Classic theatre the SPL difference between α=0.04 and 0.4 is about 7dB, whereas with diffusion applied the difference reduces to about 2-3dB. It is noted that, with various α, the sound attenuation curves with source-receiver distance have a similar slope. In the Pre-Aeschylean theatre and the early Classic theatre the area of wooden surfaces is smaller and thus, the difference between α=0.04 and 0.4 is also less, at 3dB and 1dB respectively in the case of geometrically reflecting boundaries.

Corresponding to Figure 7.7.2a, the effects of absorption and diffusion on the RT30 are shown in Figure 7.7.2b. It can be seen that with geometrically reflecting boundaries the decrease in RT30 is 30% and 27% from α=0.04 to 0.2 and from α=0.2 to 0.4 respectively, as seen in Table 7.5, whereas with the diffusion applied the RT30 decreases are systematically less, at 15% and 21% respectively. Generally, in the Pre-Aeschylean theatre and the early Classic theatre the effect of the absorption and diffusion of wooden surfaces is generally less compared to that in the Classic theatre.

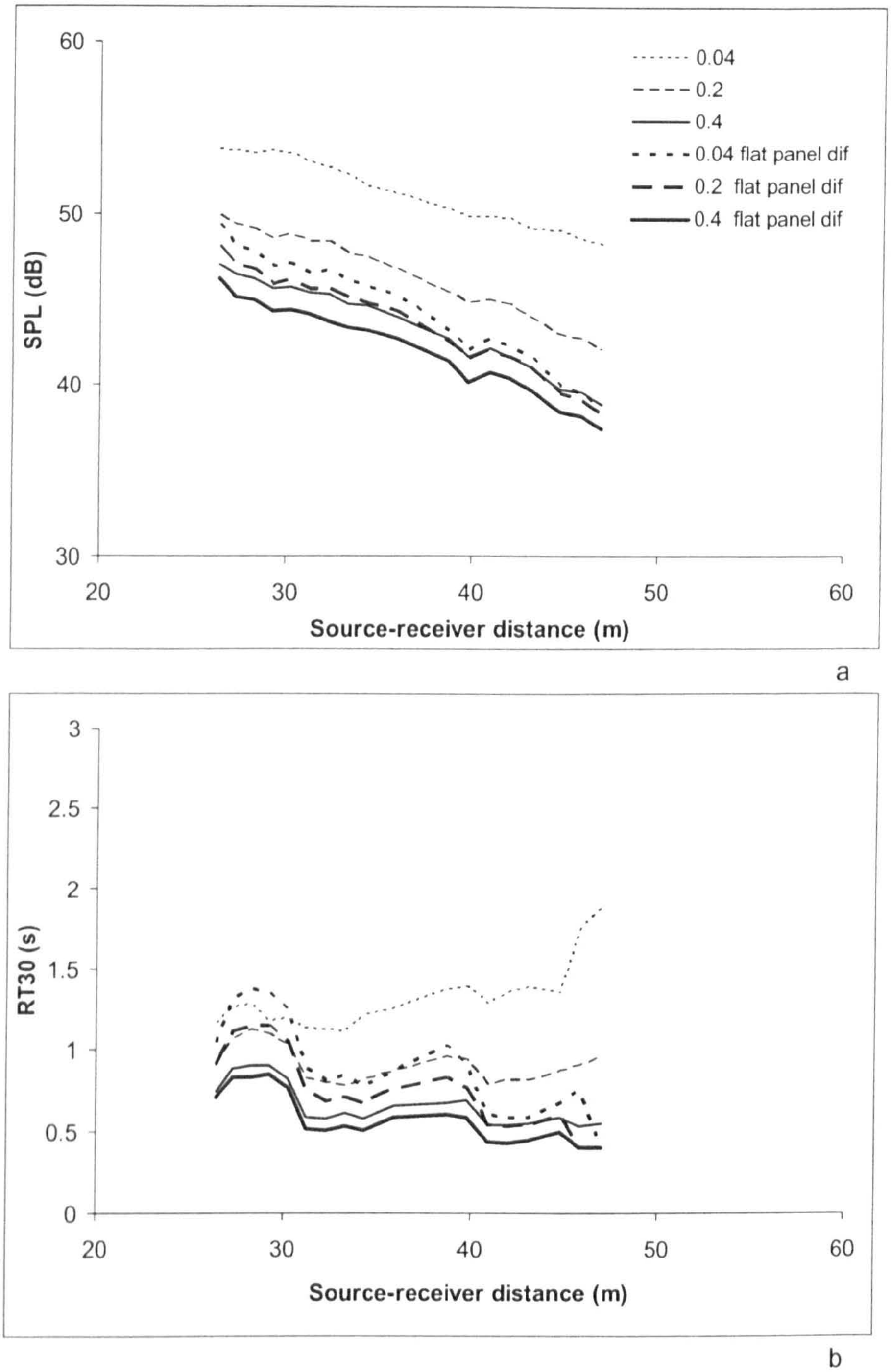


Figure 7.7.2. *Comparison between various absorption coefficients of wood at 500Hz, along the typical receiver line in the Classic theatre. a) SPL (dB) and b) RT30 (s).*

7.7.3 EARTH

The early Classic theatre is simulated in this section, since it has a large area of earth surface. Two values of the earth absorption coefficient [Egan, 1988], 0.2 and 0.4, are considered, each with two diffusion conditions, namely geometrically reflective and with the flat panel diffusion. The SPL and RT30 results at 500Hz along the typical receiver line are shown in Figure 7.7.3. It can be seen that the earth absorption has a considerable effect on the SPL, about 2.2-2.8dB from α=0.2 to 0.4 when the earth is geometrically reflective, and 0.2-1.3 dB when the diffusion is applied, whereas for the RT30 these values are about 22% and 10% in average respectively.

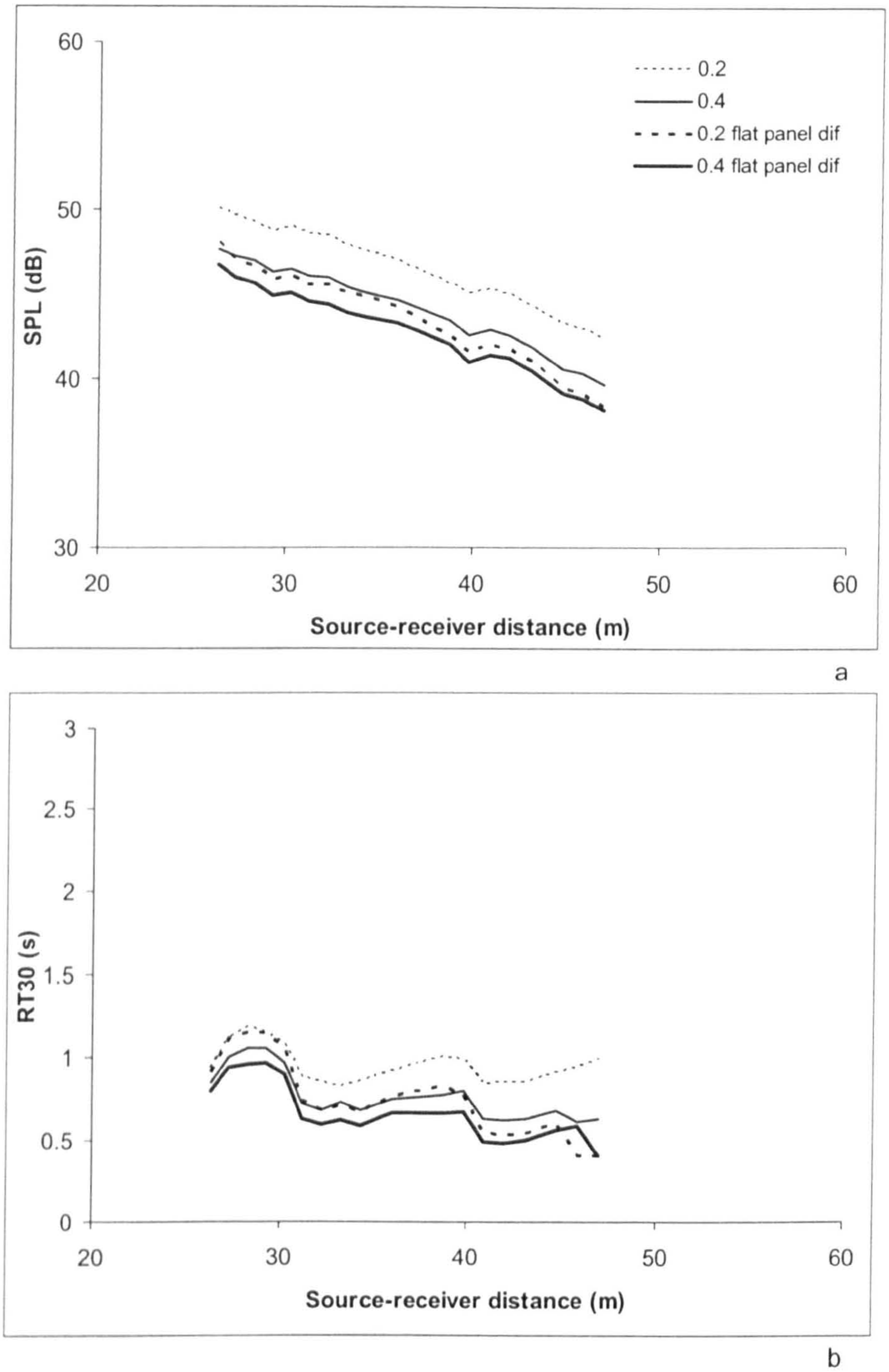


Figure 7.7.3. *Comparison between various absorption and diffusion coefficients of earth at 500 Hz, along the typical receiver line in the early Classic theatre. a) SPL (dB) and b) RT30 (s).*

7.7.4 Audience Absorption and Diffusion

For outdoor performance spaces with marble audience areas the measurement data of the absorption coefficient under occupied condition is very limited. Direct use of the measured data in auditoria may not be appropriate, especially at low frequencies, since the low-frequency absorption is mainly determined by seating configurations rather than people [Beranek and Hidaka, 1998]. Moreover, ancient performances took place both in winter and summer periods and thus, the absorption condition may vary considerably, corresponding to people's clothing. Based on commonly used audience absorption, three data sets from 125 to 4 kHz are used in the simulation [Bradley, 1996; Egan, 1998; LMS Numerical Technologies, 2001; Lord and Templeton, 1996]: 0.17, 0.24, 0.56, 0.69, 0.81, 0.78, approximately representing minimum; 0.6, 0.74, 0.88, 0.98, 0.96, 0.87, approximately representing maximum, as shown in Table 7.6, and 0.51, 0.64, 0.75, 0.80, 0.82, 0.83, representing a typical measured data set [Beranek and Hidaka, 1998]. Comparison is also made between geometrically reflective condition and a diffusion coefficient of 0.5 across the frequency range considered.

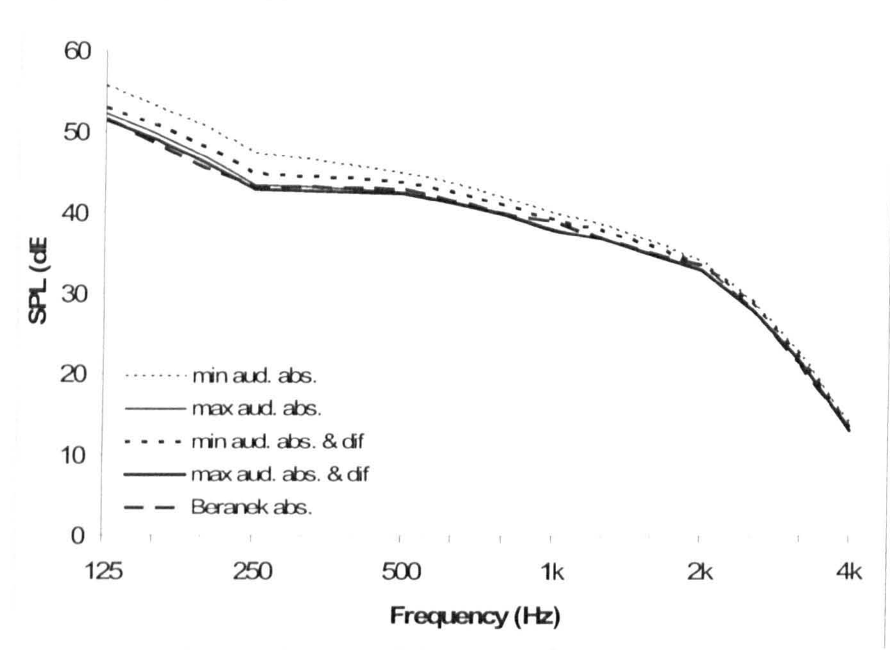
Table 7.6. *Audience absorption coefficients.*

	Frequency (Hz)					
Audience absorption coefficients	125	250	500	1k	2k	4k
Audience, seated in upholstered seats [Egan, 1988]	0.39	0.57	0.80	0.94	0.92	0.87
Congregation, seated in wooden pews [Egan, 1988	0.57	0.61	0.75	0.86	0.91	0.86
Audience on timber seats (1/m^2) [Lord and Templeton, 1996]	0.17	0.24	0.56	0.69	0.81	0.78
Audience on timber seats (2/m^2) [Lord and Templeton, 1996]	0.28	0.40	0.78	0.98	0.96	0.87
Areas with audience, orchestra or seats, including narrow aisles [Lord and Templeton, 1996]	0.60	0.74	0.88	0.96	0.93	0.85
Maximum values	**0.60**	**0.74**	**0.88**	**0.98**	**0.96**	**0.87**
Minimum values	**0.17**	**0.24**	**0.56**	**0.69**	**0.81**	**0.78**

The SPL at the typical receiver in the Roman theatre under various conditions is shown in Figure 7.7.4. It can be seen that when no diffusion is considered, between various absorption data sets the difference is generally insignificant, about 0.6-3.8dB, depending on the variation in absorption coefficient at various frequencies. When diffusion is considered, the SPL variation between different data sets becomes less, around 0.4-2dB. By comparing the SPL between with and without diffusion, it can be seen that the difference is greater if the audience absorption coefficient is smaller, and the maximum SPL difference is 2.6dB. Further calculation shows that when the diffusion coefficient changes from 0.2 to 0.8, the variation in SPL is about 0.2-1.3dB.

The RT30 results along the typical receiver line at 500Hz are illustrated in Figure 7.7.4b. The difference between the two absorption coefficients, namely 0.56 and 0.88, is 31-58% (0.20-1.40s) when no diffusion is considered and 23-45% (0.20-0.40s) when diffusion is applied. Between absorption coefficients 0.56 and 0.75, namely the typical measured value, the difference is 0.10-1.10s, with no diffusion. Again, diffusion brings considerable decrease in RT30, by 18-51% (0.10-1s) with α=0.56 and 10-34% (0.10-0.30s) with α=0.88. When the diffusion coefficient changes from 0.2 to 0.8, the variation in RT30 is 0.10-0.50s. The STI, which is closely related to the RT30, is shown in Figure 7.7.5.

In the other theatre types the effects of audience absorption and diffusion are generally similar to the above. The indices are shown in Table 7.7.



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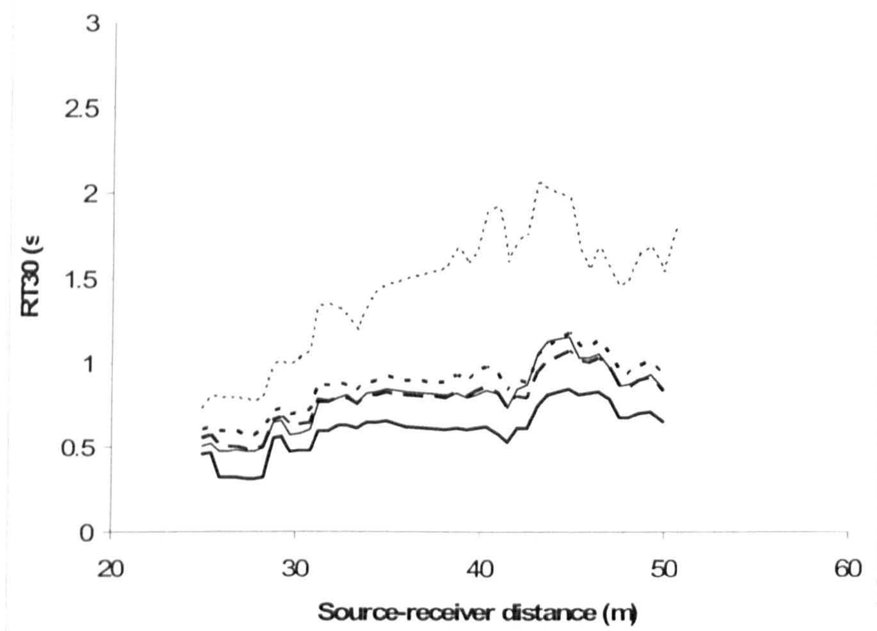


b

Figure 7.7.4. *Effects of audience absorption and diffusion on the sound field in the Roman theatre. a) SPL (dB) at the typical receiver and b) RT30 (s) at 500Hz along the typical receiver line.*

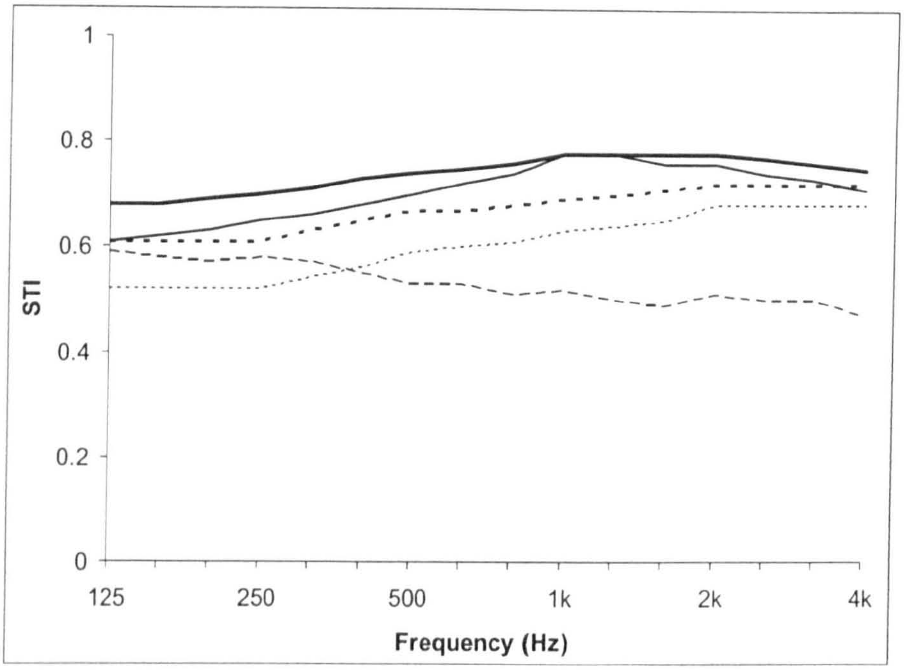


Figure 7.7.5. *Effects of audience absorption and diffusion on the STI at the typical receiver in the Roman theatre.*

7.8 ACOUSTIC EVOLUTION

The birth of drama and its development with the forms of tragedy and comedy in Greece brought significant changes in the design of theatres, including size, shape, and site conditions. Material usage and new construction techniques were also important for the theatre's architectural evolution. Moreover, there is evidence that ancient architects studied propagation of sound and could have used it in designing the theatres. There were both temporary and permanent stages, while the ancient theatres evolved for almost 2,000 years. Based on the acoustic simulation in Sections 7.4-7.7, this section analyses the acoustic evolution of ancient Greek and Roman theatres. Figure 7.8.1 shows the changes in reverberation along with theatre evolution, where the average value as well as the variation at various receivers are shown, for both occupied and unoccupied conditions.

In the Minoan and the Pre-Aeschylean theatres, since there were no enclosures or surrounding walls, sound distribution was mainly determined by the direct sound and reflections from the ground. However, compared with the later theatre types in Greece, the SPLs are relatively high because their size is smaller and the audience is closer to the source. This is further enhanced by the multiple reflections between parallel seat risers, although this effect diminishes considerably when boundary diffraction/diffusion is taken into account. This is also the case for the simulated reverberation of the unoccupied condition, whereas under the occupied condition, the reverberation time is much shorter and insufficient.

Table 7.7. *Effects of audience absorption and diffusion on the acoustic indices at 500Hz.*

Coefficients / Theatre type	Stone	Wood	Earth	Audience absorption		Audience diffusion	Typical Values (Beranek and Hidaka, 1998)	SPL (dB)	RT30 (s)	STI
				Minimum	Maximum					
Minoan	•			•				45.0	0.63	0.69
	•				•			43.6	0.28	0.81
	•			•		•		44.3	0.30	0.77
	•				•	•		43.5	0.16	0.83
Pre-Aeschylean		•	•	•				40.9	0.79	0.64
		•	•		•			40.4	0.17	0.78
		•	•	•		•		40.7	0.34	0.76
		•	•		•	•		40.4	0.16	0.89
Early Classic		•	•	•				43.2	0.53	0.72
		•	•		•			40.8	0.30	0.79
		•	•	•		•		41.8	0.44	0.76
		•	•		•	•		40.6	0.30	0.82
Classic		•	•	•				43.2	0.53	0.72
		•	•		•			40.8	0.30	0.79
		•	•	•		•		41.8	0.44	0.76
		•	•		•	•		40.6	0.30	0.82
Hellenistic	•	•		•				42.8	0.56	0.71
	•	•			•			40.9	0.18	0.78
	•	•		•		•		41.6	0.45	0.76
	•	•			•	•		40.6	0.19	0.79
Roman	•	•		•				44.9	0.99	0.59
	•	•			•			42.6	0.58	0.70
	•	•		•		•		43.8	0.70	0.67
	•	•			•	•		42.4	0.48	0.74
	•	•					•	46	1.27	0.53

The Classic Greek theatres were built on hillsides for performing tragedy during the Dionysian festivals. Their form evolved gradually, with changes in materials. The acoustics in the theatres depended mainly on the direct sound. The fan shape of these theatres implied poor visual and acoustic conditions for the audience seated at the sides of the orchestra, but interestingly, these seats were reserved for latecomers and women, who were not regarded as important guests. A noticeable characteristic of the early Classic theatres was the lack of reflections, and consequently the short reverberation, compared to the other types. Nevertheless, since the seating area was steep, sound attenuation over the audience area was less significant, although there is evidence that the chorus were performing at the orchestra, so the angle of incidence of the direct sound emitted from them could be decreased, as the chorus approached the audience.

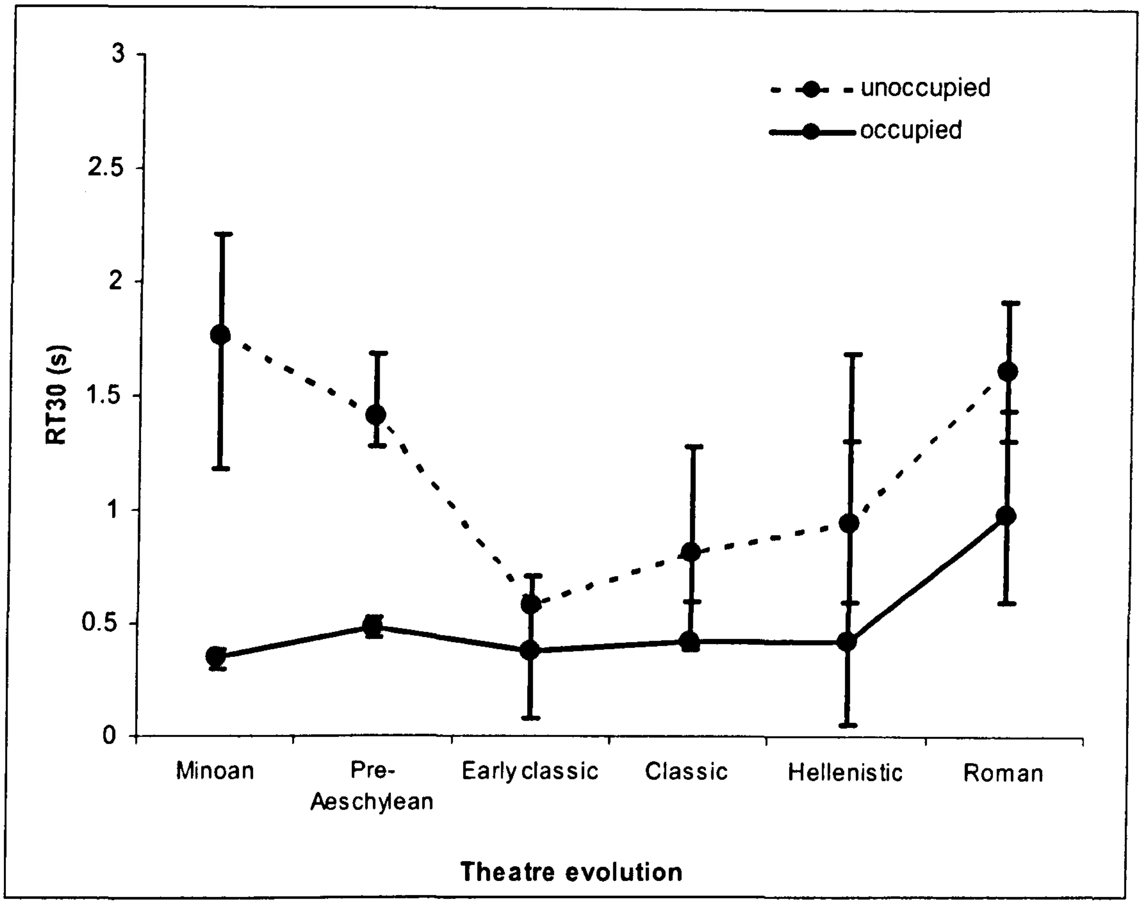


Figure 7.8.1. *Variation of RT30 (s) with the evolution of ancient Greek and Roman theatres. The error bars indicate maximum and minimum RT30 along the typical receiver line.*

Comedy, the new form of drama, brought the Hellenistic renovations, which involved raised stage, extended koilon and, in some cases, changes in the seating system. The increase of the stage height resulted in further increased angles of incidence of the direct sound, although the orchestra's reflections reduced their angles to the audience plane. The vertical surfaces of the koilon provided important first reflections, mostly to the lower part of the audience and the circular shape helped reflections to scatter. The extended part of the diazoma became steeper, so that there was more reflected sound. The use of harder materials, from earth and wood to stone, was useful for providing stronger reflections. Overall, from the early Classic to the Hellenistic theatre, the sound level and reverberation were both increased, and thus the acoustic conditions were improved, as analysed in Section 7.4.

The Roman theatre, in a more enclosed layout than the Hellenistic theatre, presented longer reverberation times for both unoccupied and occupied conditions. For occupied conditions, the acoustic indices in the Roman theatre were rather good, close to those in modern theatres, although there were considerable variations at various receivers. Under unoccupied conditions, however, the reverberation was rather long, around 1.30-1.90s, as can be seen in Figure 7.4.3, and this might lead to poor intelligibility depending on the occupancy of the theatre.

7.9 CONCLUSIONS

This chapter discussed the types of Greek and some Roman performance spaces that evolved in antiquity from the 20th century B.C. to the 1st century A.D. from the viewpoint of acoustics, in relation to the impact of layout, material changes and details in design. It revealed that innovations in construction and layout generally resulted in acoustic improvements, while the developments in the Classic and Hellenistic theatres show a clear improvement in acoustics, due to the steeper seating areas, the harder materials and the higher stage in the evolution process.

The chapter discussed the acoustic environment of the Greek theatre in more depth, through its transformation from the Classic to the Hellenistic period. Additionally, some details in design were considered. This part showed that:

- The effect of surface characteristics on the SPL is generally insignificant.
- The circular shape allows for multiple reflections, at least to the lower part of the koilon, considerably enhanced by audience diffusion.
- With audience the SPL is about 2-5dB lower than that in the unoccupied condition.
- RT is increased for the upper part of the diazoma when audience is added, because sound is diffused.
- The vertical surfaces of the koilon provide useful first reflections, and this is more effective with a raised stage, as developed during the Hellenistic renovations.

The comparison of the acoustic indices of two theatres that were constructed in antiquity, the Greek theatre of Epidaurus and the Roman theatre of Aspendus was carried out both for the unoccupied and occupied conditions. For the former it revealed that:

- SPL was higher and RT is significantly longer in the theatre of Aspendus than in Epidaurus because of the characteristic differences in layouts. In particular Aspendus presents a more uniform structure.
- Epidaurus' design encouraged reflections to the lower part, whereas Aspendus' layout provided reflections off the peripheral corridor to the upper seating area.
- Compared to contemporary acoustic criteria, the conditions were much better in Epidaurus than in Aspendus.
- The presence of the velarium increased SPL significantly and reduced RT differences between the upper and the lower part of the cavea.

For the occupied condition:

- The acoustic conditions in terms of reverberation were generally improved in the theatre of Aspendus.
- D50 in Epidaurus was higher than in Aspendus, with less spatial variation.
- The number of reflections in Aspendus was larger than in Epidaurus.

Regarding the absorption coefficient range for stone, wood, earth and audience absorption, the results showed that changes in material properties did not affect the evolution, as this was illustrated in Figure 7.8.1, although extremely low or high absorption values could have presented rather unrealistic results. Nevertheless, the comparison of the acoustic indices of all the theatre types, from the viewpoint of evolution, was of interest at this stage. With a range of possible surface absorption coefficients for stone and wood, the variation was insignificant in the Minoan, but considerable in the Pre-Aeschylean theatre respectively. Similarly, when changing the absorption of a material used for large surfaces, like wood in the Classic theatre or stone in the Roman, the results were quite affected.

Overall, from the early Classic to the Hellenistic theatre, the reverberation time had been increased and the sound level had been enhanced. Irrespectively of material properties, the tendencies during theatre evolution were the same. The long reverberation time of the Roman theatre, in a more enclosed layout than the Hellenistic, may have created speech intelligibility problems, especially in the unoccupied condition, with the possible range of material characteristics. In general, the acoustic conditions in the theatre development process had been improved. The transformations in shape, the use of new materials and the changes in the stage building were beneficial for the acoustic environment, especially of Greek theatres.

CHAPTER 8

MEASUREMENTS AND SUBJECTIVE EVALUATION

8.1 Introduction

This chapter presents a systematic study comparing measurements, simulation and subjective evaluation of the theatre of Epidaurus, the performance space of Knossos and the theatre of Philippi. Additionally, the absorption coefficient of porous stone, the main construction material of the theatre of Epidaurus, is measured and used in the simulations.

The structure of this chapter is as follows: It first describes the theatre of Epidaurus in terms of historic information and architectural layout. Porous stone, the material from which most of the theatre was built, is then measured in terms of absorption, following the method described in Section 5.6. Then, on-site reverberation measurements of the theatres of Epidaurus, Knossos and Philippi are analysed. The purpose is to validate the simulations carried out in this chapter and Chapters 7, 9 and 10, to allow comparison with on-site measurements presented in previous studies and to compare the measurements with and without the presence of ephemeral scenery. Moreover, the acoustic environment of the theatre of Epidaurus is described through subjective evaluation, with on-site questionnaire survey.

8.2 Description of the Theatre of Epidaurus

The ancient Greek city state of Epidaurus was situated on the northern side of the Argive peninsula, what is now part of southern Greece [Tomlinson, 1983]. As mentioned in Section 3.3, the plan of the ancient theatre, one of the best preserved examples of the Classic Greek theatre, had been established by the beginnings of the 4th century. Although the theatre of Epidaurus is believed to have been designed and erected by the architect Polycleitus the Younger at around 350 B.C., ancient sources, like Pausanias, suggest that Polykleitos was a famous Argive sculptor that designed the Tholos and the theatre in Epidaurus. Von Gerkan and Müller-Wiener [1961] proposed a later date for the construction of the theatre, at the end of the 4th century B.C., based on the form of a few examples of architectural mouldings and surviving decoration. However, there is an inscription, not known to the former excavators and authors, referring to the construction of the theatre, with letters and names of the period around the last part of the 4th century [Tomlinson, 1983]. The theatre was mostly used for the festival of Asclepios, which was held towards the end of April. The peculiarity of the layout of the theatre of Epidaurus is extensively recorded by Von Gerkan and Müller-Wiener [1961], following the principles described by Vitruvius and presented in a large number of books on history, archaeology and architecture [Antike Griechische theaterbauten, 1930].

8.2.1 Construction of the Theatre

The construction of the theatre of Epidaurus is associated with local interests and cultural development. Scholars in the field of theatre studies suggest that the first circular orchestra appeared in the theatre of Epidaurus rather than Dionysus [Rehm, 2002]. This innovation must have been a result of the 4th century's B.C. interest in the geometry of urban and sanctuary planning. The visits to the sanctuaries for medical purposes instituted early forms of popular gatherings where people from the Mediterranean could be found. Before the construction of the theatre of Epidaurus, which is dated between the 4th and 3rd centuries B.C. according to Lambrinoudakis[39] [2003], the old sanctuary of Asclepios was extended (7th-6th B.C.) to accommodate more visitors. Due to the competition between rival shrines to attract pilgrims, the sanctuary of Asclepius at Epidaurus needed to present spectacular productions in an equally spectacular setting. In that time their famous circular building, the Tholos, was considered to be the finest of its kind in the ancient world. It is thus possible that its distinctive shape encouraged sanctuary officials to build the new theatre. The theatre at Epidaurus was certainly surpassing earlier examples in scale, technological innovation, and architectural refinement – and, as the archaeological evidence suggests, in boasting the first orchestra circle [Rehm, 2002; Wiles, 1997]. Nevertheless, the theatre's uniqueness lies in the fact that it is not architecturally related to the sacred building. Its rake follows the 'golden section' and its horizontal layout is planned on the pentagram in accordance with a Pythagorean conception of the ideal. The theatre is the architectural expression of the flowering of Greek mathematics and the Pythagorean and Platonic idea that number is the key to the divine [Wiles, 1997]. However, from the performance's point of view it is suggested that because of certain design peculiarities, the skene-building is out of focus.

8.2.2 THEATRE COMPONENTS

As mentioned in Chapter 3, the basic components of the Greek theatres were: the orchestra circle for the performance, the koilon or auditorium for the spectators and the skene-building initially used as a background and for storage of properties [Dinsmoor, 1950], and later as a performance space for the leading actors. Figure 8.2.1 illustrates a plan of the theatre.

8.2.2.1 ORCHESTRA

In Epidaurus the orchestra formed a complete circle, with the altar of god Dionysus at its centre. The basic circle was formed by the row occupied by the *proedria*, the seats of honour, which had a diameter of almost 24.49m (80'4") [Dinsmoor, 1950]. Just below that a gutter was created, with an inner edge shaped by the curb of the circle of the orchestra, whose diameter was approximately 20.40m (66'11"). The part of the orchestra towards the audience was decorated. The gutter was about 2.08m (6'10") wide, gradually increasing in width towards the auditorium's extremities to 2.84m (9'4"), to allow the crowd to evacuate the auditorium, but also to open the horseshoe auditorium so that the spectators that sit at the extremities would obtain a better view of the performance and the stage building [Simpson, 1956]. It has been suggested

[39] Lambrinoudakis is a Professor of classical archaeology, director of the Central Archaeological Council of Greece, director of the excavations in Epidaurus and director of the Board of Restoration of the Monuments of Epidaurus.

in the literature that this was achieved by the use of three centres in the plan of the theatre [Dinsmoor, 1950]. The auditorium was in five-sixths of a semicircle laid out by the orchestra centre, while for the rest ,two centres were employed with increased radiuses by 3.50m (11'5').

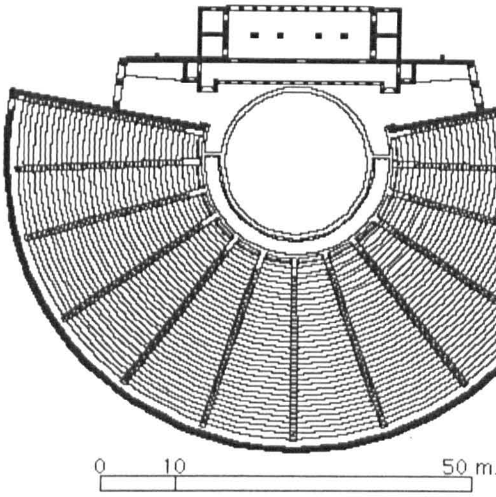


Figure 8.2.1. *Plan of the Classic theatre of Epidaurus*
[source: http://www.perseus.tufts.edu/cgi-bin/image?lookup=1990.33.0203a&type=plan].

8.2.2.2 AUDITORIUM

Based on the above calculations, the auditorium formed a little more than a semicircle, at 205° at the low and 210° at the upper part, and at 117.96m in diameter (387'). It was divided by a diazoma into two parts; the theatron, composed of 34 rows of seats, and the epitheatron, containing 21 rows. Three of these rows, the first and last of the theatron and the first of the epitheatron, formed the seats of honour, with backs, and in the case of the aisles arms, carved in fine porous stone. The rest of the seats had faces and tops with a depression, to accommodate the feet of the person seating above, as seen in Section 7.5, and allow the height to be adjusted for good sightlines. The height of the seats is 0.33m (13") at the lower part, which required cushions, and 0.43m (17") at the upper part [Dinsmoor, 1950]. The width of the seats was always almost 0.74m (2'5 ¼"), allowing the inclination to be steeper at the epitheatron (27° as opposed to 23° angle of the theatron) [Dinsmoor, 1950; Robertson, 1979; Canac, 1967]. However there is a discrepancy here. The drawings and published books of the excavator and first ever descriptor of the theatre suggest that the seat height is the same at the low and upper part of the theatre, allowing for an inclination angle of 26° for the whole koilon. These drawings are illustrated in his book 'Das theater von Epidauros' [Von Gerkan and Müller-Wiener, 1961] and supported by many researchers[40] [Tomlinson, 1983]. For this reason, the following simulations have been carried out with both koilon inclination conditions. The auditorium is divided by 13 stairways, known as furrows (*ολκοί*), radiating from the same circle, which subdivided the seats into wedge-shaped sections (*κερκίδες*). In the epitheatron additional

[40] The author has also reviewed the original drawings of Von Gerkan, located in the museum of the theatre of Epidaurus, after acquiring a permission of the Committee of Restoration of the monuments of Epidaurus, confirming the disagreement between the authors.

intermediate stairways were constructed. Vitruvius generalised this by the rule that above every diazoma the number of stairways should be doubled [Marquand, 1909]. However, an unusual characteristic found in Epidaurus is the axial staircase, which is mostly used in the Roman theatre layout. It is suggested that this was intended because the ancient Greeks disliked the flat axial viewpoint [Simpson, 1956]. Another important feature of the theatre of Epidaurus is the high podium at the epitheatron, immediately after the diazoma, which raised the height of the seats to compensate for the interruption of the inclination.

8.2.2.3 Stage building

The stage building of the theatre of Epidaurus is in a less satisfactory condition than the auditorium. Unfortunately only the foundations remain from the time of Polycleitus. The 4th century B.C. appears to have consisted of a hall 19.51m (64') long and 6.096m (20') wide, with two protruding *paraskenia* at either side. The skene-building was set at the tangent of the orchestra, containing properties and boxes. Its facade formed a background against or before which the simplified decors were arranged [Rolland, 1967]. The skene-building was separated from the auditorium by two open passages, the parodoi, one on each side, giving access to the orchestra from outside. The skene-building's date is disputed [Robertson, 1979]. Many critics assign the skene and the epitheatron to the original structure, while others suggest that they were Hellenistic innovations [Georgousopoulos, 2003]. Figure 8.2.2 shows an axonometric view of the theatre.

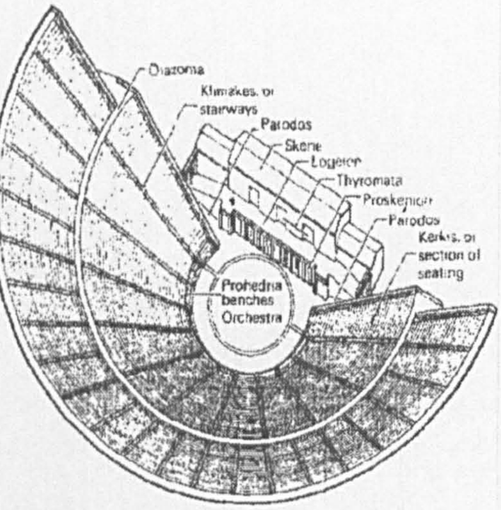


Figure 8.2.2. *The theatre of Epidaurus during the Hellenistic period [source: http://anarchon.tripod.com/indexGREEKTH.html].*

8.2.2.4 Materials and Condition

The theatre of Epidurus was built with hard porous stone, while for some parts of the koilon and the skene local pink porous stone was used. Usually, the extensive excavations of the theatre buildings last several decades. Especially concerning the theatre of Epidaurus, the restoration project was brought to completion several decades ago. The excavations have now focused on other monuments of the ancient site, like the ancient stadium and the Tholos of Epidaurus. The theatre can accommodate 13,000 to 14,000 viewers. Von Gerkan and Müller-Wiener [1961] suggest that the original form of the theatre could accommodate only 6,200 spectators, since it was only composed by the theatron, the lower part of the koilon.

8.2.3 Previous Studies on the Acoustics of the Theatre of Epidaurus

The theatre of Epidaurus is famous for the excellent acoustics, as many non-experts suggest. This may have been the result of the general layout of the theatre, the so-called bowl-shaped structure [Arnott, 1959]. Everything can be heard clearly at the top, possibly a consequence of the high standard in design. This is a feature the tourists are always font of, even in the contemporary condition of the theatre with the demolished skene-building.

It is suggested that cosmology and acoustics are closely related and since the theatre was planned according to the pentagram and divided into twelve wedges, with cosmic symbolism, it is based on the Pythagorean assumption that the planets stood in a mutual relationship of perfect music harmony [Wiles, 1997]. Other studies concerning articulation tests, reverberation measurements and acoustic simulation of ancient Greek theatres are discussed throughout Sections 8.4.1 and 8.5 [Shankland, 1974; Vassilantonopoulos and Mourjopoulos, 2003; Vassilantonopoulos and Mourjopoulos 2004; Vassilantonopoulos *et al*, 2004]. The effects of the wind and temperature have also been discussed in Chapter 2 and were carefully studied by Cremer [1975] and Goularas [1995]. The former indicated that air moves from the actor to the audience, while the steep inclination allows for good sound distribution from the actor closely situated to the skene-building, with the help of the orchestra's reflection. Goularas investigated the distribution of sound in terms of the temperature increase towards the last rows [1995]. Finally Canac [1967] has illustrated sound distribution in terms of multiple horizontal reflections from one side of a row to the other.

8.3 Absorption Coefficient Testing

This section presents the absorption coefficient measurements for porous stone, following the method described in Section 5.6. Previous studies that focused on the simulation of ancient performance spaces, mainly Greek and Roman theatres, have not published the exact absorption coefficients used for the simulation [Vassilantonopoulos, 2003], or used approximate values that were compared with on-site measurements [Gade, 2004]. In the latter, the absorption coefficient for the highly porous stone of the stage building and the vaulted colonnade in the ancient Roman theatre of Aspendus was estimated as 0.2, while the value for the smoother and harder material of the cavea was 0.05 [Gade, 2004].

Knowing the materials the theatres of this study were built from, this section focuses on the absorption coefficient measurements performed in the acoustic laboratory of the University of Sheffield. The archaeologists that studied the sites of the theatres have already examined and published the characteristics of the theatres, included the materials' nature [Karadedos, 1986; 1994; Karadedos and Koukouli-Chrysanthaki, 1993; Karadedos *et al*, 2001; Koukouli-Chrysanthaki and Karadedos, 2001]. Thus, although marble and stone are usually suggested as the main construction materials, porous stone, limestone and brick have also been used.

The material examined acoustically in this section will be porous stone. Two samples of porous stone, like the one used for the construction of the theatre of Epidaurus, were cut and sent from Greece, with diameters of 10 and 2.8cm respectively. The surfaces of the two samples were fairly smooth, with no polish. Figure 8.3.1 illustrates the material. A characteristic of this material is its porous finish. This can cause further absorption of the surface. For this reason both sides of the samples will be measured, the results will be compared and average values will be selected.

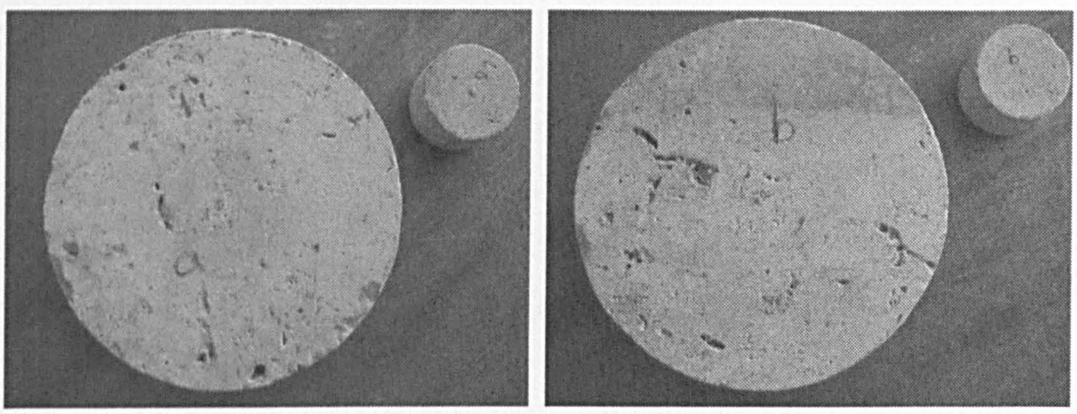


Figure 8.3.1. *Samples of materials used in the absorption coefficient testing with the use of the impedance tube.*

8.3.1 Impedance Tube Description

SCS9020 "Kundt Tubes", by S.C.S. Controlli e Sistemi s.r.l were recently installed. The sound absorption measurement is related to the capacity of materials to absorb and dissipate sound energy; Kundt tubes allow sound measurement of soft and porous materials [S.C.S. Controlli e Sistemi s.r.l., 2003]. For the hardware design the company referred to ASTM standard: E1050-98: Standard test method for impedance and absorption of acoustic material using a tube, two microphones and a digital frequency analysis system.

The system is composed by two tubes: the small for high frequency range and the large for low frequency range. In each tube two microphones were installed, namely A and B. Each tube consists of a fixed part and a movable subsystem. The fixed part is composed of a loudspeaker box, coupled with an acoustic chamber in which two microphones can be plugged. The large tube (0.10m diameter) has three microphone receptacles, two of which may be used at a time, while the small tube has two. The microphone plugs are designed to allow easy and accurate positioning, ensuring good sealing around its body. During the testing procedure the user should swap microphones and then put them again in their original position The tubes' movable subsystem is composed of a sample holding cylinder and a piston-screw-stopper assembly; this subsystem may be steadily coupled with the acoustic chamber by means of a couple of locking hooks. The piston inside the sample holding cylinder can be moved forth and back along the cylinder. The materials are cut into the exact dimensions of the tube and aligned to the tube's edge. This can be achieved by moving the piston to a deep cavity, inserting the sample and moving the piston forward to the exact position.

Additional electronic hardware is used. Electronic models, like M-V11 are used to set the Lo- and Hi-Pass and connect the outputs to the amplifier and to the noise generator [S.C.S. Controlli e Sistemi s.r.l., 2003].

8.3.2 Software Description

The software used for the measurement was dBAlpha Test, part of the 01dB-Stell, created by the MVI technologies group [2002]. It is user friendly, considering that the procedure is easy to follow. It uses the transfer function to calculate the coefficient with the use of the impedance tube. Three frequency ranges are used: 50-500Hz for the large tube, the average range from 500-1600Hz and 1600-10 kHz for the small tube. According to the manual, in order to eliminate the residual phase shift between the two microphones, it is necessary to perform a phase calibration for the microphones prior to the measurement. The phase shift is then automatically corrected by dBAlpha Test [MVI technologies group, 2002].

The procedure is initiated by entering the hardware characteristics, such as microphone specifications (sensitivity, power supply, etc.), calibrator (level, frequency) and acquisition unit. Each time dBAlpha Test is used, the configuration procedure needs either to be redefined, or downloaded.

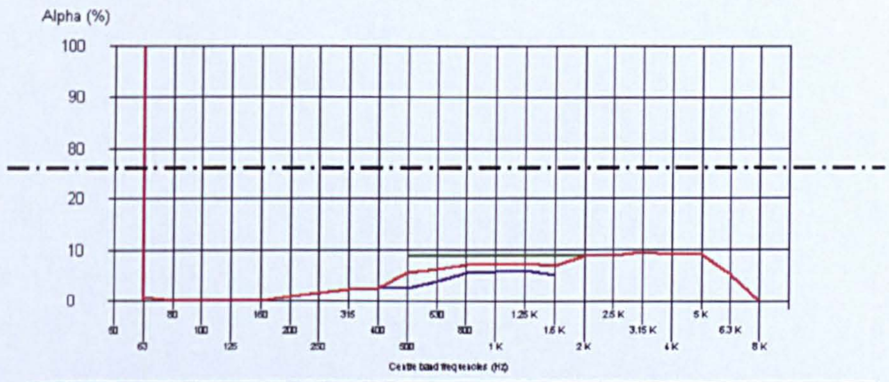
The measurement is a three-step process:

- Configuration: all parameters common to the two measurements (Large and Small Tube) are set
- Large Tube Measurement: Phase calibration of the microphones and the sample measurement
- Small Tube Measurement: Phase calibration of the microphones and the sample measurement.

This part of the study focuses on the results in the case of the porous stone measured, rather than the procedure's details. Still, it needs to be mentioned that during the calibration of the second and third phase the user should be vigilant regarding saturation (resulting from a wrong gain adjustment of the two channels) and coherence. As mentioned above, during the second and third phases the position of the microphones is switched. Moreover, for the complete measurement of a sample, both tubes are required. After the second tube is selected and the procedure is repeated, the results are complimented with the Large Tube Measurement [MVI technologies group, 2002]. The results are displayed in a window with different colour for each tube.

8.3.3 Measurement Results

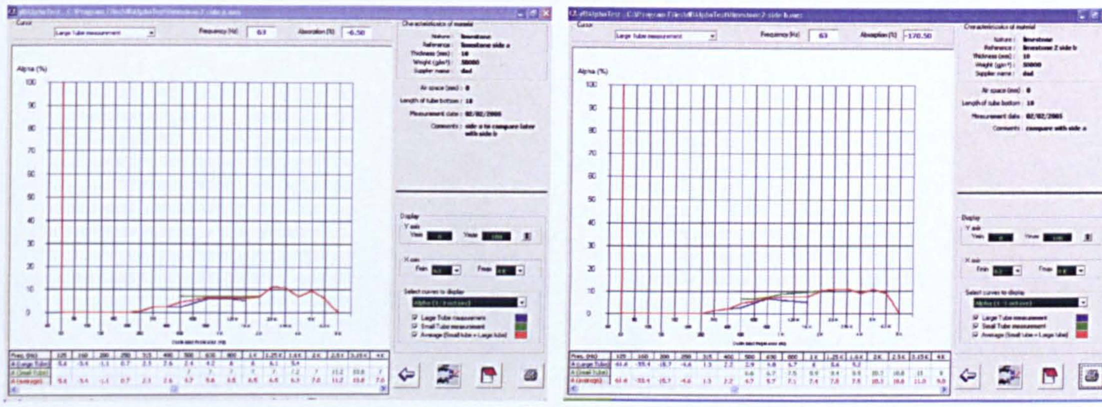
For this measurement, two samples were used, one for the Large and one for the Small Tube. The measurement was carried out three times with excellent coherence between the two microphones. As mentioned previously, both sides of each sample were later tested for average values to be selected. Names *a* and *b* are assigned to the two sides of the samples, as seen in Figure 8.3.1. Figure 8.3.2 illustrates the absorption coefficient values for a random measurement, with one only side of the sample used, namely part 1. The blue line represents the coefficient for the Large Tube, the green line for the Small Tube and the red line for the average values for the range of frequencies.



Freq. (Hz)	125	160	200	250	315	400	500	630	800	1 K	1.25 K	1.6 K	2 K	2.5 K	3.15 K	4 K
A (Large Tube)	-1.8	-0.5	0.9	1.6	2.4	2.6	2.5	4	5.6	5.9	6	5.2				
A (Small Tube)							8.8	8.8	8.8	8.8	8.8	9.1	8.8	8.8	9.5	9.1
A (average)	-1.8	-0.5	0.9	1.6	2.4	2.6	5.6	6.4	7.2	7.3	7.4	7.1	8.8	8.8	9.5	9.1

Figure 8.3.2. *Absorption coefficient results for randomly chosen sides of the sample.*

The next step of the procedure involved assigning the names and measuring the two sides of the sample. Side *a* was first measured for both the Large and the Small Tubes. Figure 8.3.3 illustrates the results obtained from each measurement. As can be seen the tendency in the results is the same, with small differences that can be attributed to the different pores of each side of the sample.



a b

Figure 8.3.3. Absorption coefficient results for the sample tested. a) Side a and b) Side b.

The average values of all situations are presented in Figure 8.3.4. For the final values the frequency ranges for the large and small tubes are calculated automatically, while from 500Hz to 1600Hz the average values are recorded. Then, from sides *a* and *b* the mean values are found, which are then compared to the first part of the results.

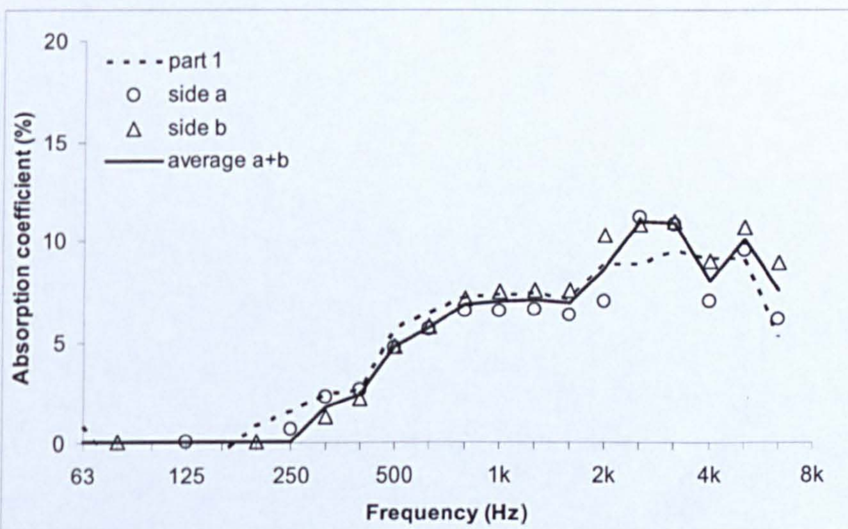


Figure 8.3.4. Average absorption coefficient results for part 1, side a and side b.

The final values of the absorption coefficient are presented in Figure 8.3.5. For the third octave band the values are: 0.01 for 63, 125, and 250Hz, 0.052 for 500Hz, 0.071 for 1kHz, 0.087 for 2kHz, 0.085 for 4kHz, and 0.063 for 8kHz. For comparison, absorption coefficient data for commonly used materials, namely marble, brick and concrete, are presented [Egan, 1988]. It can be seen that porous stone is characterised by relatively low absorption at low frequencies and relatively high absorption, compared to marble, at middle and high frequencies. This could be explained by the diameter of the pores of the porous surface, which, according to the wavelength, consequently affects certain frequencies. Compared to previous studies that used 0.2 and 0.05 absorption coefficient values for highly porous stone and smoother stone respectively for the ancient Roman theatre of Aspendus [Gade, 2004], the absorption found for porous stone in this study is closer to the latter. Nevertheless, the uniqueness of the material found in each region allows for some variations in results.

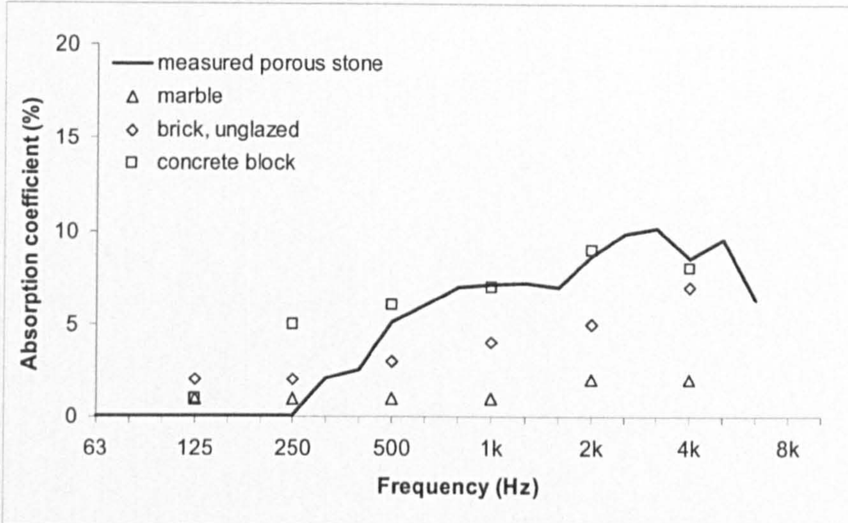


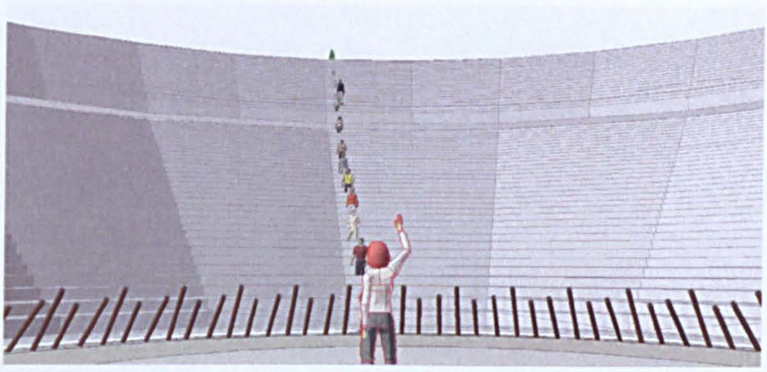
Figure 8.3.5. *Final absorption coefficient, compared with marble, brick and concrete block [source: Egan, 1988].*

8.4 On-Site Measurements – Theatres of Epidaurus, Philippi and Knossos

8.4.1 On-Site Measurements and Analysis of the Theatre of Epidaurus

Acoustic measurements in ancient theatres are difficult to carry out especially in the summer period. After several visits to the site it was decided that the SPL and RT should be measured early in the morning to avoid (a) cicadas, which are triggered by the midday's heat, (b) tourists, who always perform acoustic tests using coins and their voices, and (c) high temperatures, which would alternate sound velocity significantly compared to an evening performance. During the summer period it is impossible to find a time when there is no scenery in the theatre, due to the frequent performances. After getting permission by the Board of Antiquities for the acoustic measurements in the unoccupied theatre, the construction manager was contacted to arrange for the builders and the technicians to start work on the site after the measurements were carried out.

Measurements for both sound level and reverberation were carried out with simple equipment. The reverberation measurements were carried out using the balloon-popping method with a SONY mini-disc recorder, under unoccupied condition and were analysed using Symphony 01dB software dBBATI32 [01 dB-Stell, 2001], as described in Section 5.4. The measurements were taken at 17 points along a receiver line off the central axis of the theatre, as well as at a number of randomly distributed receivers at the far end of the theatre and in the orchestra, as shown in Figure 8.4.1. Figure 8.4.1 also illustrates the temporary scenery that was installed in the theatre during the measurements, namely the scenery of the performance of 'Electra' designed by G. Patsas. It consisted of a background skene-building, which was an abstract adaptation of the ancient skene-building, an additional orchestra floor, around 40cm above the original, made of plywood, and a circle of inclined javelins that surrounded the orchestra. Regarding the background building, it was only one story high, with three doors, connected to the orchestra by ramps.



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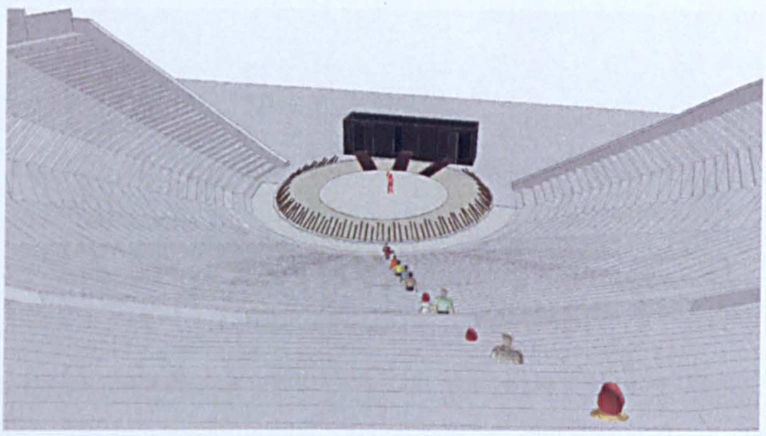

b

Figure 8.4.1. *Axonometric view of the theatre of Epidaurus. a) View from the source and b) View from the receivers.*

In Figure 8.4.2 the main window is shown, after the signals at all receiver positions have been imported. At the left side of the main window one can see the signal files, while the signal of the receiver seating in the first row is selected and its plot is shown on the right. From the signal it is clear that there is some reverberation. Figure 8.4.2b illustrates the reverberation analysis in the software. After the signal has been selected the user performs the analysis and the results are presented for each frequency, as seen in Figure 8.4.2c. The user can either obtain the automatic results or re-adjust the decay line to be represented as accurately as possible. In this case the RT is re-calculated. In Automatic Calculations 1 and 2 the decays used are from -5 to -35dB and from -5 to -25dB respectively.

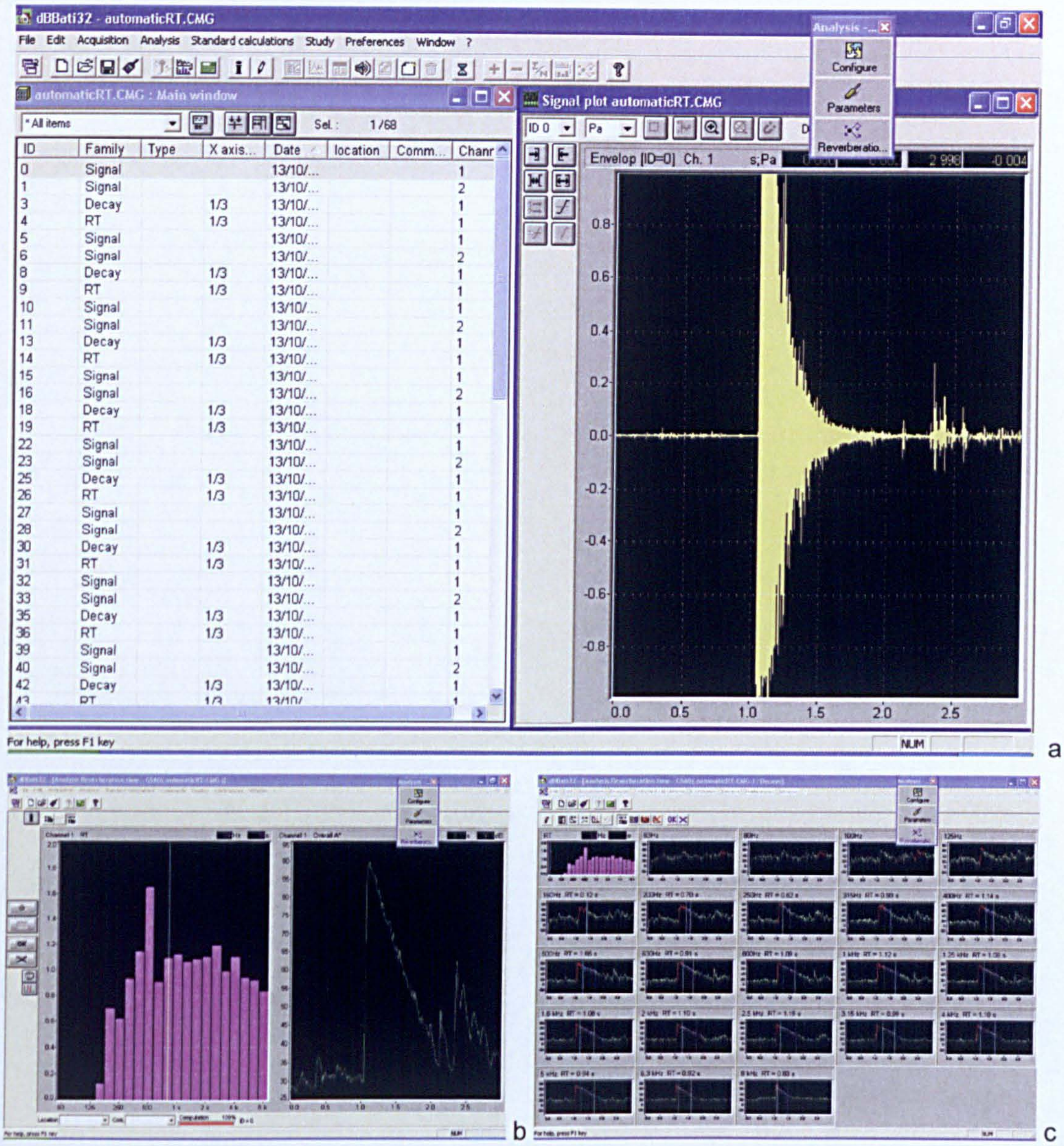

Figure 8.4.2. *dBBATI32 process with the automatic calculation. a) Main window with signal files and plot, b) Reverberation time analysis and c) Decays in all frequencies.*

The results of the automatic calculations are shown in Figure 8.4.3. Automatic Calculation 1, shown in Figure 8.4.3a, presents a variety of values from 0 to 2.39s and Automatic Calculation 2, in Figure 8.4.2b, from 0 to 1.89s. Generally, it is evident that there is a rather wide distribution of RT among the frequencies and the receivers, particularly at low-to-mid frequencies where the ratio of the standard deviation (STD) to the average RT could reach 200%. Less variation can be found at high frequencies and for receivers seated at the upper part of the koilon, especially for Calculation 1. Still, it is not appropriate to give values for RT before the results are further examined. Generally it seems that RT is longer at high frequencies, around 1.0-1.1s, illustrated by the average values that are represented by the thick black lines.

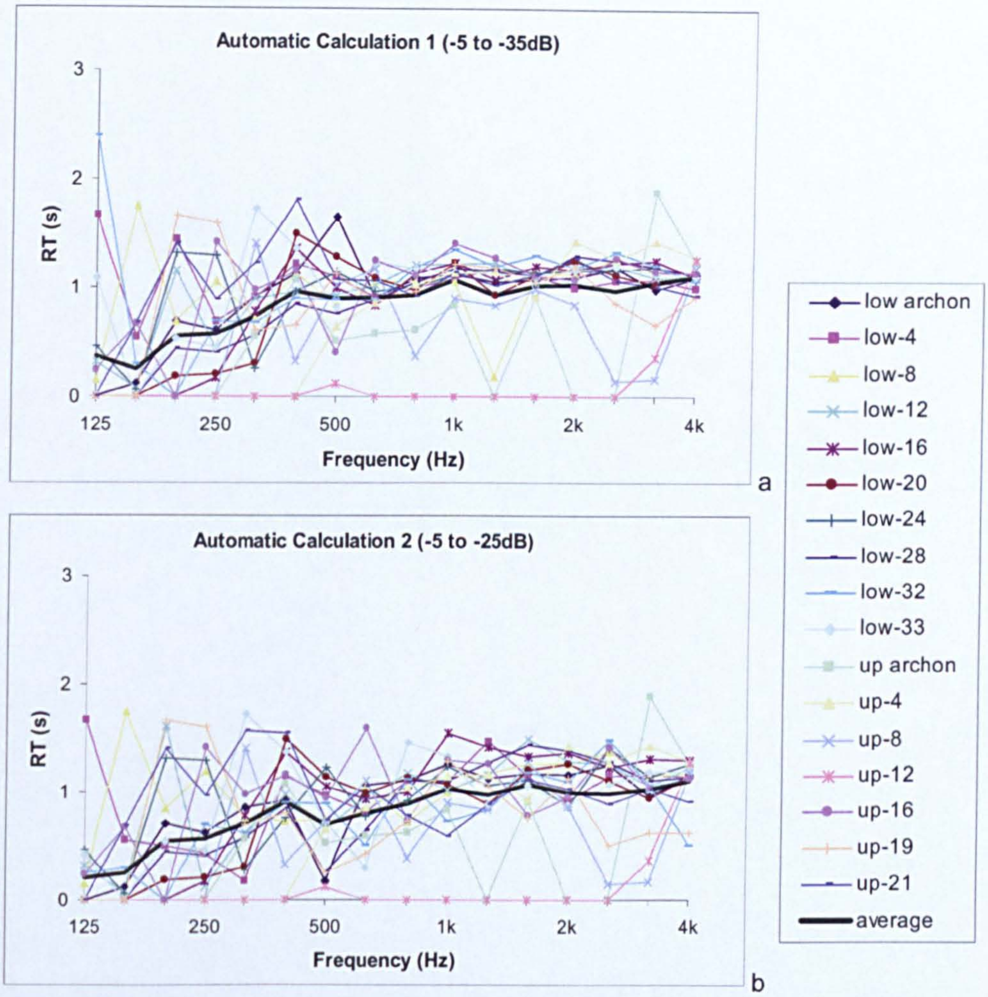

Figure 8.4.3. *RT (s) results after measurement analysis. a) Automatic Calculation 1 with 30dB decay and b) Automatic Calculation 2 with 20dB decay.*

The results have been repeatedly investigated manually, referred to as the 1st, 2nd and 3rd Manual Calculations. Figure 8.4.4 demonstrates the retrieved RT values. Evidently, the variation has been significantly decreased and the RT values are clearer and less wide-ranging. The ratio of the standard deviation to the average values is in all cases especially low, less than 10% at middle and high frequencies, which is extremely valuable for the measurement results. From these values the average estimate for the RT in the theatre of Epidaurus is 0.6s at low frequencies and 1.1s at middle and high frequencies. Later, 4 points of the receiver line are selected and presented, including the signals.

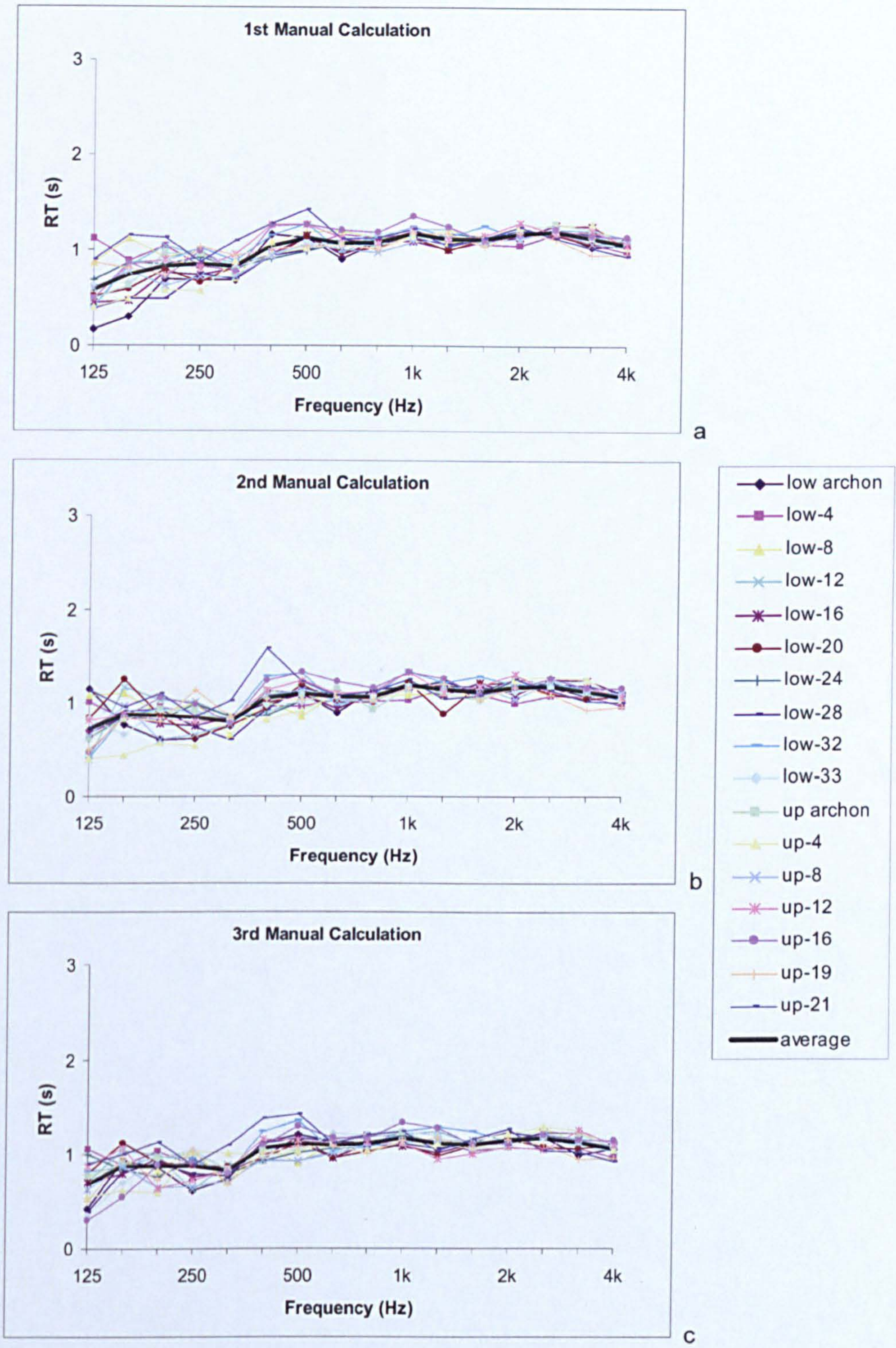

Figure 8.4.4. *RT (s) for the range of frequencies. a) 1st Manual Calculation, b) 2nd Manual Calculation and c) 3rd Manual Calculation.*

Figure 8.4.5 clearly illustrates the dissimilarities between the methods of reverberation calculation in dBBATI32. The variation in RT is, as mentioned before, wider at 125Hz, than at 500Hz and at 4kHz. This applies to the whole receiver line, and the average values become smoother at high frequencies. The averages for all receiver points are calculated in this way for all methods and frequencies.

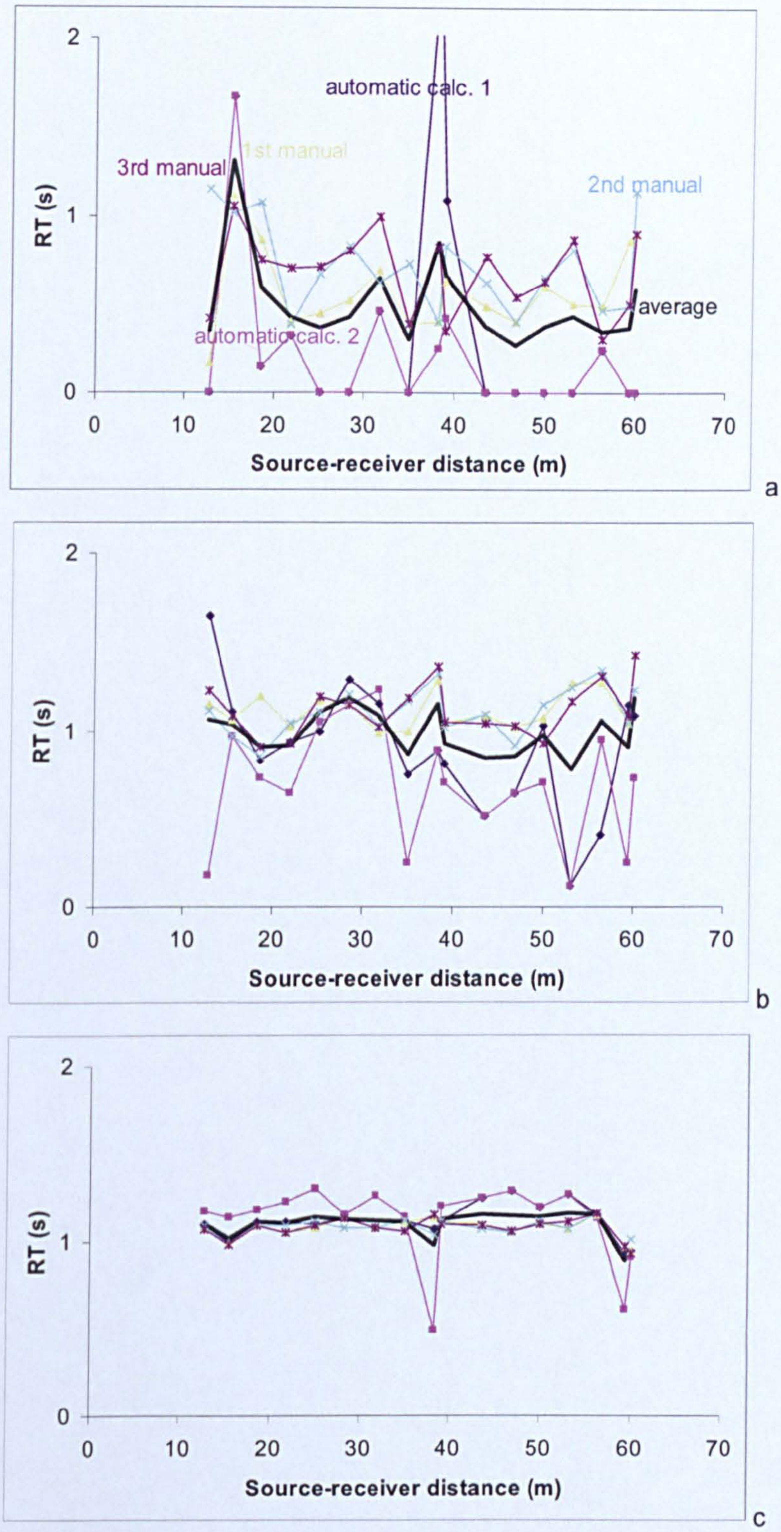

Figure 8.4.5. *RT (s) across the source-receiver distance. a) 125Hz, b) 500Hz and c) 4kHz.*

Figure 8.4.6 illustrates the average RT values for all receiver points at 500Hz, a corresponding frequency for speech and drama. It demonstrates that the final values of reverberation across the source-receiver distance are low at 125Hz, around 0.5s, increasing with high frequencies up to the value of 1.1s.

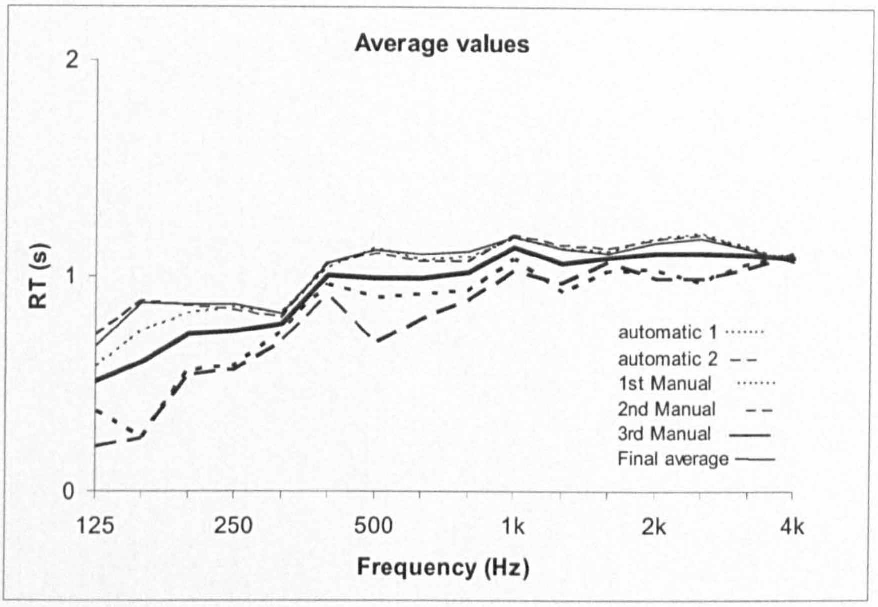

Figure 8.4.6. *Average RT (s) for all methods at the frequency range.*

These values do not correspond to previous research on the acoustics of the theatre of Epidaurus. The commonly accepted view is that no reverberation exists in an outdoor theatre [Shankland, 1973; Vassilantonopoulos *et al*, 2004]. However, in 1995 a dissertation carried out by the department of Electrical Engineering in the Aristotle University of Thessaloniki involved measurements in two open-air theatres, the ancient theatre of Epidaurus and the contemporary theatre Dasous, which will also be discussed in Chapter 11 [Goularas, 1995]. It revealed that the former had RT30 up to 1s, depending on the position of the microphone in the theatre. Usually the sides had rather long RT30 compared to the theatre axis. It is noted that Goularas's measurements were carried out with no scenery installed. Also, there are several examples of recent measurements carried out in open-air theatres of the Roman period, which revealed long RT values, at the range of 1.5-2.0s [Gade *et al*, 2004; Gade *et al*, 2005; Lisa *et al*, 2005]. It is obviously expected that an ancient theatre of the Greek type cannot present RT at the same range as a Roman, as previous studies also suggest [Vassilantonopoulos and Mourjopoulos, 2004], although it seems that most of the researchers are misled by preconception and by acoustic software that imprudently provide zero reverberation, just because of the fact that the space is not enclosed, like CATT, as discussed in Section 2.6. However, Epidaurus' unique layout, with small parallel sides of the koilon, steep seating areas and curved inclinations, as mentioned in Shankland's study [1973], allow for further research. Still, recently published reverberation measurements concerning the theatre of Epidaurus were carried out without the presence of scenery [Vassilantonopoulos *et al*, 2004]. It is thus possible that scenery like 'Electra's', with raised orchestra floor and reflective materials could increase reverberation. This could provide the initiative for a systematic investigation of the effect of several scenery types on the acoustics of ancient performance spaces, and especially reverberation, since the problem of hearing as a result of the missing skene-building has been raised in previous studies [Schubert and Tzekakis, 1999].

Section 8.5 will present a comparison between RT measurements and simulation results regarding the ancient theatre of Epidaurus.

8.4.2 On-Site Measurements and Analysis of the Performance space of Knossos

Following the same methodology as in the theatre of Epidaurus, on-site measurements were recently carried out in the theatre of Knossos, presented in Section 3.2.1. The measurements were taken on the 20th September 2006, a rather rainy and cool day. The theatre was most of the times relatively occupied, since groups of tourists were guided throughout the palace of Knossos, as shown in Figure 8.4.7. The theatre presents sinking at the first rows, as shown in Figure 8.4.7, which has been carefully represented when designing the theatre in Archicad 8.

Figure 8.4.7. *Photos of the theatre of Knossos just before the measurements.*

The measurements used the balloon-popping method and were analysed similarly to Section 8.4.1. In order to evaluate the reverberation each position was measured several times. Measurements were taken for nine positions in the theatre, shown in Figure 8.4.8.

The decays used for the measurements are shown in Figure 8.4.9, although with different time scales. As can be seen, especially in the case of receiver point 7, there is a distinguishable decay in the sound. The results from dBBATI32 are analysed automatically, with 30dB and 20dB decay, and manually. In this way for every receiver position there are at least eight reverberation results. In each occasion the average is taken.

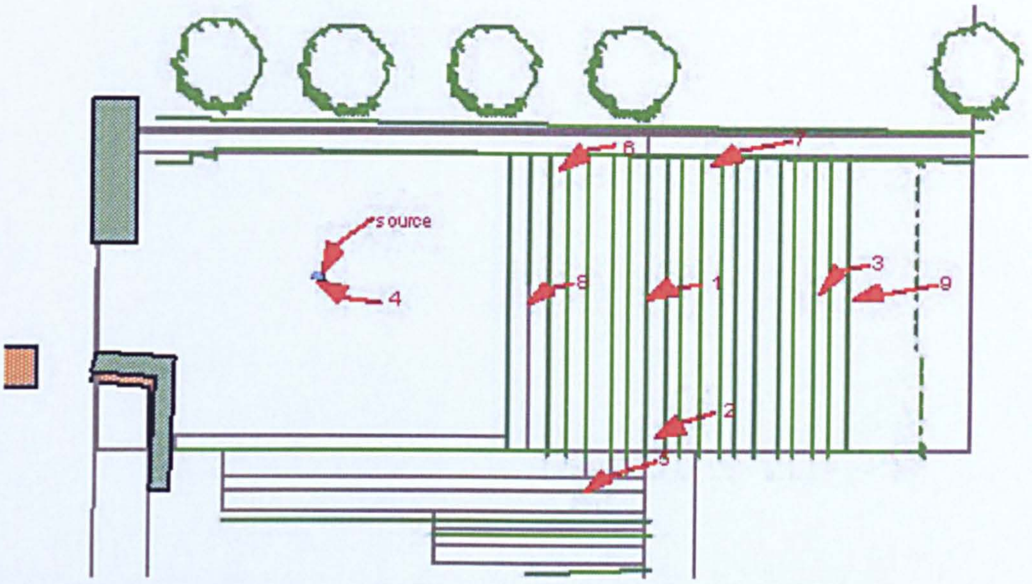

Figure 8.4.8. *Plan of the theatre of Knossos, illustrating the source and receiver points.*

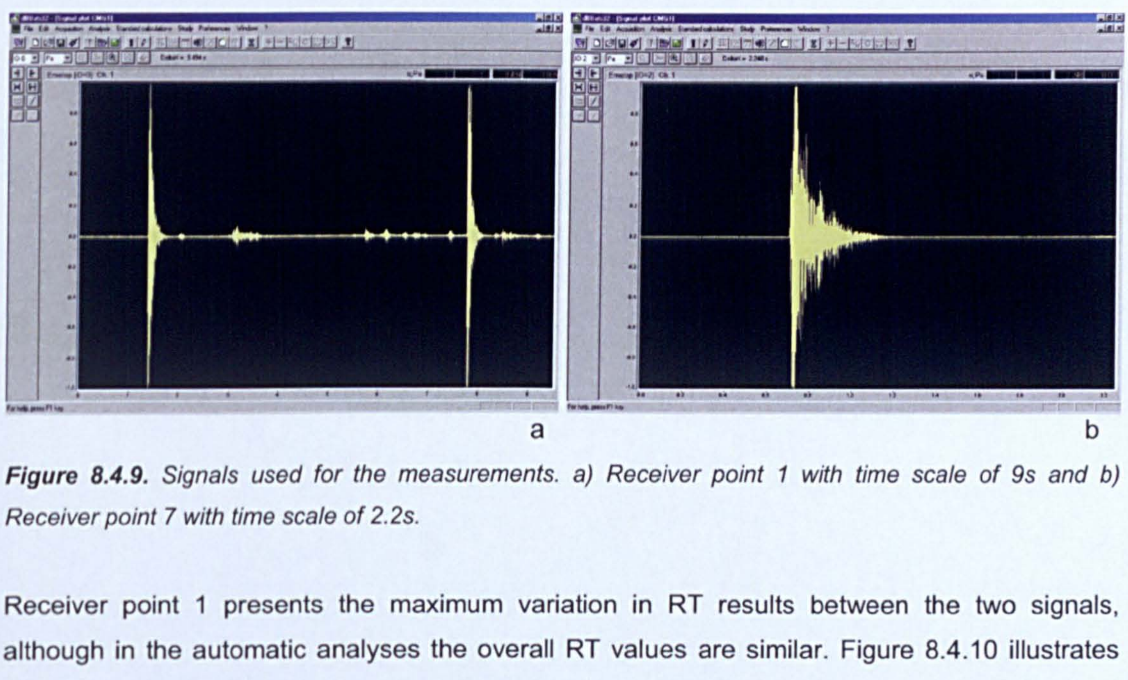

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Figure 8.4.9. *Signals used for the measurements. a) Receiver point 1 with time scale of 9s and b) Receiver point 7 with time scale of 2.2s.*

Receiver point 1 presents the maximum variation in RT results between the two signals, although in the automatic analyses the overall RT values are similar. Figure 8.4.10 illustrates the RT analysis under the four methods, namely the two automatic and the two manual. It needs to be noted that receiver point 1 presents the maximum variations between the signals and the four methods of analysis. In Figure 8.4.10a the variation between the two signals is found at 250Hz, at 1.29s. Regarding the other receiver positions the maximum variations are at the range of 0-0.25s.

To obtain the overall RT values, the points situated on a line, namely 4, 8, 3, 1 and 9, are calculated in all methods. After extracting the average values, as seen in Figure 8.4.10, for all the points, the RT curves of Figure 8.4.11 were created, showing that most of the methods almost coincide. The final reverberation is 0.43-0.58s for the receiver line.

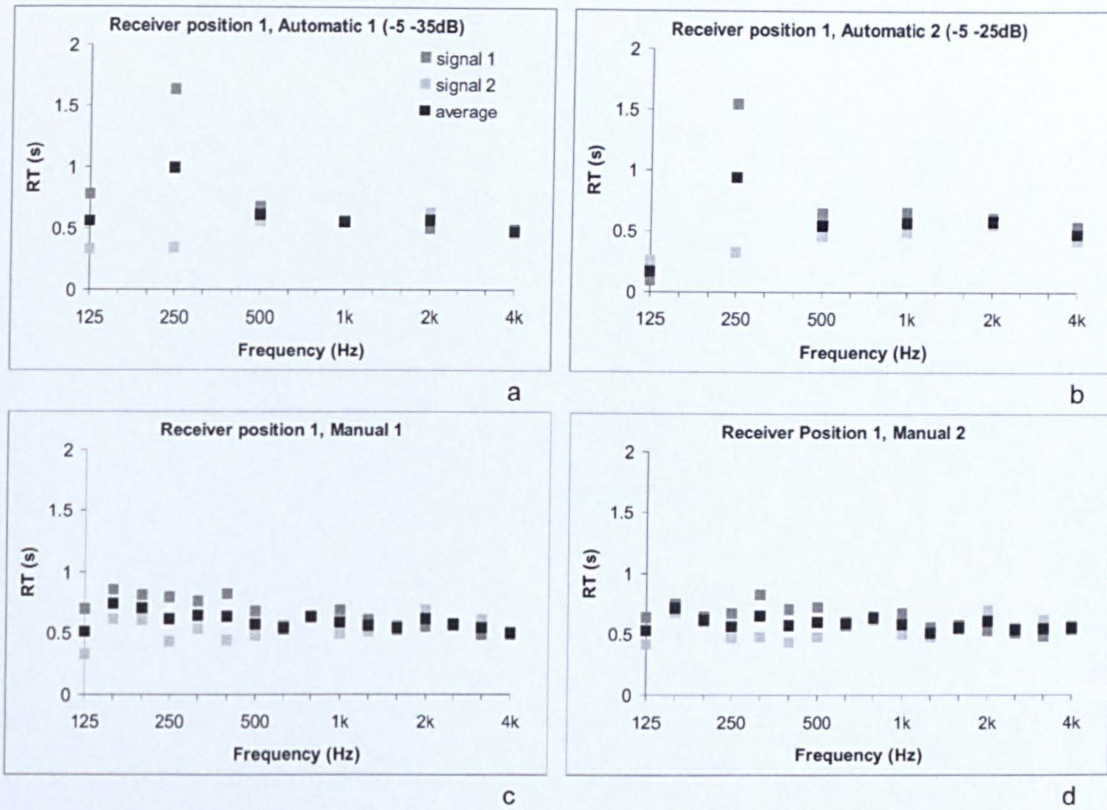

Figure 8.4.10. *Analysis of reverberation for receiver position 1. a) Automatic -5 -35, b) Automatic -5 -25, c) Manual 1 and d) Manual 2.*

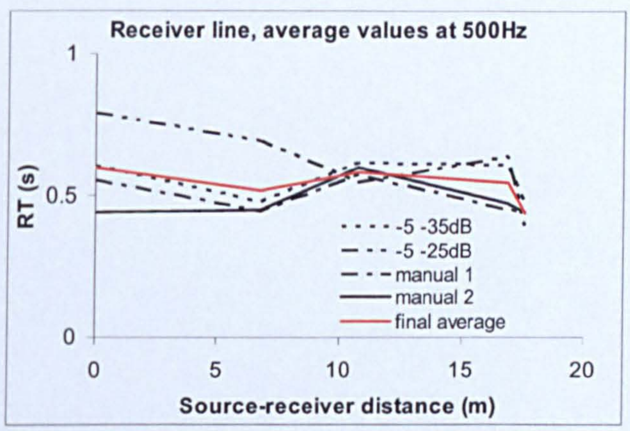

Figure 8.4.11. *Average values of reverberation for all the method and final values.*

Moreover, the results for all receivers at 500Hz are shown in Figure 8.4.12. In general, other frequencies present the same value range. The reverberation is around 0.50s for the majority of the performance space. However, as mentioned before, the space was occupied at the upper rows. The fully occupied space would produce shorter RT values, while the unoccupied would present relatively long RT. It is noted that, due to the size of the performance space, the number of rows and their inclination, the RT values could not possibly reach the same levels as in Epidaurus, as was also shown in Chapter 7.

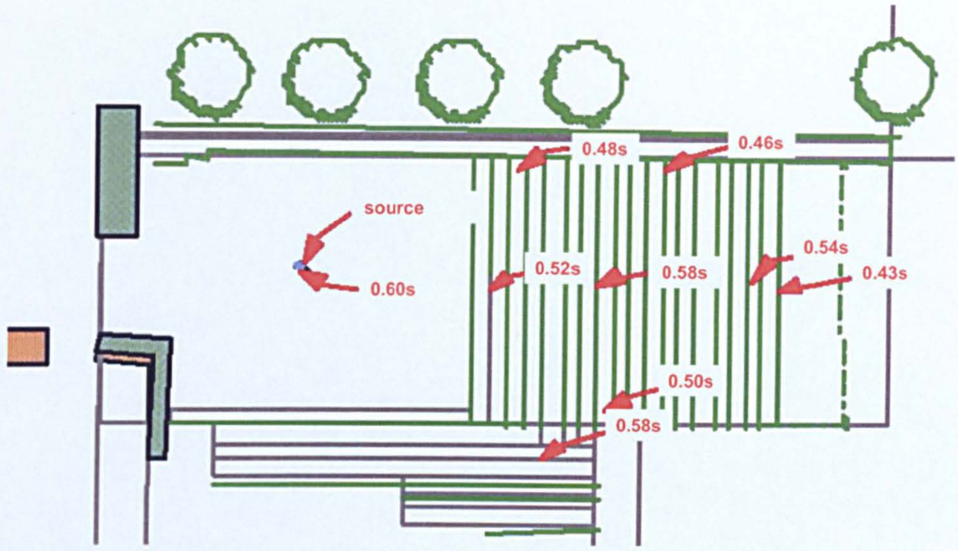

Figure 8.4.12. *Reverberation for all receiver positions at 500Hz.*

8.4.3 ON-SITE MEASUREMENTS AND ANALYSIS OF THE THEATRE OF PHILIPPI

On-site measurements have been performed in the theatre of Philippi, which will be further described in Chapter 9. The uniqueness of the specific theatre is that it is situated next to a motorway. Hence, the conditions in terms of traffic noise are quite obtrusive, especially in the case of a performance taking place. Figure 8.4.13 illustrates two sources and twelve receiver positions. It is noted that for receivers 8-12 source 2 has been used.

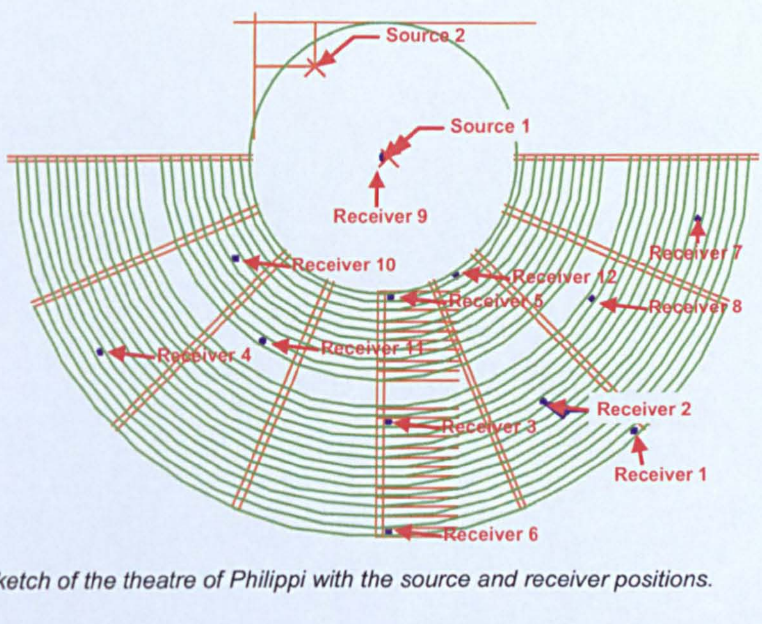

Figure 8.4.13. *Sketch of the theatre of Philippi with the source and receiver positions.*

The fact that during the measurements there were quite harsh levels of wind, in addition to the background noise, did not allow the samples to present a normal decay. Figure 8.4.14 presents the signals for receivers 1 and 2. It is clear that in the former the background noise levels are comparatively higher, and the decay difficult to be calculated. Due to this problem, only for a few frequencies RT could be calculated.

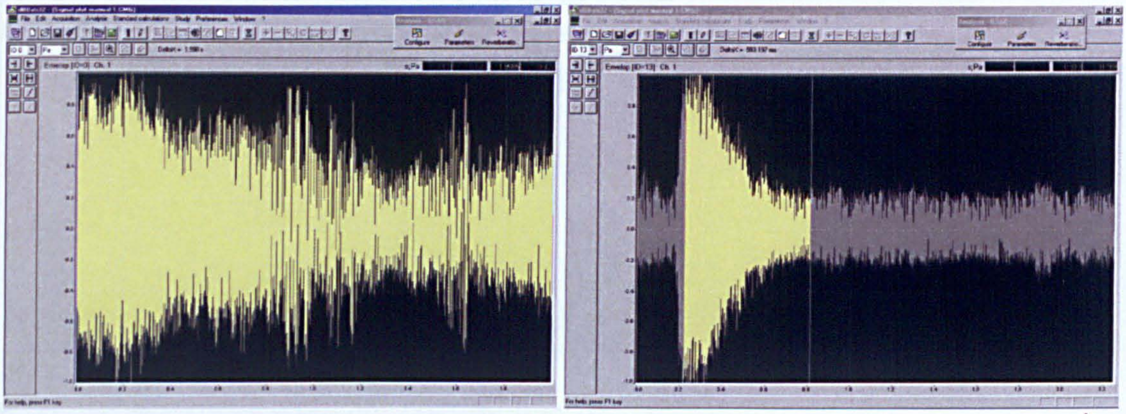

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Figure 8.4.14. *Signals used for the measurements. a) Receiver point 1 and b) Receiver point 3.*

The reverberation for all the receivers shown in Figure 8.4.13 was calculated in the same way as in Sections 8.4.1 and 8.4.2, namely for decays from -5 to -35, -5 to -25 and manually. The automatic calculation did not provide RT results for most of the receivers and most of the frequencies. By comparing source 1 and 2 it was found that the points that received sound from the latter provided better signals, in terms of background noise. It needs to be noted that when there is high background noise it is very difficult to find representative decay curves in the signals. There are two possibilities that would provide inaccurate results: the decay is very abrupt, since in order to get rid of the background noise possible reflections are lost, or the decay is very long, since some of the noise is taken into account as well.

Figure 8.4.15 illustrates the RT for all the analysis' methods for four receiver positions. Clearly positions 8, 9 and 10, where source 2 was used for the signal, present better agreement between the methods, while RT was easily calculated, especially for the manual analysis. Although the results need further validation, with measurements carried out with better weather conditions for the whole frequency range, it is still an indication of RT values in the theatre.

Figure 8.4.16 shows an indication of RT values for all the receivers in the theatre. It needs to be noted that the values represented are averages extracted from three methods, and the whole frequency range. Reverberation varies from 0.31 to 1.08s, although most of the values are around 0.5-0.8s. The simulation results from Chapters 9 and 10 indicate the RT30 at around 0.3s, although with no stage building taken into account.

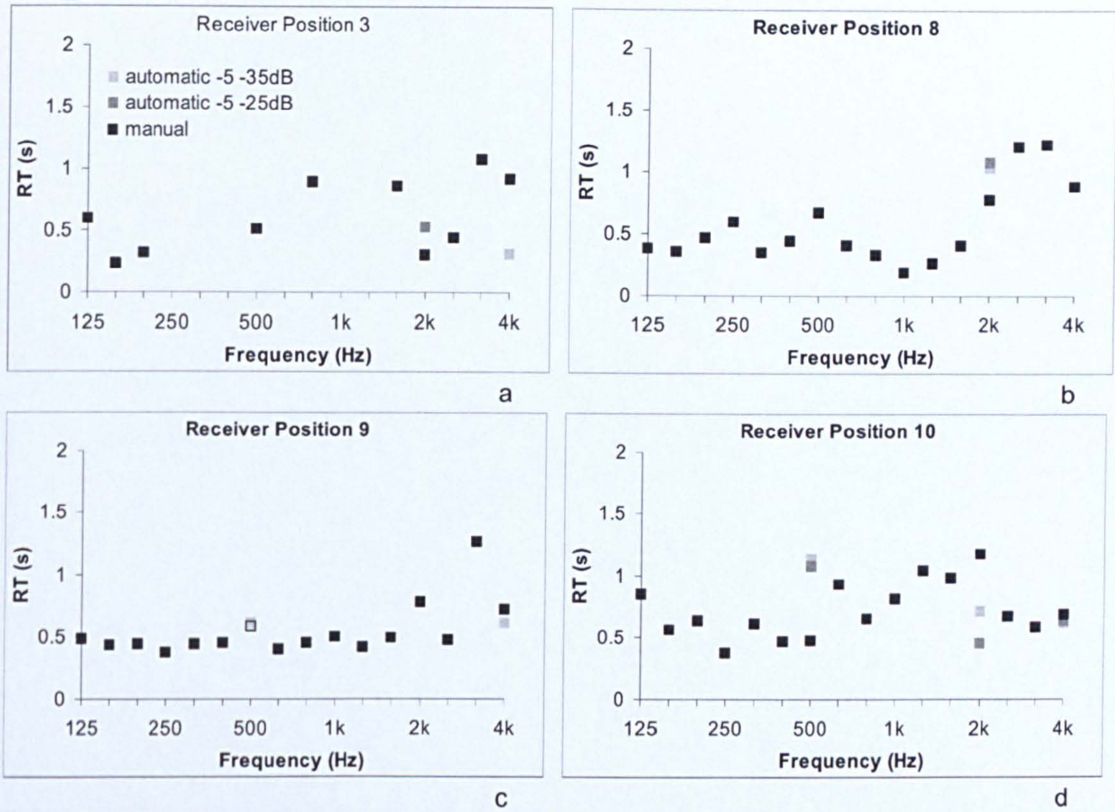


Figure 8.4.15. Reverberation at four receiver positions with three methods of analysis. a) Receiver position 3, b) Receiver position 8, c) Receiver position 9, and d) Receiver position 10.

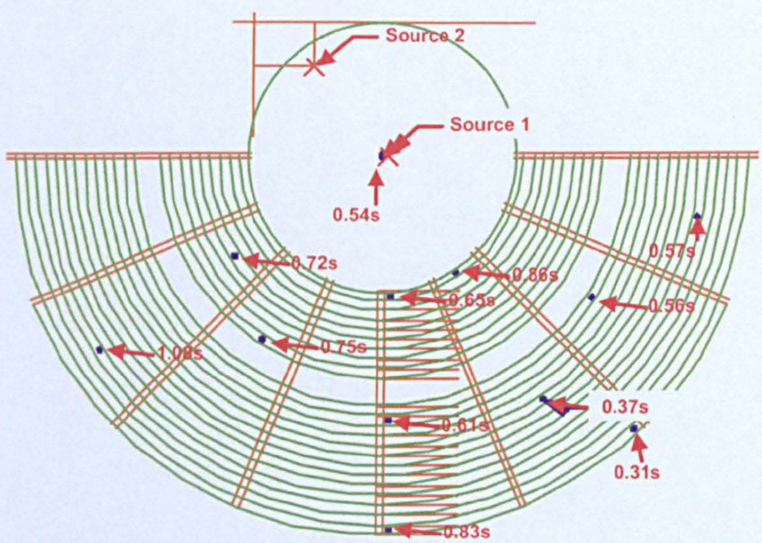


Figure 8.4.16. Average RT values from all methods and the frequency range for Receivers 1-12.

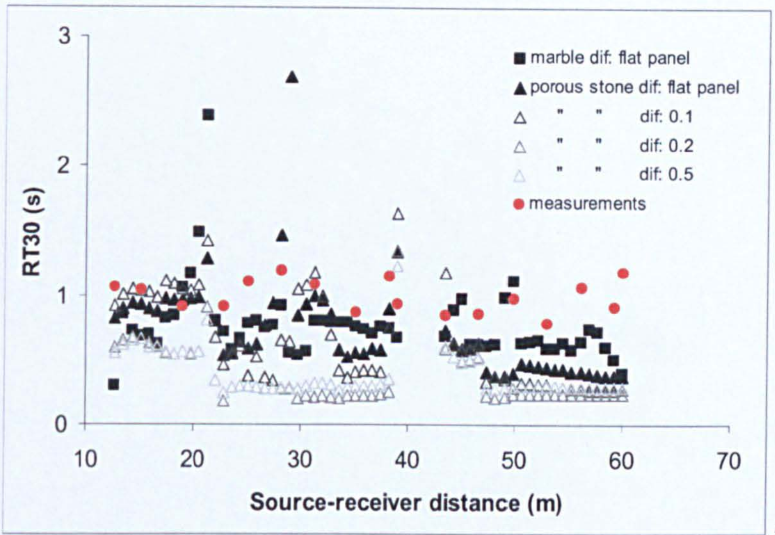
8.5 Acoustic Simulation of the Theatre of Epidaurus and Comparison with Measurements

This section presents a series of simulation results of the theatre of Epidaurus, to allow evaluation of the acoustic environment and comparison with measurement results [Chourmouziadou and Kang, 2006a]. In order for the theatre to be represented as accurately as possible, an application was submitted to the Committee of Restoration of the Monuments of Epidaurus to obtain the original drawings created by Von Gerkan, when the theatre was excavated, and his proposal for restoration, which was recently completed. In this way the 3D representation of the theatre is based on three centres, instead of one, as discussed in Section 8.2.2.1 [Dinsmoor, 1950]. Due to the discrepancy on the koilon's inclination found in several references, which was briefly discussed in Section 8.2.2.2, it is represented in two ways, with 26° angle for both the theatron and epitheatron and with 23° and 27° respectively. The representation of the theatre was simplified according to Section 5.3, while the risers of the koilon were represented both vertically and with an imperceptible backward inclination, following previous suggestions that the risers were inclined by almost 10° [Vassilantonopoulos and Mourjopoulos, 2003].

As mentioned before, the theatre of Epidaurus was constructed by porous stone, with the exception of the base of the skene-building, which was made of marble. According to measurements carried out for identifying the absorption coefficients of porous stone in Section 8.3, 0.01 at 125 and 250Hz, 0.052 at 500Hz, 0.071 at 1kHz, 0.087 at 2kHz and 0.085 at 4kHz will be used. For comparison, marble absorption has also been simulated (0.01 for the frequency range). However, the exact values of the diffusion coefficient have not been identified yet, thus diffusion coefficients of 0.1, 0.2, 0.5, 1 and flat panel, at 0.3 at 125Hz, 0.2 at 250Hz, 0.15 at 500Hz, 0.1 at 1kHz, 0.09 at 2kHz and 0.07 at 4kHz have been used. This allows a validation of the simulation procedure, as also discussed in Chapter 6.

8.5.1 Inclination of 26° with Vertical Risers

Figure 8.5.1a illustrates the RT30 results at 500Hz for the simulation of the theatre of Epidaurus with vertical koilon risers and one inclination, of 26° as discussed in Section 8.2.2.2. It can clearly be seen that the results that agree reasonably well with the measurements are retrieved when the theatre is simulated with marble or porous stone and flat panel diffusion (0.15 at 500Hz). For the former the average difference between the simulation and the measurements is 0.30s (30%), and for the latter 0.34s (35%), whereas for diffusion of 0.1, 0.2 and 0.5 the average differences are 0.6s, 0.63s and 0.44s respectively (differences of 60, 64 and 44%). Very low diffusion presents similar results mostly near the source, at distances between 11 and 20m. If no diffusion is applied, the results present very long reverberation, exceeding 5s, which is unrealistic. Thus diffusion coefficients, even very low, must always be applied to the calculations. For 1kHz the absorption coefficients of marble approach the measurement values when the diffusion coefficients are either for flat panel (0.1 at 1kHz) or for 0.5.



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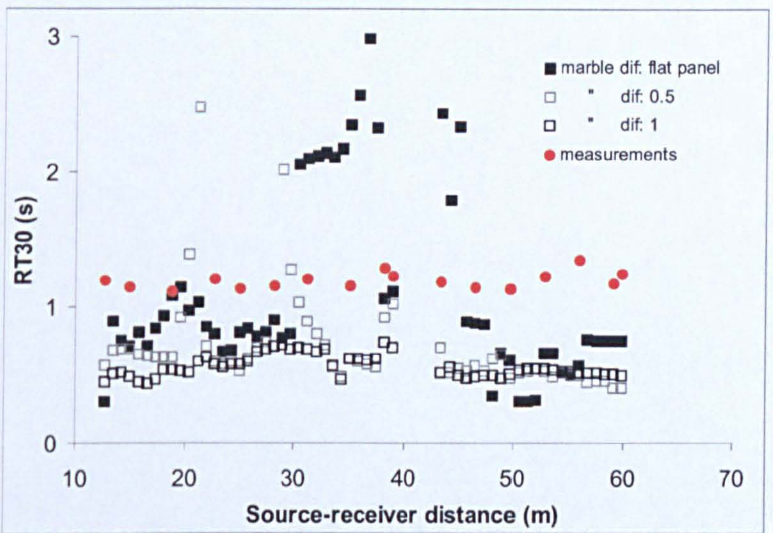

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Figure 8.5.1. *RT30 (s) results for the simulation using several absorption and diffusion coefficients. a) Marble and porous stone for 500Hz and b) Marble for 1kHz.*

In order to compare the simulation and measurement result, Figure 8.5.2 illustrates C80, D50 and SPL for both marble and porous stone with flat panel diffusion. Previous studies have also calculated the same indices for the theatre of Epidaurus and these are discussed in this section. Corresponding to the studies, including measurements and simulations, carried out by Vasilantonopoulos and Mourjopoulos [2004] and Vasilantonopoulos *et al* [2004], the majority of clarity results for the theatre with no scenery are higher than 15dB, at the range of 15 to 24dB, while definition is approaching 100%, at the range of 91 to 99% for most of the receivers. It is noted that there is hardly any difference between the two materials when scenery is not installed, at least for C80 and D50. However, with the scenery for the performance of Electra, as this was described in Section 8.4.1, the C80 is comparatively low, at an average of 15dB with marble koilon and 17 with porous stone. Similarly D50 is 84 and 86% for marble and porous stone respectively.

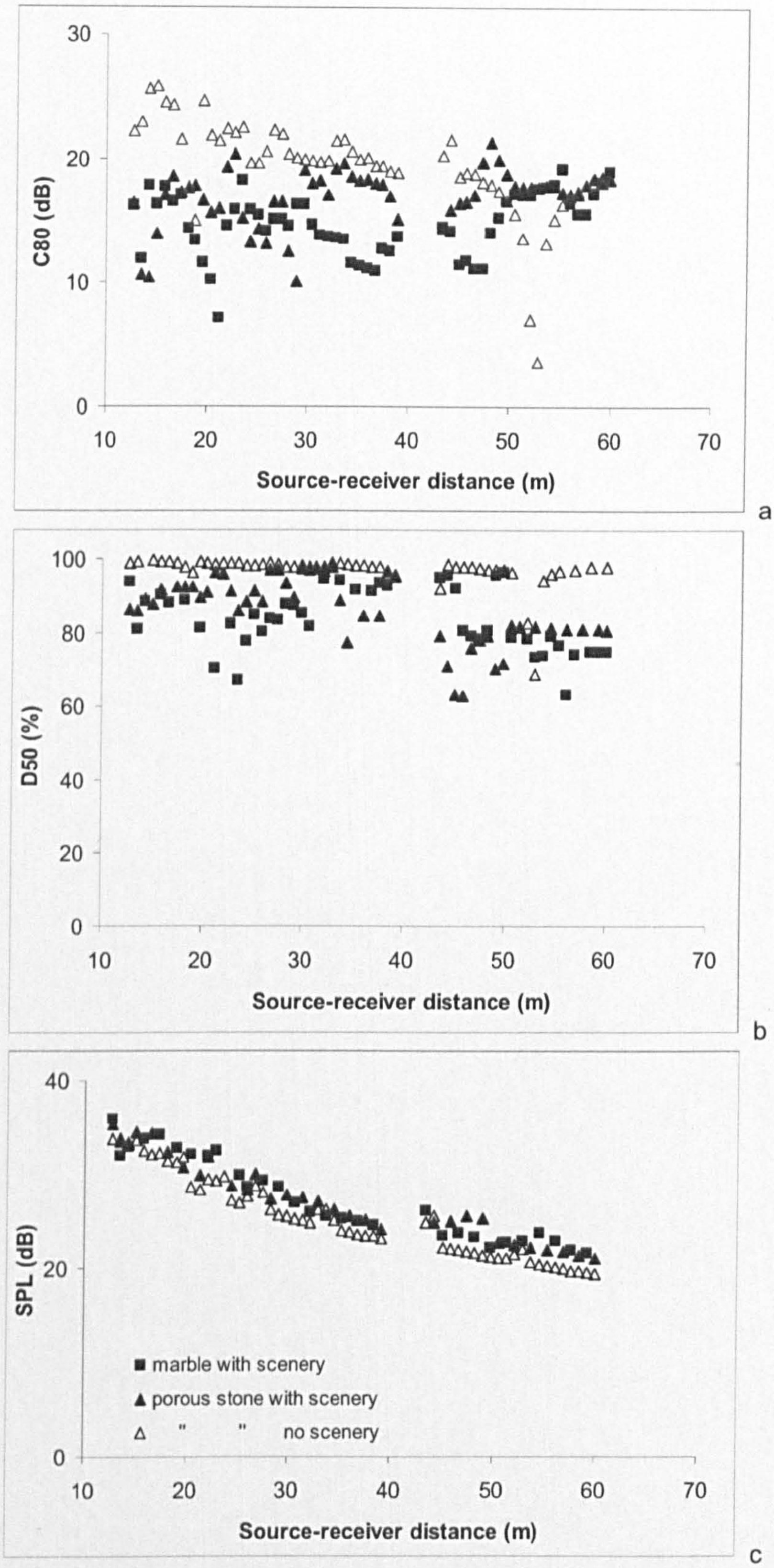


Figure 8.5.2. *Simulation of the theatre of Epidaurus with marble and porous stone and flat panel diffusion. a) C80 (dB), b) D50 (%) and c) SPL (dB).*

The SPL values, shown in Figure 8.5.2c, start at around 36dB at the first receiver seating at almost 13m from the source, while at 60m it has been deduced to 21.4dB. Thus the deduction is 14.6dB for a sound source emitting 64dB at 500Hz, while there is already a reduction of 28 and 43.6dB for the first and last row respectively due to the source-receiver distance. When there is no scenery in the theatre the SPL reduction due to the source-receiver distance is 30dB and 40.6dB for the first and last row. For a source emitting 105dB, the SPL for the measurements carried out by Vasilantonoloulos *et al* [2004] showed that the reduction was 25dB for the first receiver and a further 20dB for the last, indicating a disagreement in the values.

8.5.2 INCLINATION OF 26° WITH INCLINED RISERS

Further simulation has been carried out for the slightly inclined risers of the koilon, of about 2°, with marble absorption coefficients. Flat panel diffusion coefficients are used, since their values are the most appropriate, as shown in Section 8.5.1, adjusted later to match the measurements at: 0.1 for the koilon, 0.2 for the wooden stick of the scenery and 0.05 for the flat plywood of the scenery presented Figure 8.4.1.

Figure 8.5.3 shows the RT30 values. For flat panel diffusion the maximum difference between the flat panel and the measurements is 0.49s at selected receiver points, at distances of about 28m from the source, while the minimum is 0.024s, which is hardly noticeable, and the average difference is 0.25s, thus 26%. Overall, although the values fluctuate considerably, they tend to maintain the same overall range as the measurements. Readjusting diffusion has not particularly altered the results, although it provides slightly decreased average values, at 0.75s, with differences between simulation and measurement at 23%. By comparing the present 3D representation of the theatre, namely with the inclined risers, with the vertical, discussed in Section 8.5.1, it is noted that difference between the former and the measurement are smaller. Therefore in terms of reverberation, the slightly tilted risers combined with a same inclination of the low and upper part of the koilon agree better with measurements.

Figure 8.5.4 compares the source signal and the decay curve produced by dBBATI32 with the impulse response retrieved from the acoustic simulation, for a receiver seating on the 4th row of the low part of the koilon. Figure 8.5.4a shows a clear decay of the signal with a time scale of 3s, with multiple reflections from the scenery and the koilon surfaces. Analysed by the software, the decay curve with the same time scale in Figure 8.5.4b produces RT at around 1.5s. Similarly, the energy response in Figure 8.5.4c illustrates that Raynoise also calculates a lot of specular and diffuse reflections that reach the receiver until 500ms after the direct sound. Hence, it can be clearly seen that the tendency regarding the decay in the measurements matches the simulated impulse response.

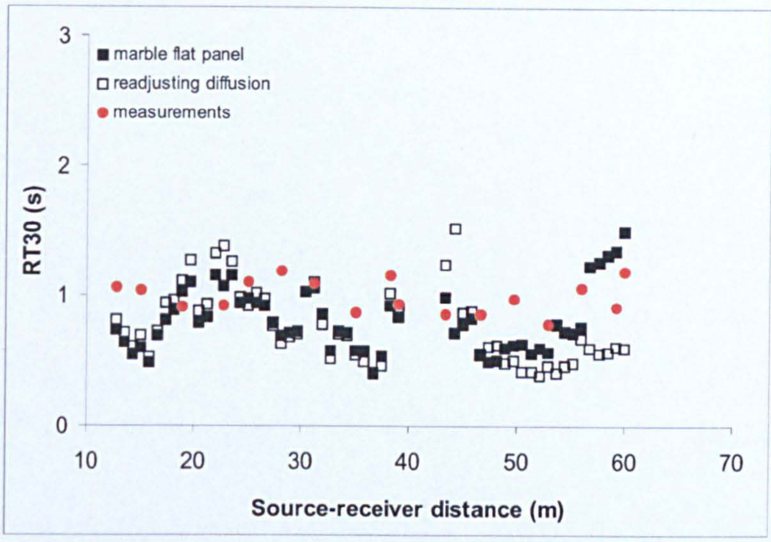


Figure 8.5.3. *RT30 (s) results of simulating the theatre of Epidaurus with inclined koilon risers and 26° inclination for the whole koilon.*

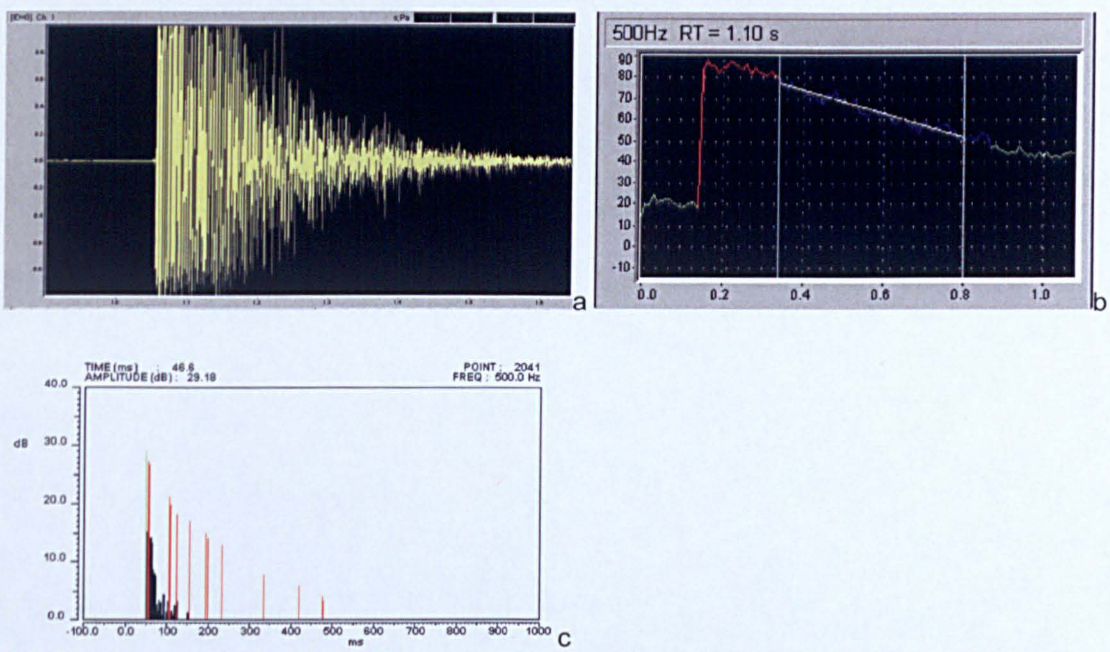


Figure 8.5.4. *dBBATI32 and simulation analysis for a receiver seating at around 15m from the source. a) Source signal, b) Decay and c) Energy response.*

Comparison has been also made between calculation and measurements at low and high frequencies. Figure 8.5.5 illustrates the RT30 results, revealing that at low frequencies there is an extremely good agreement, while at 4kHz the simulation tends to underestimate reverberation. To experiment with simulation parameters the flat panel diffusion used in this section (0.07 at 4kHz) has been replaced by either merely specular reflections or by diffusion coefficients of 0.02, and 0.5 to examine extreme cases. The results have revealed that highly diffusive boundaries, namely with 0.5 diffusion coefficient, lead to a non-reverberant acoustic environment, with reverberation values approaching zero, while the low diffusion or the absence of diffusion, namely 0.02 and 0 respectively, cause RT30 at around 0.15-0.42s at selective receiver points [Chourmouziadou and Kang, 2006a]. Still, comparing the results with measurements shows that more research needs to be carried out in the acoustic software algorithms in the way they handle diffusion. Unfortunately in previous studies concerning the theatre of Epidaurus no mention has been made about high frequency results.

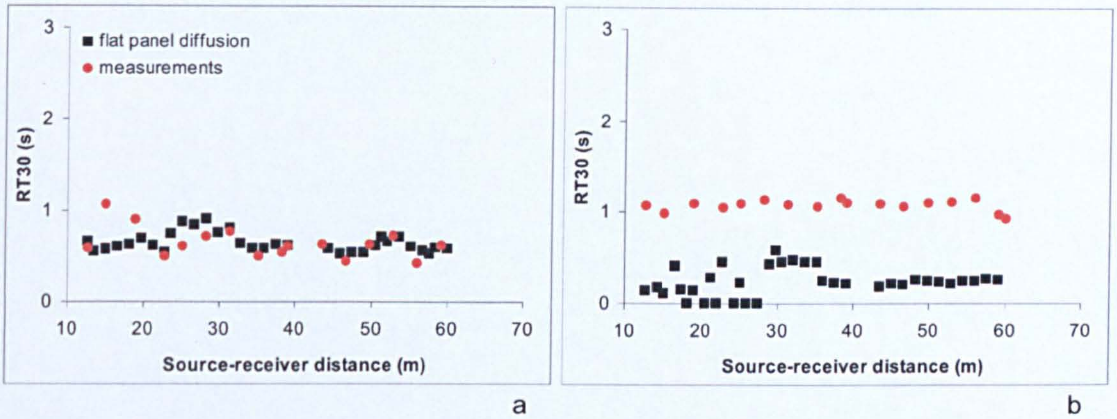


Figure 8.5.5. *Comparison between simulations and measurements for RT30 (s). a) 125Hz and b) 4kHz.*

After the appropriate layout representation and material property conditions have been found for the theatre of Epidaurus, the rest of the acoustic indices can be examined. As this simulation and measurements were carried out with the scenery of 'Electra' installed in the theatre, STI, C80, D50 and LE% can be briefly discussed regarding the theatre with the scenery, and compared with previous research. It is noted that in previous studies, except for Shankland's [1973], the theatre was examined through simulations and measurements without any scenery and for specific frequencies only.

Figure 8.5.6 presents the above indices at 125, 500 and 4kHz. The STI at 500Hz is presented in Figure 8.5.6a. The values are shown in the solid line, at around 0.57-0.76, with an average of 0.68. Since RASTI results in previous research are as high as 80-90% [Vasilantonopoulos *et al*, 2004], it seems that the scenery's presence, which increased reverberation in the theatre, led to a decrease in speech intelligibility. Nevertheless, articulation tests carried out by Shankland [1973] in the theatre, with a temporary wooden platform installed, resulted in scores at the range of 59-90%, with the majority of receivers at around 70-80% [1973]. However, the exact design of the wooden platform was not presented by Shankland, so it cannot be compared with the scenery used in this study. Still, variations of around 0.07-0.1 between different scenery shapes are acceptable. Nevertheless, both Shankland's [1973] and this study reveal that the scenery's presence affects speech intelligibility.

Moreover, clarity, presented in Figure 8.5.6b, is high at the very front of the audience area, at around 15-18dB, reducing towards 30m from the source (at 8.4dB) and reaching the highest levels at the rear of the theatre, at 29dB, as also indicated by Shankland [1973]. This, in relation to the low reverberation, leads to very good conditions for speech. Vasilantonopoulos *et al*

[2004] agree with the above results in terms of values, although with slightly different distribution. Similarly, for definition Figure 8.5.6c shows that the average is 76%. Compared to Vasilantonopoulos *et al* [2004] D50 is decreased by almost 18%, probably due to the increase in reverberation. Finally, there is a variation in the values from one receiver point to the other for the lateral efficiency, as seen in Figure 8.5.6d. The average value is 4.5% at 500Hz and 6% at 125Hz.

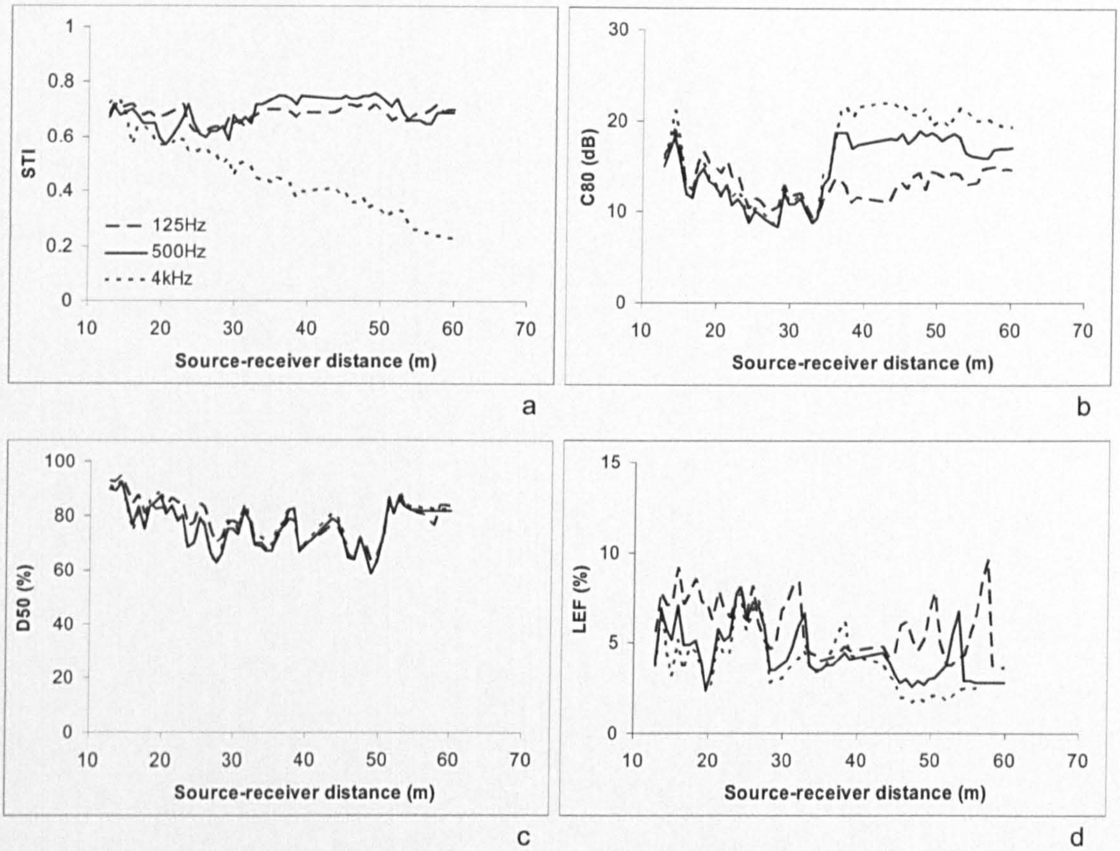


Figure 8.5.6. *Acoustic indices at low, middle and high frequencies. a) STI, b) C80 (dB), c) D50 (%) and d) LEF (%).*

8.5.3 Inclination of 23° and 27° with Inclined Risers

The two inclinations of the koilon, namely 23° for the low part (theatron) and 27° for the high part (epitheatron) that allow more reflections and better view for the audience seating far from the source, as indicated in previous studies and discussed in Section 8.2.2.2, have also been simulated and compared with the measurements. Flat panel diffusion coefficients as well as 0.15 for the rough soil of the orchestra, 0.1 for the koilon, 0.5 for the wooden sticks and 0.1 for the smooth plywood of the scenery are used. Also, for the sake of comparison, a simulation was carried out with only geometrically reflective surfaces. Figure 8.5.7 presents the RT30 values for all cases at 500Hz revealing that the simulation hardly matches the measurements. This can be the result of the inclined koilon risers, which, in addition to the two inclinations, direct the reflection to the sky, thus produce short reverberation values. Compared to Sections 8.5.1 and 8.5.2, and Figures 8.5.1a and 8.5.3 respectively, that simulate the theatre with one only one inclination of 26°, the simulation results in this section differ significantly from the measurements and thus cannot be considered valid for the theatre.

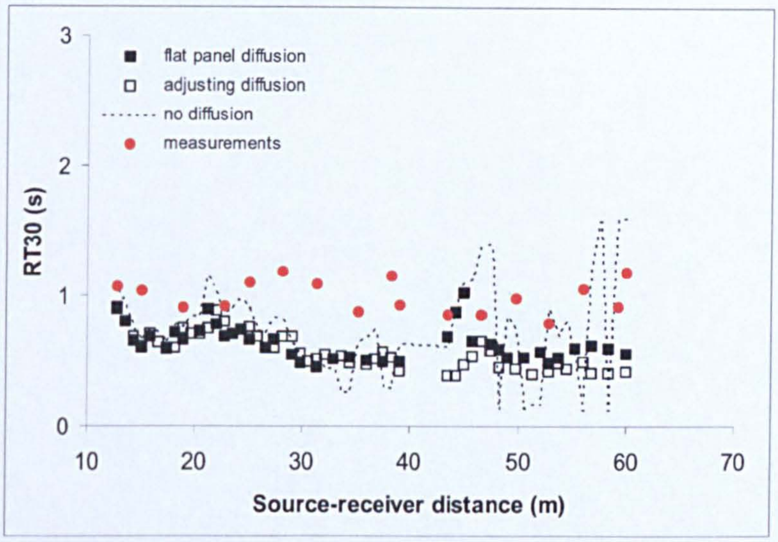
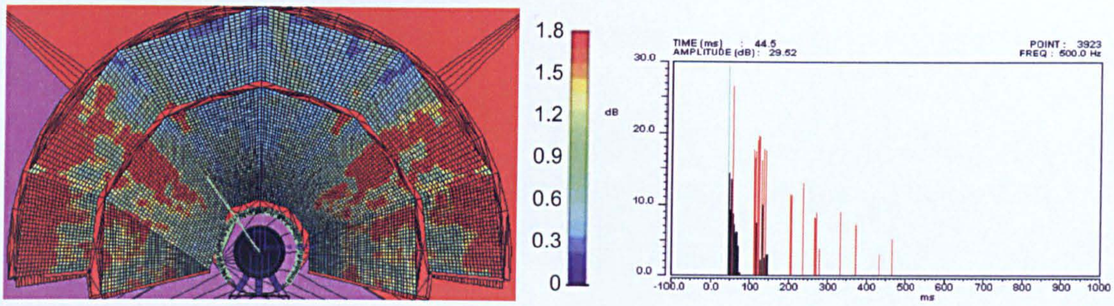


Figure 8.5.7. *RT30 (s) of the theatre of Epidaurus with inclined koilon risers and 23° inclination for the theatron and 27° for the epitheatron.*

8.5.4 Analysis of the Acoustic Characteristics of the Theatre

As mentioned in Shankland's [1973] paper on the acoustics of Greek theatres and especially Epidaurus, the unique layout of the theatre, including many refinements in design and construction such as the bowl-shaped auditorium, in relation to the excellent condition after its restoration, lead to excellent acoustic conditions for theatre and speech. Previous studies have focused on the effectiveness of the early reflections provided by the koilon risers, the orchestra floor and the skene-building [Chourmouziadou and Kang, 2002] as well as the multiple reflections between the theatre sides, which are almost parallel extensions of the theatre semicircle. These result in long reverberation times at these areas, as will be illustrated in Figure 8.5.8 that presents the colour map of the theatre of Epidaurus with one inclination of 26°, illustrating RT30 and impulse response. It can be seen in the colour map that, for the areas at the sides, the unoccupied condition reveals long RT30 values, around 1.7s, due to multiple reflections between the opposite seating areas, in contrast with the middle part of the koilon, where RT30 is between 0.65 and 1s. This is obviously reinforced by the reflections from the temporary scenery. Figure 8.5.8b shows the reflections a point at the sides of the koilon receives, indicating a decay that leads to comparatively long reverberation. It is noted that most of the studies have also commented on the fact that sound is not appropriately distributed to the area immediately after the diazoma, the first rows in the epitheatron [Chourmouziadou and Kang, 2002; Shankland, 1973].



a b

Figure 8.5.8. *The theatre of Epidaurus with temporary scenery. a) RT30 (s) colour map and b) Impulse response for a receiver at the sides of the koilon.*

It has also been noted in previous studies that with the presence of the skene-building the acoustic conditions in Epidaurus are adversely affected, because of late reflections [Vasilantonopoulos and Mourjopoulos, 2003]. The prerequisite for this observation is that the skene-building is at exactly the same position as in antiquity, at the tangent of the orchestra, and that the actor is located at the centre of the orchestra. Also, since reverberation is increased by the presence of the stage building, it is expected that speech intelligibility, clarity and definition will be affected. However, the advantage of the scenery's presence, not particularly in the shape or position of the ancient skene-building, is that it especially increases intimacy, which, in the case of drama, definitely balances the reduction in STI.

From the above simulation and measurement analysis it is assumed that temporary scenery affects the acoustic indices significantly and in particular reverberation. Although it is common understanding that ancient Greek theatres are non-reverberant fields, due to the open layout and the absence of a background boundary, this chapter shows that temporary scenery can produce relatively long reverberation. Still, it should be indicated that the perception of reverberation outdoors is different from indoors. Contemporary performances count on temporary scenery designs. Hence, the form of the scenery created for each performance can influence the acoustics of open-air theatres accordingly. This will be the subject of Chapters 9 and 10.

8.6 Analysis of Subjective evaluation – Theatre of Epidaurus

The research on the acoustics of ancient performance spaces, especially of the Classic and Hellenistic times, has to be carried out in consideration of the performance itself, as also discussed in Section 5.5. This section discusses the subjective evaluations carried out in summer 2003, in relation to the measurements analysed in Section 8.4.1. The surveys were designed in the form of the questionnaire presented in Table 5.8, for two performances, where the viewers were asked to characterise the acoustics in the ancient theatre in terms of SPL, reverberation, speech intelligibility and echo presence. Previously, the participants had been presented with the basic theory of sound and its application to open-air theatres, to be acquainted with the basic acoustic indices and their meaning in terms of perception [Chourmouziadou, 2003].

The two performances, the subjective surveys were designed for, were a tragedy and a comedy, part of the Festival of Epidaurus. At the same time the author attended the "Intensive Summer Course on the Study and Performance of Ancient Greek Drama", which was held in Epidaurus on 6-20 July 2003, organised by the European Network of Research and Documentation of Performances of Ancient Greek Drama, in collaboration with the Department of Theatrical Studies of the University of Athens, to identify the parameters of the performance that can influence theatre acoustics through lectures and personal discussions. The members of the network are institutions and universities from around the world and the lectures were given by academics, in the fields of Classic studies, theatrical studies and Greek literature, with a common aim – the analysis of ancient Greek performances and their adaptations today. Professors and students of *theatrology* (the theoretical analysis of drama/theatre) and linguistics, classicists, directors, performers, stage and costume designers, architects, writers, musicians, translators and archaeologists took part in the course and helped at the execution of the acoustic survey.

8.6.1 Questionnaire Analysis and Discussion

To emphasise on the reverberant nature of the theatre of Epidaurus, although the opposite is rather the widely accepted view, questionnaires were prepared to be distributed and filled in during the rehearsals and performances of 'Thesmophoriazousai' on 11th July 2003 and 'Electra' on 18th July 2003. The latter used the scenery with which measurements were performed, while the former was mainly examined to identify possible differences between the two kinds of performance, namely comedy and tragedy respectively, and compare different seating positions in the theatre. The performances took place at the same time of the year, so no significant differences in terms of environmental and climatic variables occurred. Figure 8.6.1 presents the seating areas for the subjective evaluation during the two performances.

It is noted that no loudspeakers were used in the performances, except for the case of previously recorded music. Also, they were two different performances, with variations in style, attendance and positions in the theatre, hence no direct comparison can be carried out. The group that filled in the questionnaires was composed by non-experts and experts on theory of theatre, as briefly mentioned above. Questions about the scenery and its effect on the acoustics were not used, since there is a tendency to focus on the aesthetics of the performances, which would consequently influence the results on the acoustics.

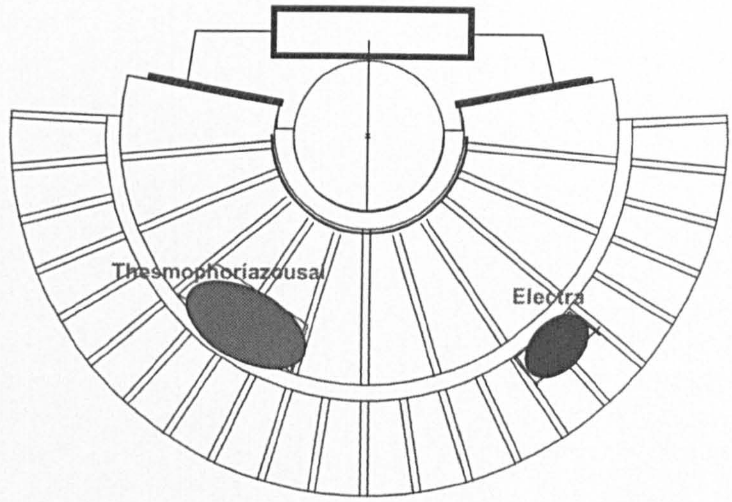


Figure 8.6.1. Plan of the theatre of Epidaurus with the areas where the audience used for the subjective evaluation was seating.

The rehearsals of the performances were also attended. Following the tradition of the Festival of Epidaurus, the theatre was partly occupied during rehearsals, by some local people, the drama studios teams and the course's attendants. Clarity was high, especially when the actors were facing the audience. There were no microphones for the actors or the chorus [Tsianos, 2003]. Instead there was recorded music to accompany the performers while singing. There was some reverberation time, and one could nearly identify the reflection paths from the sides of the koilon, considered the 'weak' parts of the theatre, from the viewpoint of sight lines and acoustics. It is important to consider that since this part was the last to be occupied by audience – the latecomers and some women were seating there [Barron, 1993] – it always provided reflections with relatively short time delays. These reflections and the sceneries used for the performances clearly helped with sound distribution. What also needs mentioning is that the spectator in the theatre of Epidaurus has a general feeling of being in an indoor space from the acoustic viewpoint due to the intimacy the theatre provides, and this was discussed with several members of the course.

8.6.1.1 Performance of 'Electra'

The results on the performance of 'Electra' are first presented in this section, to be compared with previous discussion based on the measurements and simulations presented in Sections 8.4.1 and 8.5 respectively. It is expected that because of the seating area, seen in Figure 8.6.1, and the characteristics of the theatre in terms of acoustics, including the 'good' and 'bad' areas, the responses in 'Electra' will be less positive than at 'Thesmophoriazousai'. The scenery in 'Electra' was designed by G. Patsas, described in Section 8.4.1. It consisted of low box-like scenery at the background, resembling a skene-building, a raised orchestra floor, and a circle of inclined javelins that surrounded the orchestra, as previously seen in Figure 8.4.1. It's worth mentioning that the new orchestra level was smaller in surface area than the original, 12m in diameter instead of 24m. For a frequent visitor of the theatre of Epidaurus the acoustic result of the use of this additional floor level was easily perceived – the actor's voice was clearer and louder compared to the original earth orchestra of the theatre, probably due to the reflection off the new hard surface.

The questionnaires were answered by 17 participants of the course, 12 female and 5 male. There were located at the upper part of the theatre, as shown in Figure 8.6.1. About the actor's sound level 50% of the answers described it as medium, while 36.5% was equally divided into faint and loud, and the remaining 12.5% into very faint and very loud as well. It needs to be noted here that the perception of loudness is subjective, depending on the listener and the actor/source. Reverberation was considered short by 62.5%, which was expected, since the absorption of the audience reaching 14,000 was dominant and, clearly, the overall sound level depended on the direct sound and the reflections off the orchestra, the scenery and the heads of the audience. 82% of the group believed that there were no delayed reflections.

Background noise was highly discussed. It was relatively increased at the beginnings of the play. In general, 29% of the answers suggested a 'noisy' background, which in this case is a very high ratio. Speech intelligibility was considered 'normal', which is a surprise if one considers the effect of the background noise in relation to the seat position. The noise was mostly coming from people changing seats, chattering and laughing, insects, especially cicadas, birds, animals, kids, planes and mobile phones. It is especially noteworthy that during this performance the group was seating closer to the background trees, so the noise coming from cicadas was more noticeable. Still, because cicadas' noise is continuous it is easily acceptable, except for the occasions it covers the sound level of the actor. On the other hand mobile phones were regarded as the most irritating noise, because it is abrupt and intense.

8.6.1.2 PERFORMANCE OF 'THESMOPHORIAZOUSAI'

With reference to the second performance of 'Thesmophoriazousai', which is regarded a very important play, because, like all Aristophane's comedies, gives a lot of information about Euripides and the Athenian festival [Taplin, 2003], the scenery was a representation of the stage building in antiquity, made probably by plasterboard or plywood, and painted in bright colours. The scenery is illustrated in Figure 8.6.2. The gravel and the earth of the orchestra were covered with a plastic membrane. The premiere was attended by 10,000 people, from which 36 filled in the questionnaires. However the rehearsal was also attended, as discussed before.

About the actor's sound level in general, considering that no electroacoustics were used, 50% and 44% suggested that it was high and medium respectively. However, several factors can influence the sound level in ancient drama, like the actor's power level, the number of people performing simultaneously (the chorus), or directors suggestions on how the actors should perform. The most important is the type of drama, loud comedy versus quiet tragic actors. General comments included that: the acoustics depended on the actor's ability, there were different sound power levels from time to time and from different source positions, either on the orchestra or the stage, and sound was reduced when the actor was turning his back to the audience.

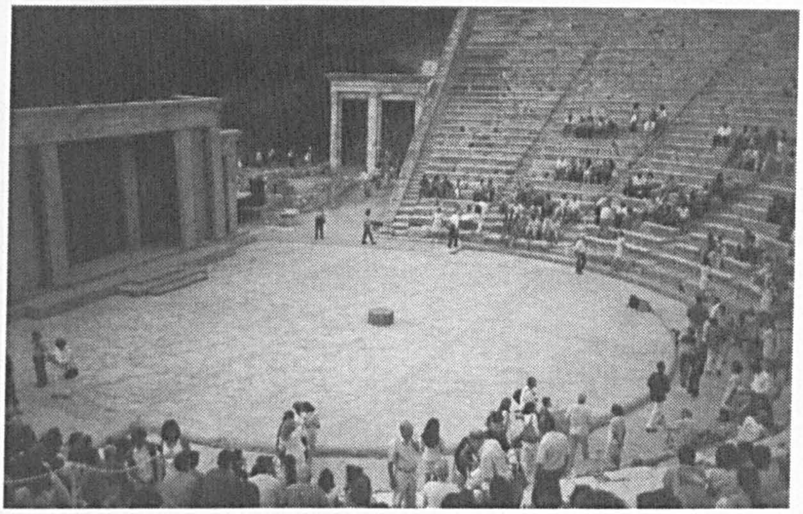


Figure 8.6.2. *Photo from the scenery of the performance of 'Thesmophoriazousai', taken from the seating position shown in Figure 8.6.1.*

For reverberation the opinions were mostly divided between short and medium, at a ratio of 50:44, while there was a viewer suggesting that there was very long reverberation time in the occupied condition. The specific question proved to be rather confusing for them, since four people did not give any answer. Regarding this, 16% believed that there were some delayed reflections. Moreover, the background noise was loud for 19%, medium for 41%, and quiet for 37%, with normal speech intelligibility (46%) as opposed to clear (34%), very clear (11.4%) and confusing (8.6%).

General comments also suggested that there was resonance during rehearsal, it needed more power, the sound was clear, except for specific actors, the production used recorded sound (for music, as previously discussed), which wasn't synchronised with the clear actor's voices. The acoustics were described as good, astonishing, very good as expected for such a theatre, surprisingly good, that they depend on the actor's technique, on the spectators position, and that they were better during the rehearsal.

8.6.2 Discussion on Performances

In general, although no direct comparison can be carried out, it is noted that due to the attendance of each performance, the type of drama and the different seating positions, the acoustic attributes were rather diverse. This short discussion is based on the questionnaires presented in Section 8.6.1.

First of all, the sound level was higher in 'Thesmophoriazousai' than in 'Electra', mainly due to the shorter source-receiver distance. Reverberation was regarded comparatively shorter in 'Electra', since the listener's ratio that identified it was slightly larger (62.5%) than in 'Thesmophoriazousai (53%). Apart from the characteristic of the Greek theatres to be related with shorter reverberation at the upper part of the koilon, as discussed in Section 7.6, the attendance in 'Electra' was greater, while the scenery was also different.

Similarly, the background noise was highly increased during 'Electra'. Although the people that filled in the questionnaires replied almost in the same way to the questions on background noise, there was a great difference in its amplitude. One reason was the increase of the audience by 4,000. Moreover, the background noise in the comedy was due to the audience's reaction. During the tragic play the audience's noise was constant. Also, the cicadas on the trees that surround the theatre were extremely loud in the second case because of the heat and the proximity to the seating area.

8.7 Conclusions

This chapter presented systematic case studies on existing theatres in Greece, extensively used during the summer. It used a variation of research methods, and compared the results. The theatre of Epidaurus was investigated through reverberation time measurements, absorption coefficient measurements, acoustic simulation and subjective evaluation analysis. Also, reverberation time measurements were carried out for the performance space of Knossos and the theatre of Philippi to be compared with simulation results from Chapters 7 and 9 respectively.

The examination of the theatre of Epidaurus revealed refinements in design and construction that led to excellent acoustic conditions for theatre and speech. Early reflections provided by the koilon risers, the orchestra floor and the ancient stage building, as well as multiple reflections between the theatre sides, resulted in relatively long reverberation time. The absorption coefficient of porous stone, a material many ancient theatres, including the theatre of Epidaurus, were built from was measured. The final values for porous stone are: 0.01 for 63, 125 and 250 Hz, 0.052 for 500Hz, 0.071 for 1kHz, 0.87 for 2kHz, 0.085 for 4kHz, and 0.063 for 8kHz. Compared with commonly used hard materials minimum absorption is found at low frequencies, similar to marble, increasing at middle and high frequencies, resembling concrete.

The reverberation of the theatre of Epidaurus was measured and compared with previous studies. The effect of the temporary scenery that was already installed is significant, causing RT30 increase at the range of 0.5-1s compared to the theatre with no scenery. Consequently, since contemporary performances count on temporary scenery design, which influences the acoustics of open-air theatres, the need for investigating their effect arises. Moreover, with appropriately designed scenery, reverberation can be adjusted for other uses of theatre, like music.

The measurement results have also been compared with simulations, which were carried out according to the methodology of Chapters 5 and Chapter 6, with two koilon inclination possibilities and absorption coefficient of porous stone. It was indicated that there is good agreement between the simulation and measurement results of the theatre of Epidaurus, especially when the koilon is represented by one only inclination of 26^{o} and the risers are inclined backwards by almost 2^{o}, according to the original drawings of the theatre and previous references on acoustic evaluation respectively. A variety of absorption coefficients for hard surfaces was considered, including marble and porous stone, as well as flat panel diffusion and extreme cases of high and low diffusion, to get an indication of appropriate material characteristics to be used in the acoustic simulation of open-air theatres. Good agreement was achieved with porous stone (the actual material the theatre was built from) and flat panel diffusion; hence the latter should be selected for the simulations of Chapters 9 and 10 and other studies on ancient Greek theatres, as also indicated in Chapter 6.

The subjective evaluation has also indicated that reverberation is definitely perceived in ancient theatres, as well as background noise. Medium sound levels, depending on the actor's position and ability, short but identifiable reverberation, no delayed reflections, noisy background, and 'normal' speech intelligibility were some of the observations. Sudden and intense noises were more irritating than insects and animals. The uniqueness of the theatre in providing intimacy, regardless of the vast crowd attending, was also indicated.

Furthermore, the on-site measurements of the performance space in Knossos and the theatre of Philippi were presented, as representative examples of the Minoan and the Hellenistic type respectively, revealing that the reverberation is at the range of 0.5s in the former, and 0.5-0.8s in the latter.

CHAPTER 9

PAST, PRESENT AND FUTURE USE OF ANCIENT GREEK THEATRES: THREE CASE STUDIES

9.1 INTRODUCTION

This chapter presents three systematic studies on ancient Greek theatres, particularly on forms that have been recently excavated and have never been examined from the acoustic viewpoint. These theatres were found in northern Greece and were mostly constructions of the Hellenistic times, especially in the years that Fillipos, the father of Alexander the Great, ruled. Because of the importance of these theatres in northern Greece, both in antiquity and today, due to the revival of ancient Greek drama, they are also compared in terms of the performance conditions.

The importance of this chapter lies in the fact that the investigation will provide information on the acoustic characteristics of the theatres, with respect to the individual characteristics, namely layout, overall height, angle in plan and inclination. The uniqueness of each theatre is also related to material use, while the approach taken by the archaeologists and the Boards of Antiquities for their reuse is different in each case. This is a link between the previous hypotheses that hard materials improved the acoustic environment of the theatres of the Classic and the Hellenistic times, in Chapter 7, and the present use of the theatres for the revival of ancient drama, mentioned in Chapters 4 and 8, concentrated on specific cases instead of general layouts, as will be further described in Chapter 10. With the examination of their acoustic environment in antiquity, today and possibly the future, based on restoration proposals, this chapter also aims to connect the original and contemporary conditions of the theatres with their function when using temporary scenery design. The process of adding or transforming temporary scenery, to improve the acoustic conditions is described and examined. Additionally, effects of background noise are taken into account.

The first case study presents the theatre at Mieza. It was selected due to its location, the unique materials, the combination of Greek and Roman characteristics and the interesting restoration proposal. First, a brief review of the historic information about the theatre will be presented, as recorded by the archaeologists and architects that carried out the excavations. It will then illustrate the new proposals for the theatre's restoration. Moreover, the results from a series of acoustic simulations will be discussed, with particular attention to the initial form of the theatre, its present condition and the restoration proposed. Then, several types of sceneries will be applied to the theatre's layout, in order to investigate the acoustic environment that will be appropriate for performances of ancient drama. Purposely designed scenery in the form of an enclosure has also been created especially for the theatre of Mieza.

The second case study presented in this chapter concerns the theatre of Philippi. It is one of the most important theatre buildings of northern Greece, of Hellenistic/Roman type, widely used for the performances of ancient drama during the summer. The position of the theatre next to a motorway formulates the necessity of examining the impact of traffic on the performance, the influence of scenery and the appropriate interventions. The section initiates with a description of the historic information and the process of evolution/development the theatre underwent. Then, the acoustic simulation of the theatre in antiquity and in the present condition is carried out, as well as the application of a carefully designed stage enclosure that reinforces initial reflections. The simulation for the contemporary condition is carried out for an actor performing on the orchestra and for traffic noise.

Furthermore, the third case study involves the investigation of the ancient and present condition of the theatre of Dion and the application of appropriate stage enclosure that reinforces sound and minimises possible deficiencies. The theatre of Dion has been selected due to its strict Hellenistic characteristics, its frequent use, its unique construction method that involved the use of brick, and its relatively small size. First, the information provided by the archaeologists/excavators is presented. Acoustic simulation is carried out both for the ancient and the present condition of the theatre. Purposely-built scenery design is also simulated. According to suggestions provided by the simulation of the theatre of Mieza, complex scenery is created and transformed gradually, to improve reflection patterns and acoustic indices.

9.2 Case Study 1: The Theatre of Mieza

At the eastern part of Naoussa, a city in northern Greece, the ancient city of Mieza is located. A theatre was found there by chance in 1992, situated at the southwest part of Mieza. The excavations between 1993 and 1995 uncovered the orchestra, the skene-building, and the surviving tiers of seats in the koilon. It is considered a small provincial theatre, which, despite its simple construction, was found to be based on a very interesting system of geometric proportions.

9.2.1 Background Information

From the investigations carried out by the archaeologists until 1999, it was suggested that the theatre was probably constructed during the late Hellenistic-early Roman periods, due to the predomination of features connected with Greek theatres. However, at some later phase, after the retaining walls and the parodoi had collapsed, the area of the koilon was reduced to the present asymmetrical shape. Figure 9.2.1 illustrates the present condition of the theatre. In 1997 a research project on its conservation and restoration started by the Aristotle University of Thessaloniki, funded by the Greek Ministry of Culture [Karadedos *et al*, 2001].

Figure 9.2.1. The theatre of Mieza in its present condition [source: http://www.akalanthis.gr/mieza-theatro.htm].

The theatre is facing east, in semicircular shape, extending towards the skene-building. The diameter of the orchestra is 22m, with compact earth ground. Two layers of orchestra were found; the first dating in the initial construction of the theatre, while the second was added during its operation. Close to the centre of the orchestra there was drainage for rainwater. The level of the orchestra was identified by its remains, the proskenion and the entrances near the parodoi. The koilon was formed at the slope of a hill, partly by boasting/digging into the rock, or by backfilling it. There are four ascending staircases, dividing the koilon into five wedge-shaped sections, and the seating rows start immediately off the orchestra. Figures 9.2.2a and b illustrate the plans of the theatre in antiquity and today. It is noted that it wasn't possible for the excavators to identify the number of rows, since from the 8^{th} to the 14^{th} row one can only see the support of the seating system, namely the excavated rock [Karadedos *et al*, 2001]. However, there are indications of 19 rows of seats, constructed by soft porous stone. The present condition reveals an asymmetric theatre, since careful investigation showed that the initial supporting walls were destroyed the replacing later by asymmetric walls that are closely connected with the parodoi.

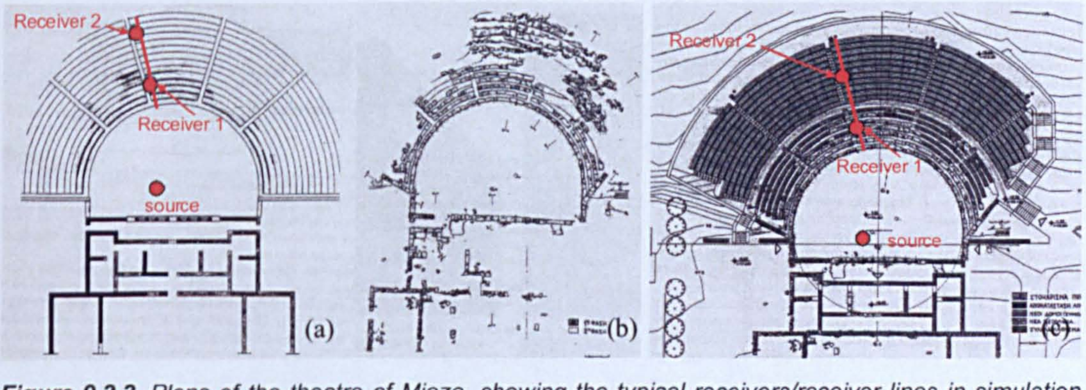


Figure 9.2.2. Plans of the theatre of Mieza, showing the typical receivers/receiver lines in simulation. a) Original condition, b) Present condition and c) Restoration proposal [source: Karadedos et al, 2001].

The skene-building was also built by soft local porous stone. The proskenion and the paraskenia were two-storied structures. Doric columns were decorating the skene-building, coated with lime and marble mortar. The stage building was coloured and had the same coating. Figure 9.2.3 shows a perspective view of the theatre.

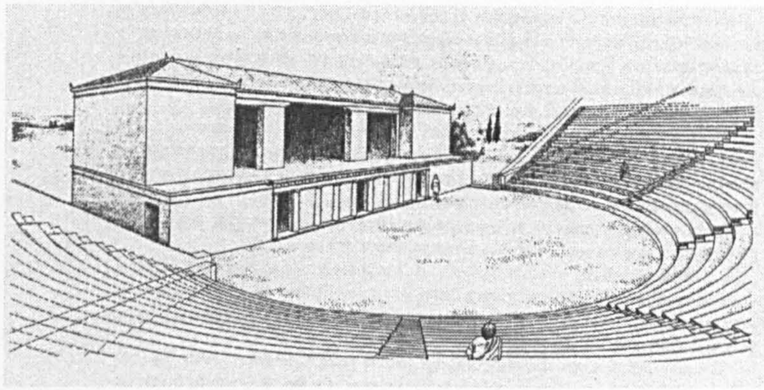


Figure 9.2.3. *Reconstruction of the theatre of Mieza [source: Karadedos et al, 2001].*

9.2.2 Characteristics and Date

The geometric plan of the theatre is exceptionally interesting, since it combines Vitruvius' guidelines for both the Greek and the Roman theatres. In the excavation reports the sequence of planning the theatre is presented in detail [Karadedos *et al*, 2001]. Figure 9.2.4 illustrates the plan of the geometry of the theatre. Karadedos *et al* [2001] suggested that this and possibly many other theatres of that period were carefully designed, after following strict geometric rules. Characteristics of both Hellenistic and Roman theatres are found, as described below.

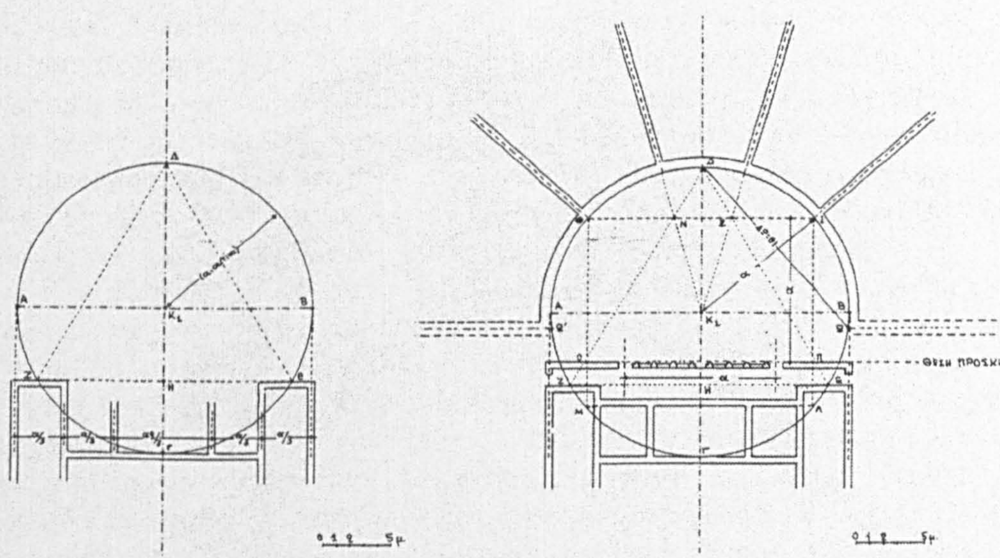


Figure 9.2.4. *Geometric principles in the design of the theatre of Mieza [source:Karadedos et al, 2001].*

Hellenistic type characteristics found in the theatre:

- Proskenion with semi-columns
- Uncovered parodoi
- Lack of ascending staircase at the axis of the theatre
- Koilon, formed on the slope of the hill and
- Lack of raised podium at the low part of the koilon.

Roman type characteristics found in the theatre:

- Geometric planning of the theatre with the use of squares and equilateral triangles
- Parallel supporting walls of the koilon and the parodoi
- Shape of the orchestra, determined by a semi-circumference and the tangents at its ends
- Findings from the excavations and especially pottery.

9.2.3 RESTORATION PRINCIPLES

This section presents the restoration proposal by the archaeologists and Aristotle University of Thessaloniki [Karadedos *et al*, 2001]. It is vital to examine this part because any intervention should incorporate acoustic evaluation in order for the theatre to function appropriately as a performance space. The study of the restoration of the theatre was carried out, due to its importance as a monument, the cultural, educational and tourist function of the area and its location adjacent to a Hellenistic city. It is feasible to use the theatre for contemporary performances, based on the remaining parts, but the necessity to follow a restoration procedure that will balance the needs for its appropriate function without spoiling its characteristics was very important in the project. Authenticity, history, limited and distinguishable additions were the restoration principles proposed by the research team.

The proposed project includes work on the orchestra, the koilon, the stage building and additional structures. The orchestra will be fully excavated and restored, by applying beaten earth, combined with marble sand, in order to avoid mud and unwanted plants appearing. The orchestra will also have a small inclination towards the centre, in order help water drainage, as in antiquity. The koilon will retain its present asymmetric form to avoid extensive work and respect the evolution of the theatre. The seven lower rows of seats will be completed, using the original material found and adding local porous stone with different treatment, to be distinguished from the original. The rest of the koilon will be constructed with prefabricated temporary structures, including a metal structural base and movable wooden seats. The plan of the reconstruction proposal is shown in Figure 9.2.2c.

9.2.4 Acoustic Simulation of Original Condition, Present Condition and Restoration Proposal

As discussed in Chapter 5, the 3D representation of the theatre layout with the use of CAAD software is of great importance. According to the pilot study, the theatre of Mieza has been represented by 24 segments.

The acoustic simulation of the theatre of Mieza involves 3 configurations. It examines the original form of the theatre with approximate material coefficients, either with boundary diffusion applied to the stage building and the orchestra (Configuration 1), or to the whole theatre (Configuration 2), and the form the theatre will get after the restoration proposal is materialised, with the new prefabricated temporary structures, involving a metal base and movable wooden seats (Configuration 3). For the restoration proposal the upper part of the koilon is simulated as wood. The absorption coefficients are shown in Table 9.1. It is noted that for the original form the absorption coefficients are only an approximation.

A parametric study has been carried out regarding the way the upper part of the koilon is simulated, namely the purposely-built lightweight structure. This involved simulating the specific area as wood fixed on the slope, as wooden platform with airspace, as wooden benches with an airspace underneath and inclined earth, and as wooden benches with no earth underneath. Diffraction has also been considered. The results have shown that no particular difference could be found in the acoustic indices, although some fluctuations were observed, especially in the last two cases. The simulations carried out at this stage are for wooden platform, which presented the average and probably the most realistic values.

Table 9.1. *Absorption coefficients used in the simulation.*

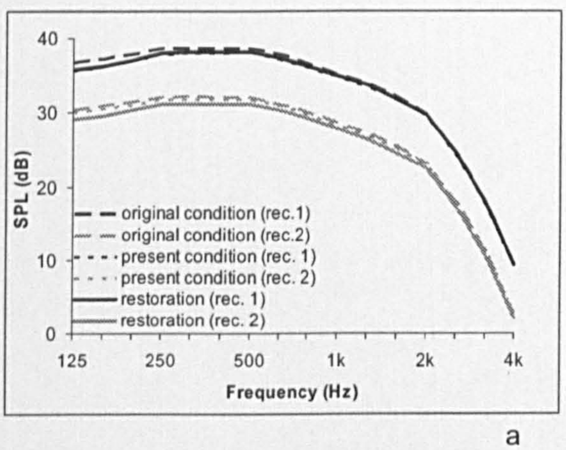
	Frequency (Hz)	**125**	**250**	**500**	**1k**	**2k**	**4k**
Absorption	Porous Stone	0.01	0.01	0.052	0.071	0.087	0.085
	Wooden platform	0.40	0.30	0.20	0.17	0.15	0.10
	Soil (for the orchestra)	0.34	0.55	0.60	0.42	0.55	0.56
	Gravel (for surrounding area)	0.25	0.60	0.65	0.70	0.75	0.80

Flat panel diffusion coefficients are applied, at 0.30 at 125Hz, 0.20 at 250Hz, 0.15 at 500Hz, 0.10 at 1kHz, 0.09 at 2kHz, and 0.07 at 4kHz, according to the methodology in Chapter 6 and the results of Chapter 8. However, the unique present condition of the theatre allowed for further diffusion for the koilon, at 0.50 at 125-250Hz, 0.60 at 500Hz, 0.70 at 1kHz, 0.65 at 2kHz, and 0.60 at 4kHz. The simulation parameters, including number of rays, reflection order, temperature and relative humidity, beam method and frequency range, are selected according to Chapter 5 and previous studies [Chourmouziadou and Kang, 2002; 2003; 2007a]. The source simulates a male actor standing near the centre of the orchestra, at a height of 1.8m, with power level at 62dB at 125Hz, 64dB at 250Hz and 500Hz, 60dB at 1kHz, 55dB at 2kHz and 35dB at 4kHz. No background noise is applied and all simulations are carried out for the unoccupied condition of the theatre.

9.2.4.1 SPL

The results refer to two receivers, situated at different distances from the source, one at the front and one around the middle of the koilon, as shown in Figure 9.2.2. Figure 9.2.5a illustrates the SPL at these receiver positions, for all configurations. For both receivers the effect of additional diffusion in Configuration 2 is a reduction of about 1-2dB in SPL. However, the values in Configuration 3, namely the restoration proposal, are almost identical with Configuration 2 for receiver 1 and lower than the previous two conditions for receiver 2, with a difference of 1dB. The highest differences appear at low frequencies.

Similar results are illustrated in Figure 9.2.5b, for the receiver line shown in Figure 9.2.2, at 500Hz. The results are at the region of 30 to 40dB, the former for the last rows of the theatre. Generally the impact of diffusion in the empty theatre is small in terms of SPL, since it is mostly determined by the direct sound. However, it needs to be mentioned that although the restoration proposal is effective for the receivers close to the orchestra, for receivers that are seated further than 15m from the source the SPL is reduced compared to the original condition. Moreover, the absolute values of SPL are low, due to the use of normal human speech power level. In reality, the actors usually have strong voices, so an addition of 12dB should be considered in SPL, according to Cavanaugh *et al* [1962].



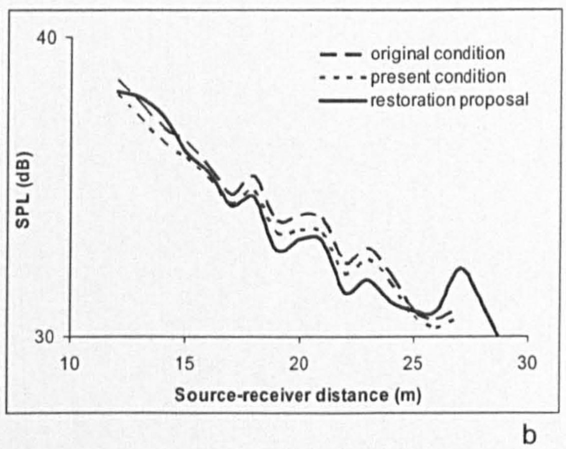


Figure 9.2.5. *SPL at the theatre of Mieza for the original, the present condition and the restoration proposal. a) SPL at the two typical receivers of Figure 9.2.2 for the range of frequencies and b) SPL for the receiver line at 500Hz.*

9.2.4.2 RT30

The results on reverberation demonstrate the effect of the stage building in Configurations 1 and 2. As seen in Figure 9.2.6 the reflections provided by the stage building contribute to longer

RT30 values, compared to the restoration, where the stage building is omitted. The lack of this acoustically and theatrically important structure creates differences to RT30 up to 1s. It is therefore vital for the architects/designers to create appropriate acoustic conditions for each play, using temporary stage design. In Section 9.2.5 and Chapter 10 generic design will be created, in order to study the effect of different styles of scenery on the acoustic environment of the theatre of Mieza. Generally, for the original condition of the theatre, the RT30 for the receivers high at the koilon is longer than for the restoration, due to the multiple reflections between the koilon and the stage. This is a phenomenon that resembles the characteristics of Roman theatres, although in this case it is not a surrounded space, but a Hellenistic theatre type with separate structures, one opposite to the other. Diffusion creates shorter RT30 values, around 0.20-0.30s, as expected. Similar design treatment can recreate the same effect, by providing reflections.

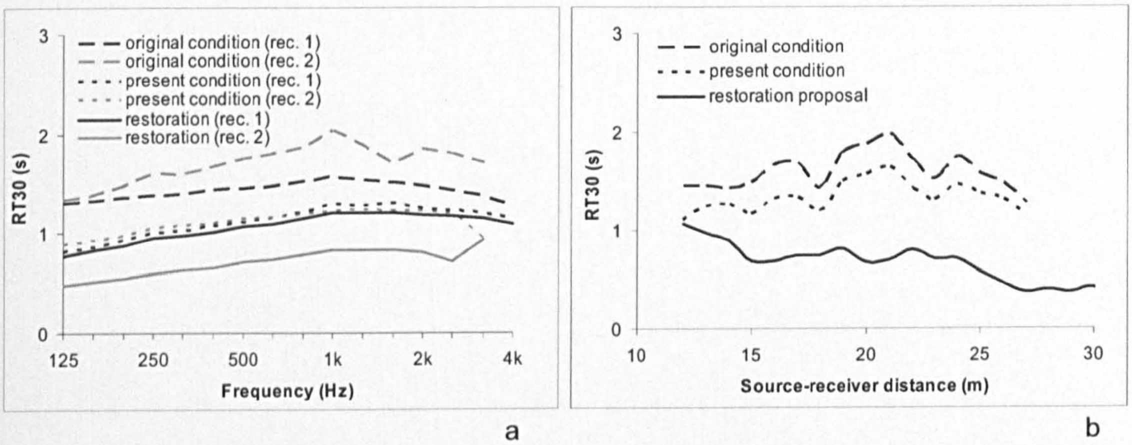


Figure 9.2.6. *RT30 (s). a) For receivers 1 and 2 for the range of frequencies and b) For the receiver line at 500Hz.*

9.2.4.3 STI

Figure 9.2.7 shows the STI for the typical receiver line. Corresponding to RT30 the results of STI show that the restoration proposal, namely Configuration 3, presents the best values, between 0.64-0.84 for the receivers at the upper part and 0.57-0.67 at the low part of the koilon at 500Hz. However, it needs to be noted that no background noise has been applied to the simulations and the results are basically used for comparison.

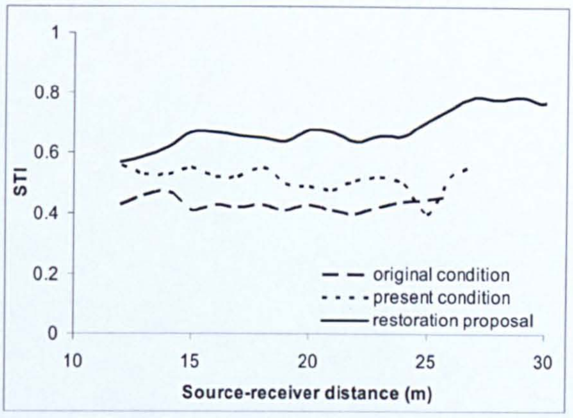


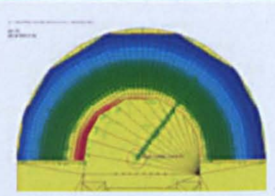
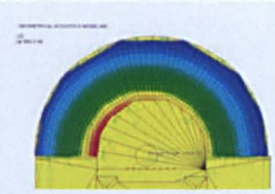
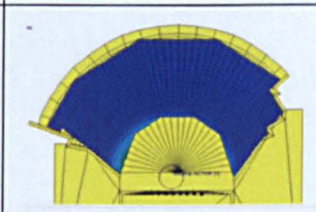
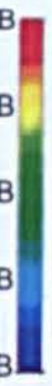
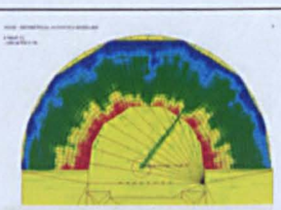
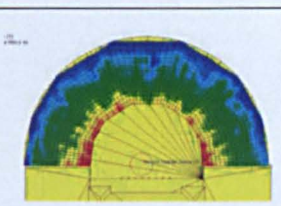
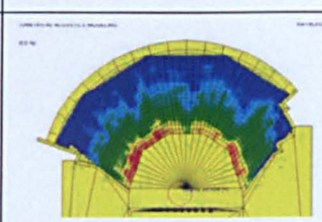
Figure 9.2.7. *STI for the theatre of Mieza for the receiver line.*

9.2.4.4 Colour Maps of other Acoustic Indices and Energy Responses

This section involves the acoustic indices at the three configurations of the theatre of Mieza, especially in the form of colour maps, as well as the energy responses at several receiver positions.

As seen in Table 9.2, especially for D50, which compares the reflections that arrive to the listener's position within 50ms after the direct sound with the total sound energy, the results show that increased diffusion improves the conditions, especially for the sides of the koilon, while the restoration proposal creates an equally advanced acoustic environment for the whole theatre. Similarly, the lateral efficiency (LE), as a measure for the impression of spaciousness, based on the ratio of lateral-arriving reflections to total reflections [Jordan, 1980[41]], suggests that the restoration proposal is successful. However, the lack of symmetry in the new shape of the theatre seems to differentiate the results significantly between the two sides of the theatre.

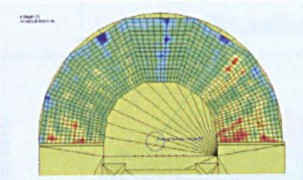
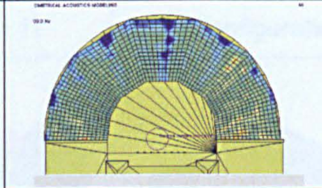
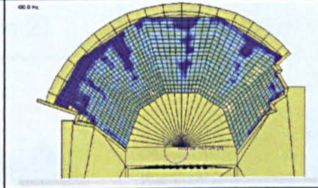
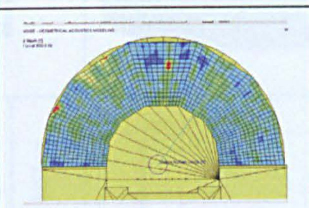
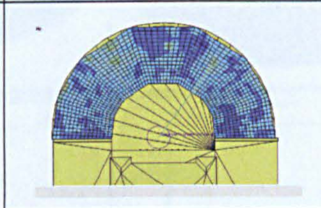
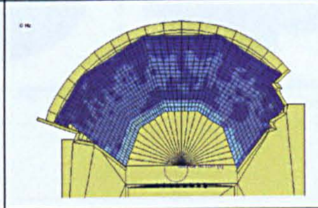
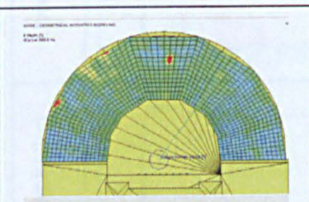
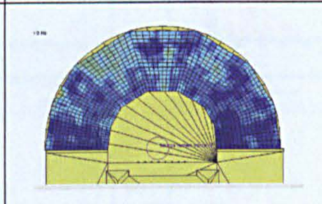
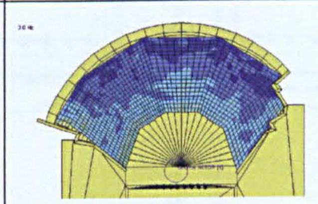
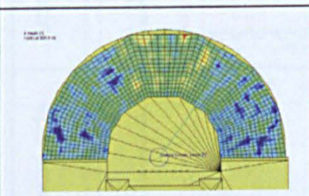
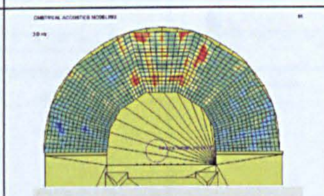
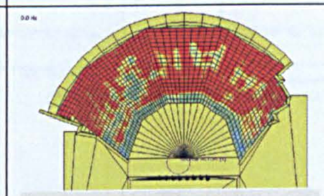
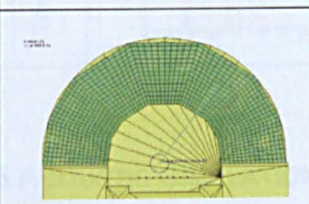
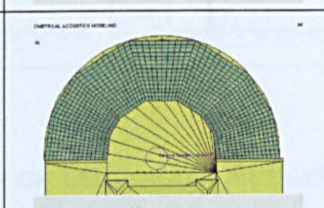
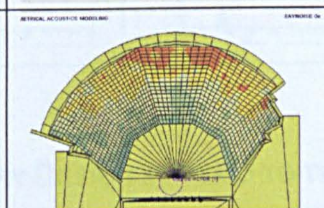
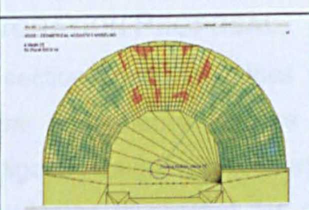
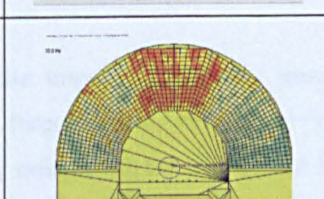
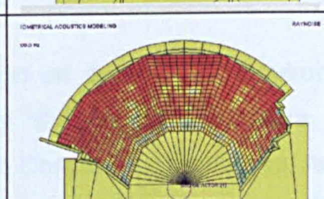
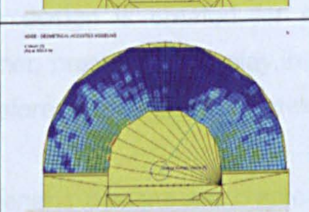
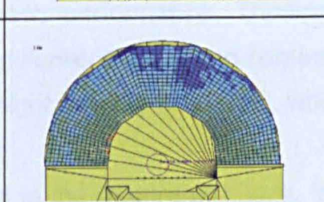
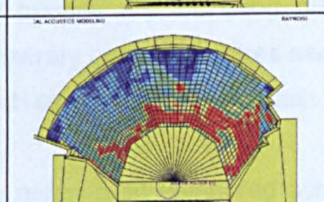
Table 9.2. *Acoustic indices for the three theatre conditions.*

	Original condition (Configuration 1)	**Original with diffusion** (Configuration 2)	**Restoration** (Configuration 3)	**Range**
Direct				 33dB 31dB 29dB 27dB 25dB
SPL				 40dB 38dB 36dB 34dB 32dB 30dB

...continued

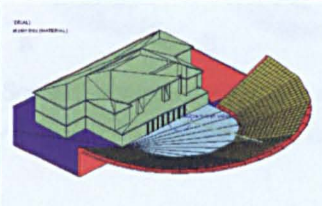
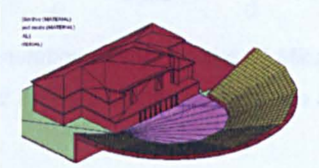
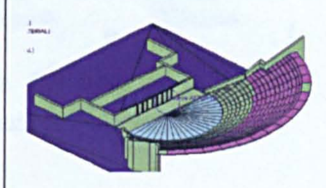
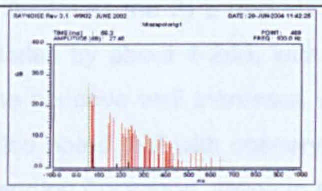
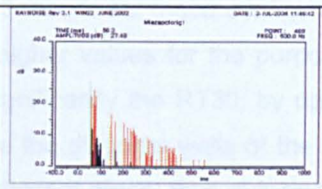
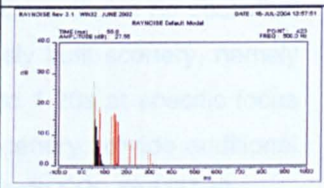
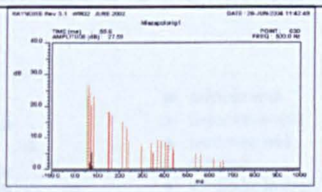
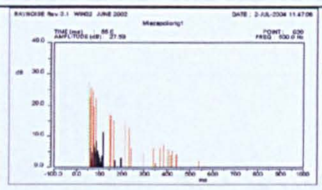
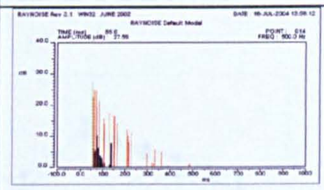
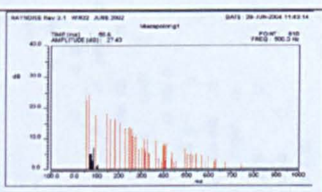
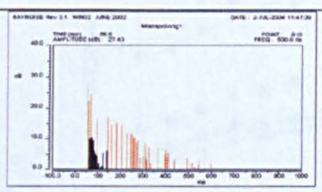
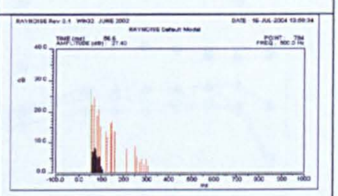
[41] pp. 159, 191

Table 9.2. ...*Continued from page 248.*

	Original condition (Configuration 1)	**Original with diffusion** (Configuration 2)	**Restoration** (Configuration 3)	**Range**
TDSR				10dB 9dB 8dB 7dB 6dB 5dB 4dB 3dB
EDT				4s 3s 2s 1s 0s
RT30				4s 3s 2s 1s 0s
C80				10dB 8dB 6dB 4dB 2dB 0dB
STI				1 0.8 0.6 0.4 0.2 0
D50				100 80 60 40 20 0
LE%				15 12 9 6 3 0

The energy responses at three receivers in the audience area are shown in Table 9.3. As can be seen, the reflections in Configuration 1 last longer than those in the other two configurations, up to 650ms after the direct source, and are also far more in number. This corresponds to the previous results showing the effect of increased diffusion and the stage building, allowing for further research regarding the addition of scenery in the layout of the restoration proposal.

Table 9.3. *Energy responses for the three theatre conditions.*

		Original condition (Configuration 1)	**Original with diffusion** (Configuration 2)	**Restoration** (Configuration 3)
Materials				
Energy responses	Low koilon			
	Upper koilon			
	Theatre side			

9.2.5 Acoustic Simulation of Temporary Scenery Design Applied to the Restoration Proposal

This section briefly examines the impact of scenery design on the acoustic environment of ancient performance spaces through the simulation of the theatre of Mieza. Further investigation on generic scenery design will be carried out in Chapter 10. Nowadays, temporary stage design is created for each performance. Theatre troupes are travelling during the summer, presenting the play in different ancient and contemporary outdoor theatres each week. Therefore, prefabricated, lightweight scenery is created, which can be adopted by each theatre.

Six generic designs are created in the theatre of Mieza, in order to be compared acoustically and provide initial guidelines for further research and design. The sceneries are: (*a*) a linear, (*b*) a concave and (*c*) a convex wall situated in front of the original stage building, 10m high, (*d*) an enclosure in the shape of a quarter of a sphere, with 10m radius, (*e*) a scenery design that has been created by G. Patsas for the performance of 'Ecclesiazousai' in Epidaurus in 1993, which involved walls in *v*-shape, diagonally placed on the orchestra, with different heights

[Patsas, 1995], and (*f*) a purposely-built scenery design, created by the author for the theatre of Mieza based on reflection patterns.

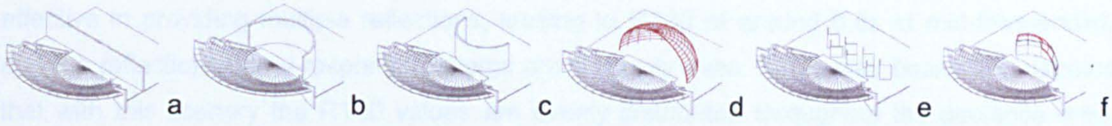
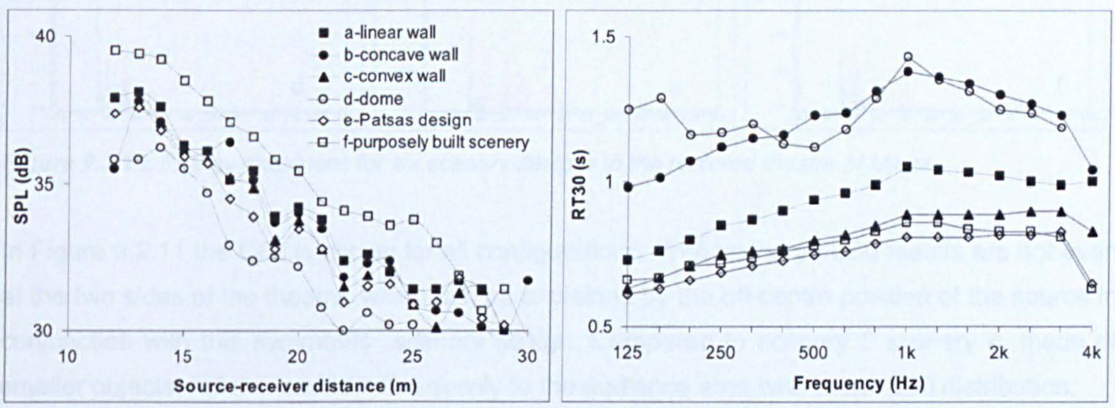


Figure 9.2.8. *Scenery designs used in the simulation of the theatre of Mieza. Sceneries a-d are generic forms, scenery e is designed by G. Patsas, and scenery f is designed by the author.*

Figure 9.2.9 illustrates the SPL and RT30 results for these configurations. It can be seen that SPL differentiates by about 1-2dB, with higher values for the purposely built scenery, namely scenery *f*. The concave wall increases significantly the RT30, by up to 1.20s at specific focus points. It is also noted that with scenery *e* the diagonal walls of the scenery provide additional reflections, sending the sound waves to adjacent areas, thus reducing both SPL and RT30.



a b

Figure 9.2.9. *Acoustic indices for six scenery designs in the restored theatre of Mieza. a) SPL at 500Hz along the receiver line and b) RT30 for receiver 1.*

The SPL at 500Hz along the receiver line and the RT30 at receiver 1 are shown in Figure 9.2.9a and b respectively. The effects of the sceneries on the soundscape of the performance space can be seen. The maximum difference in SPL can be found between scenery *d* and *f*, at 4.2dB. The high values with scenery *f* can be explained by early reflections that are purposely produced, while the low values with scenery *d* are due to its shape that creates focus areas at the centre of the dome, but does not provide many early reflections to the audience area. The same rules apply to scenery *b*, which is also low in SPL. On the other hand, scenery *a* is effective in increasing SPL because it produces multiple reflections, while *c* and *e* scatter sound away from the audience area. It is interesting to note that scenery *f* provides a smooth curve in SPL along the source-receiver distance, suggesting that this scenery distributes reflections evenly to the audience area. In Figure 9.2.10 the energy responses at a point near receiver 1 are shown for the six sceneries, where the reflection patterns can be seen.

Sceneries *b* and *d* produce relatively long RT30, between 1 and 1.50s, but it is noted that this is associated with rather uneven reflection/energy-response patterns (see Figure 9.2.10), which are not preferred in terms of acoustic quality. The simple linear wall, scenery *a*, is rather effective in providing multiple reflections, leading to RT30 of around 0.8s at mid-frequencies, and the reflection/energy-response patterns are relatively even. It has also been demonstrated that with this scenery the RT30 values are evenly distributed throughout the audience area, which is again preferable.

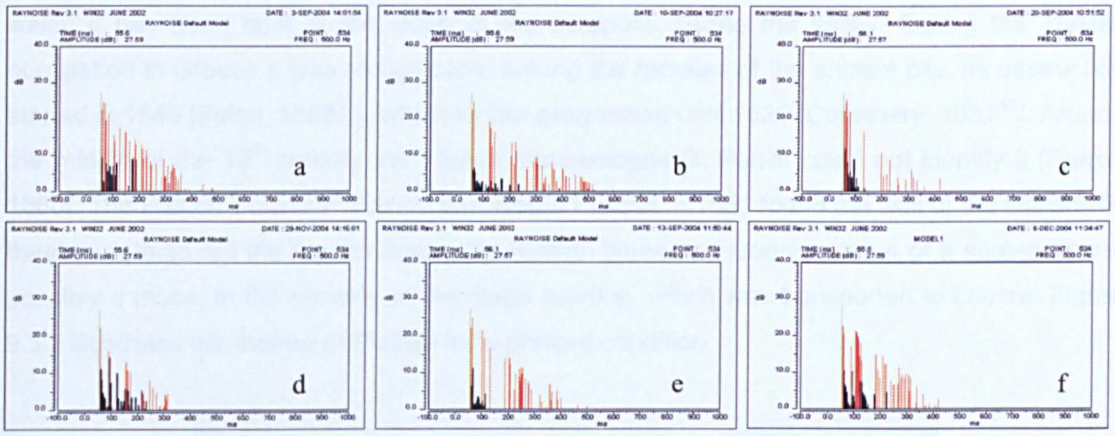


Figure 9.2.10. *Energy responses for six scenery designs in the restored theatre of Mieza.*

In Figure 9.2.11 the C80 is shown for all configurations. With scenery *f* C80 results are not even at the two sides of the theatre, which can be explained by the off-centre position of the source in conjunction with this symmetric scenery design. Compared to scenery *f*, scenery *e*, made of smaller objects, reflects sound more evenly to the audience area with better C80 distribution.

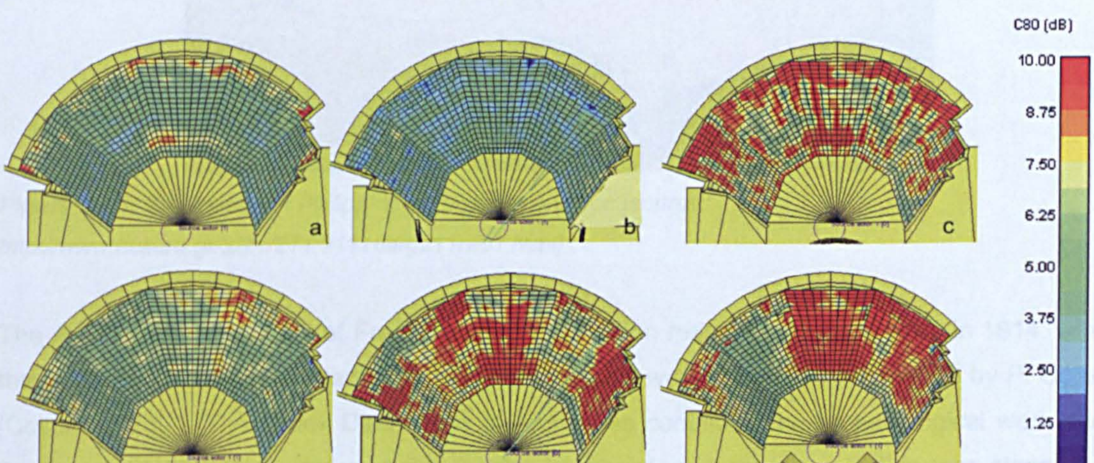


Figure 9.2.11. *Clarity (C80) for six scenery designs in the restored theatre of Mieza.*

Overall, the results in Figures 9.2.9-11 demonstrate that the acoustic indices of the theatre can be significantly improved by strategically designed sceneries, although this section is not aimed to find the optimal design. Moreover, due to the layout of the theatre, no parallel audience areas are created and flutter echoes are avoided.

9.3 Case Study 2: The Theatre of Philippi

9.3.1 Background Information

The theatre is situated at the southeast part of the ancient city of Philippi, adjacent to the east walls. It has been built at the slope of the acropolis, facing the valley. During the Turkish occupation in Greece it was recognisable among the remains of the ancient city. Its destruction started in 1546 [Belon, 1588[42]], which further progressed until 1820 [Cousinery, 1831[43]]. Around the middle of the 19th century the French archaeologist G. Perrot could not identify it [Perrot, 1860]. The French Scientific Mission that visited Philippi in 1861 found the wall of the Hellenistic theatre, pointed out the repairs during the Roman times and found a statue of a seated figure, possibly a muse, in the remains of the stage building, which was transported to Louvre. Figure 9.3.1 illustrates the theatre of Philippi in its present condition.

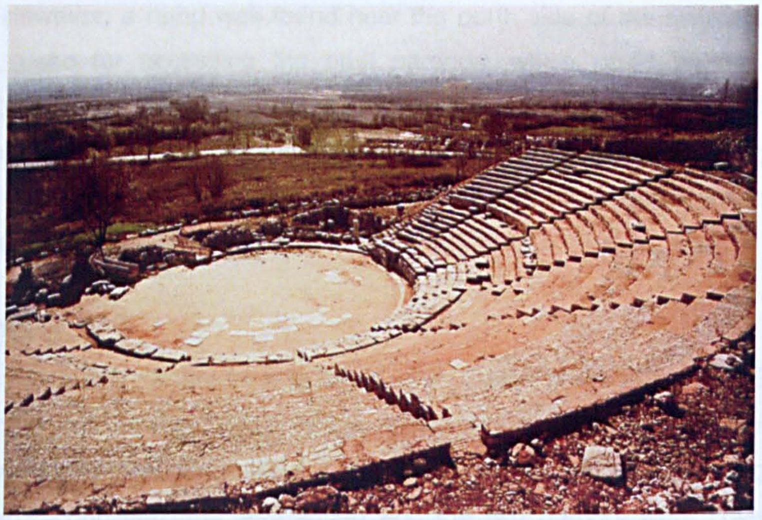


Figure 9.3.1. *The theatre of Philippi in its present condition [source: http://www.culture.gr/2/21/211/21118a/g211ra01.html].*

The Archaeological School of France started excavation research on the theatre in 1914, while the systematic excavation started in 1921. The theatre was first published in 1928 by P. Collart [Collart, 1928[44]]. The Greek Directorate of Antiquities continued the archaeological work after the Second World War, restoring the theatre in a quick and rough way. This was stopped in 1967 and began again in 1974-6, mostly at the upper part of the diazoma. The work focused on the east parodos in 1984-1987, due to structural problems. The excavations that started in

[42] pp. 128-129
[43] pp. 29
[44] pp. 74-124

1994, by the Directorate of Antiquities, in association with the School of Architecture of the Aristotle University of Thessaloniki included the stage building, the parodoi and part of the east wall of the ancient city. The aim was to complete the exposure of the stage building and to connect the theatre with the road network of the city. Another concern was and still is the excavation of the upper part of the koilon, the epitheatron, and the west entrance [Koukouli-Chrysanthaki, 2001].

9.3.2 THEATRE EVOLUTION

9.3.2.1 CREATION

The original theatre is dated around 356 B.C., connected with the founding of Philippi, one of the most important cities in that time in Macedonia, a region in northern Greece, and with Philip the II, father of Alexander the Great [Platon, 1998]. It is a late Classic/early Hellenistic theatre, according to some elements that were revealed through the excavations. These include the retaining walls of the koilon and the parodoi, and the draining canal of the orchestra. There is limited information about that period and nothing was found regarding the stage building. It was either wooden or totally destroyed during the construction of the skene-building during the Roman times. However, a ramp was found near the north side of the staircase of the Roman stage building, used for accessing the east parodos, which could be an indication of a permanent stage building in the early theatre. There are also a large number of carved marble stones found in different spots in the theatre that enforce the existence of a stage. A number of shards, pieces of ancient vases, and coins from the Hellenistic period were found during the excavations of the skene-building of the 2nd century B.C.

9.3.2.2 ROMAN TIMES

The first phase of the Roman theatre was dated by P. Collart in the 2nd century B.C., due to the architectural sculptures of the theatre stage. When Philippi became a Roman colony, the theatre went under major reconstruction. It was then that the monumental stage building was constructed; the second diazoma was added and the two parodoi were covered by vaulted structures. The vaulted passages transferred the load from the retaining walls to reinforced walls. The stage building had three stories at the south and two at the north, in front of the orchestra. It had seven depressions and five doors, which lead to a corridor, parallel to the stage length. Two staircases were leading to the proscenium's level. Corridors parallel to the porodoi were leading to the hyposkenium [Karadedos and Koukouli-Chrysanthaki, 1993]. The south facade of the stage building, facing the city, was a *stoa* (gallery) with seven arched openings.

The second phase of the Roman times, dated in the middle 3rd century A.D. transformed the theatre into an arena. The orchestra level was heightened, the proscenium was destroyed, two rows of honoured seats were taken out, a protective barrier was placed in front of the first seats, and two supporting arches were created at the east retaining wall. Also, the corridor between the facade of the skene-building and the south stoa was covered with soil.

The theatre was abandoned as a performance space around the end of the 4th – beginnings of the 5th century A.D. Then, during the old Christian, Byzantine and Turkish periods in Greece, the stage building, the east parodos and some other parts of the theatre were divided by new stone walls into smaller rooms, used as workshops. Their character was revealed by the findings during the excavations that included vases, other storage objects, stone and stoves. Figure 9.3.2 illustrates the theatre with elements of three periods of transformation and Figure 9.3.3 is a three dimensional view of the theatre in Roman times.

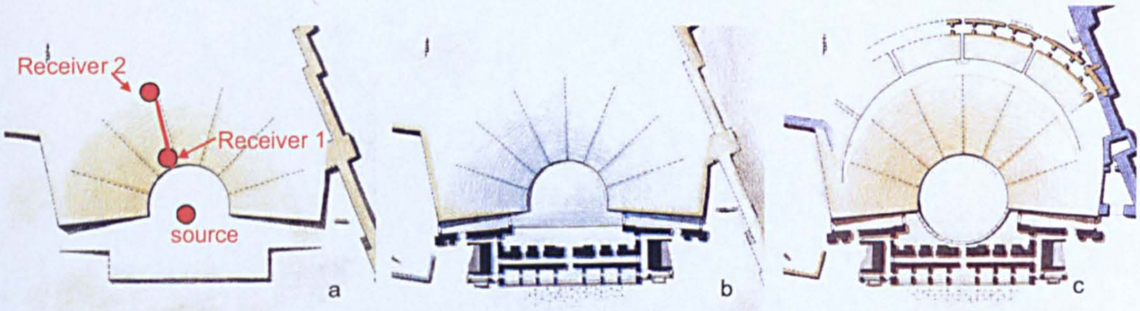


Figure 9.3.2. *Plans of the theatre of Philippi showing the typical receivers and receiver line. a) Late Classic/early Hellenistic period, b) Roman period and c) Post-Roman period.*

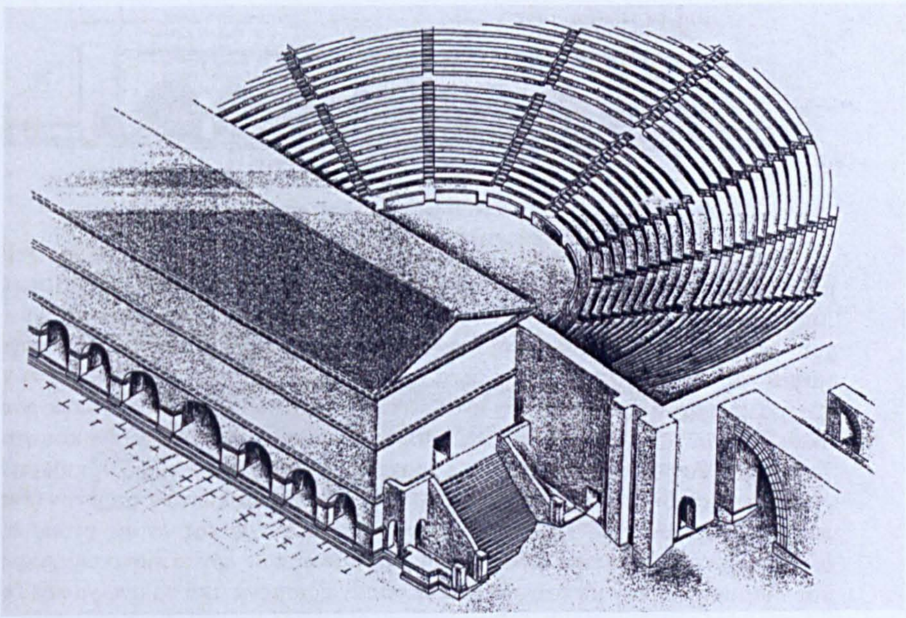


Figure 9.3.3. *Three-dimensional representation of the theatre of Philippi in Roman times [source: Koukouli-Chrysanthaki and Karadedos, 2001].*

Recent research has been carried out regarding the acoustics of the theatre of Philippi in antiquity, the reflection patterns, especially when the actor was situated on and above the stage building, with limited indices presented [Mparkas, 2004; 2006].

9.3.3 Acoustic Simulation

The acoustic simulation of the theatre is based on its present layout, considering two sound sources, a single actor, shown in Figure 9.3.2, and a line source representing the traffic behind the scenery, at around 100m south from the orchestra and almost parallel to the ancient stage building [Koukouli-Chrysanthaki and Karadedos, 2001]. For each source, comparison has been made between the theatre without scenery and the theatre with scenery. The simulation parameters are the same with Section 9.2.4. The scenery design was created in the form of a stage enclosure, with carefully studied reflection patterns, both in the horizontal and vertical directions. Initially, the enclosure consisted of three parts, positioned at the orchestra's perimeter. These were adjusted in length according to reflection patterns and acoustic lines, as shown in Figure 9.3.4 with the blue, yellow and red lines. At the same time, the section of the enclosure was designed, so that the reflection would reach the last receivers. This was accomplished by dividing the height of the enclosure into three parts, occupying 4/8, 3/8 and 1/8 of the total height of the theatre, at around 11m, with inclinations increasing with height. Figure 9.3.4 illustrates the plan and the section of the enclosure.

The material for the koilon is marble with absorption coefficient of 0.01 from 125 to 4k Hz, while the orchestra is made of soil, as illustrated in Table 9.1. Flat panel diffusion coefficients are applied to all surfaces, as previously investigated (Chapter 6). The simulation parameters are based on the investigation presented in Chapter 5 and the source's sound power is the same as in Section 9.2.4.

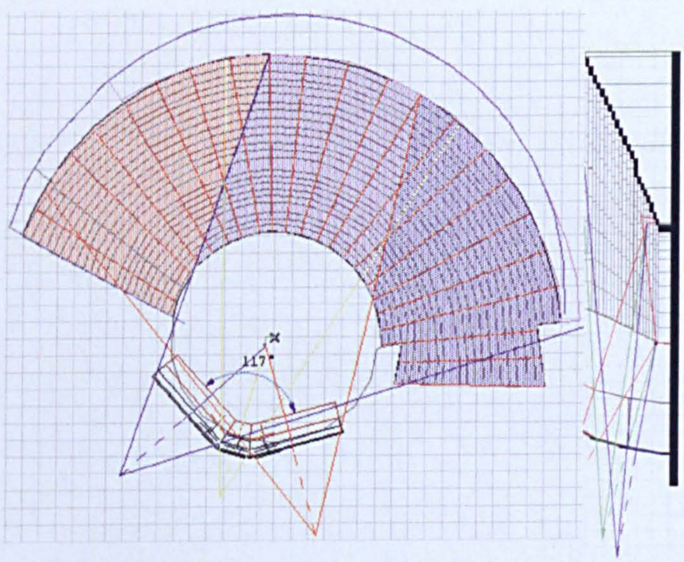


Figure 9.3.4. *Plan and section of the stage enclosure designed for the theatre of Philippi.*

The SPL for the condition of the theatre in antiquity, in particular during the Roman times (since it is the period the remains have provided the information for), in the present condition, and for a purposely-built stage enclosure is presented in Figure 9.3.5a for the receiver line at 500Hz. It can be seen that the enclosure provides high amplitude results, followed by the condition in antiquity. The present condition presents the lowest SPL results, since the great number of reflections from the background area is lost.

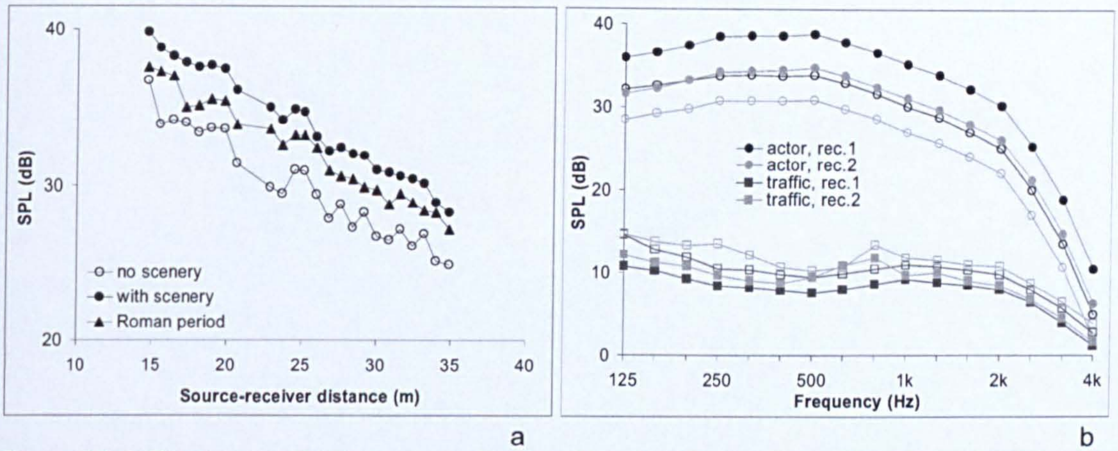


Figure 9.3.5. *The theatre of Philippi in antiquity and today. a) SPL along the receiver line at 500Hz and b) SPL over 125-4k Hz, at receivers 1 and 2. Empty symbols, without scenery; solid symbols, with stage-building/scenery.*

The SPL at two receivers (see Figure 9.3.2a) is presented in Figure 9.3.5b. Correspondingly, the colour maps are illustrated in Figure 9.3.6. It needs to be noted that the levels of traffic noise are for relative comparison between different layouts only, since the absolute sound power levels are unknown. It can be seen that the scenery enhances the actor's SPL by 3-5.5dB and reduces traffic noise by up to 4dB in the audience area. Overall, the strategically located scenery improves the soundscape of the performance space. In Figure 9.3.6 it can be seen that the scenery is more effective for the audience near the axis of the theatre, in terms of the actor source. This is due to the overlapping reflections from the two symmetric sides of the scenery. To make the sound field more even, refined design can be created by adjusting the angle between them or by appropriately positioning panels to provide diffusion.

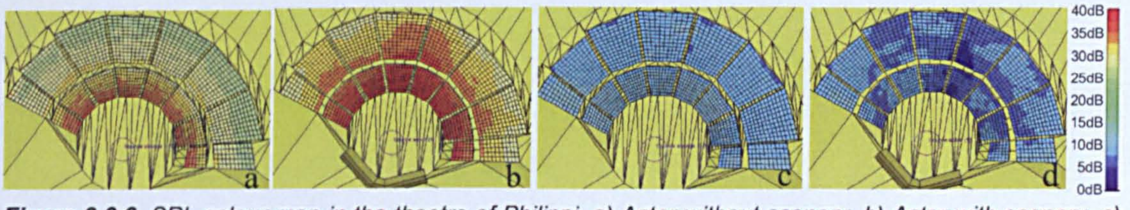


Figure 9.3.6. *SPL colour map in the theatre of Philippi. a) Actor without scenery, b) Actor with scenery, c) Traffic without scenery and d) Traffic with scenery.*

Figure 9.3.7a and b shows the RT30 for the actor source, for both conditions, namely with and without scenery. It is seen that the scenery increases the RT30 from around 0.30 to 1s, due to increased reflections, which can be seen from the energy responses shown in Figure 9.3.8. Moreover, the RT30 is similar at the two receivers across frequencies, suggesting that the scenery is helpful for providing an even reverberation field. The condition in Roman times is characterised by even higher RT30, especially for the upper parts of the koilon. Corresponding to the increase in RT30, STI and D50 shown in Figures 9.3.7c and d respectively, as well as C80 decrease slightly when the scenery or the stage building are added. The variation presented in the STI and D50 curves for the present condition of the theatre with no scenery is mainly caused by the relatively small number of reflections, especially for the higher seating areas in relation to the analysis of Raynoise.

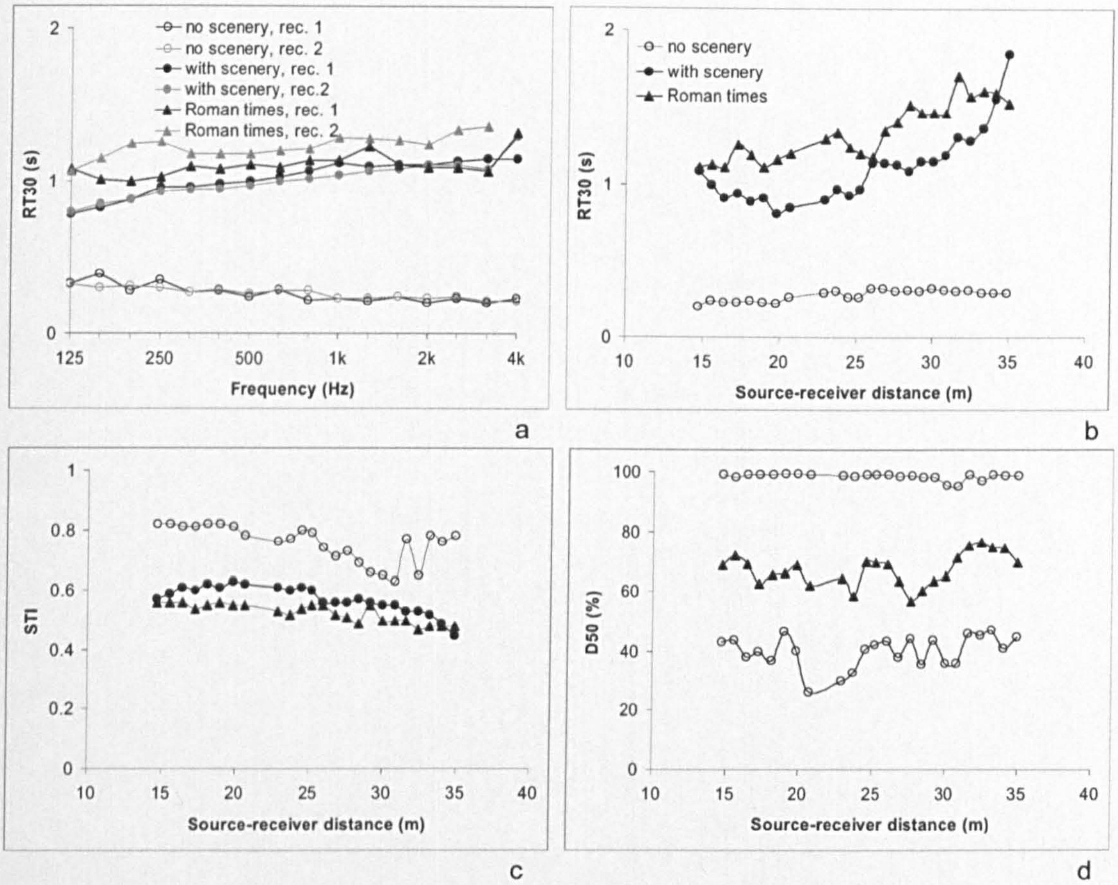
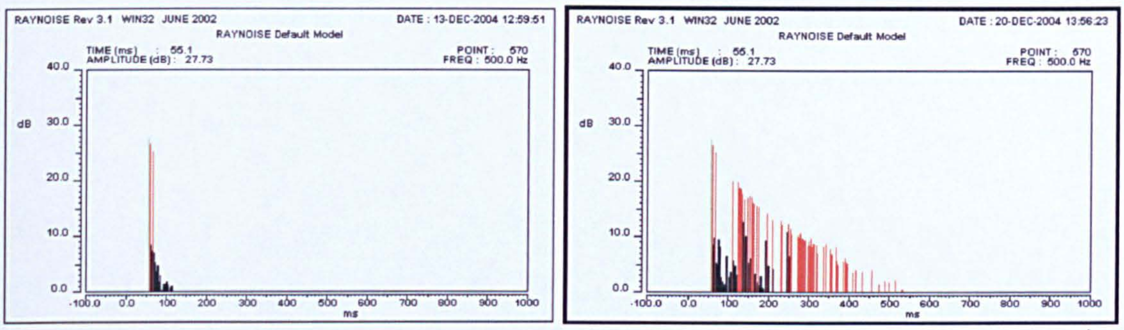


Figure 9.3.7. RT30 (s), STI and D50 (%) of the theatre of Philippi in ancient and present condition for receivers 1 and 2 and receiver line. a) RT30 over 125-4k Hz b) RT30 at 500Hz, c) STI at 500Hz and d) D50 at 500Hz.

From the two energy responses in Figure 9.3.8 the effect of the scenery can be clearly seen. It is noted that with the scenery there is a delay gap of about 50ms, approximately 70ms after the direct sound. Such a gap, caused by higher than 2nd order reflections, is a common characteristic of ancient Greek/Roman theatres. It could be avoided by the use of extra reflectors as a part of the scenery.



a b

Figure 9.3.8. *Energy responses in the theatre of Philippi. a) Without scenery and b) With scenery.*

9.4 Case Study 3: The Theatre of Dion

In the beginnings of the 19th century Leake indicated the location of the Hellenistic theatre of Dion and Sotiriadis verified its existence in 1928 due to the fan shape of the ground at the south of the ancient city of Dion. It was excavated by Mpakalakis in 1970 and by Pantermalis in 1973 onwards [Karadedos, 1986]. Publications on the theatre have stopped at 1996, while excavations are still carried out. Figure 9.4.1 shows the present condition of the theatre of Dion.

Figure 9.4.1. *Present condition of the theatre of Dion [source: http://www.dion.gr/el/sacredcity.asp?action=SubArea&pID=7 --><HTML].*

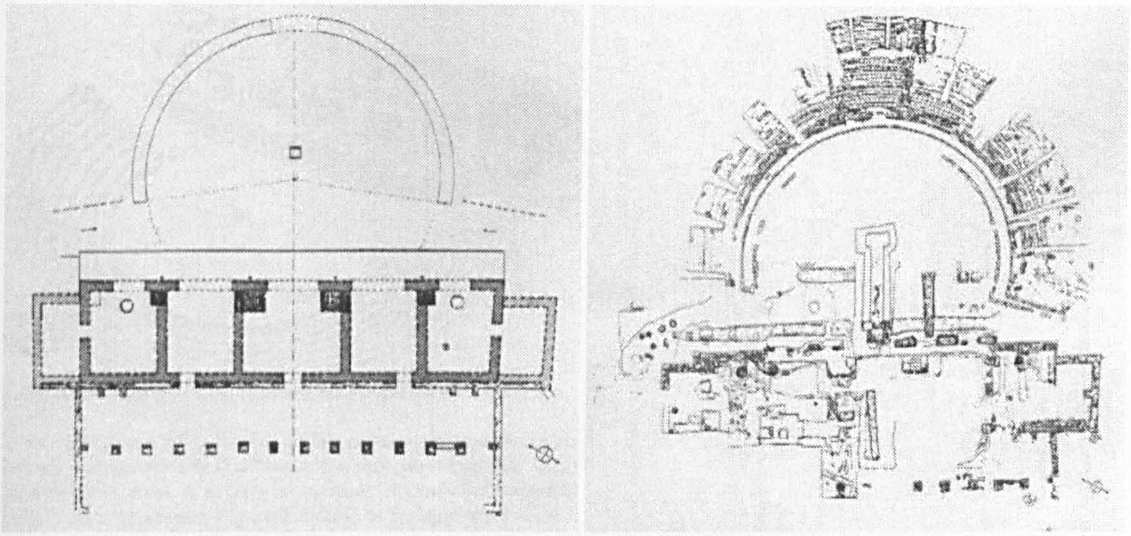
9.4.1 Background Information

The theatre seems to have been a very important construction for the ancient city of Dion. It has a typically Hellenistic layout, and it is carefully positioned in relation to the city and the temples. Its big orchestra and its careful construction are some of its characteristics.

The theatre's location, at the foot of mountain Olympus, the 'home' of ancient Greek Gods is related to its construction and usage. According to the history, King Archelaos established 'scenic competitions' and celebration in honour of Zeus and the Muses. These lasted nine days, establishing Dion as the great cultural centre of Macedonia. Tragic and comic poets were competing, including Euripides. The descendants of Archelaos, Philip the II and Alexander the Great also attempted to culturally establish Dion. The topologic significance of the theatre is based on its location that offered the city protection from the north winds and the water coming from mountain Olympus. Figure 9.4.1 also shows its typical Hellenistic layout, although constructed on the slope of a purposely built hill. The theatre is facing north-east, opposite to the usual south orientation, assuring better conditions in ventilation and sun exposure, following Vitruvius' suggestions [Karadedos, 1986].

9.4.1.1 Orchestra

The orchestra is surrounded by a stone pipe/sewage system, illustrated in Figure 9.4.2. Two centres have been found for the orchestra, one placed on the axis of the theatre, with radiuses of 13.07m and 12.78m respectively. Also, the circle of the orchestra is cut by the proskenion. At the middle of the orchestra there is an underground passage, most probably the 'χαρώνειος κλίμακα', described in Chapter 4, which is supposed to be the passage to the underworld, and was possibly created later than the initial construction of the theatre.



a b

Figure 9.4.2. *The original and present condition of the theatre of Dion. a) Original orchestra and stage building and b) Plan of the present condition with the different phases indicated [source:Karadedos, 1994].*

9.4.1.2 Koilon

The uniqueness of the koilon lies in the fact that the seats were made by special bricks rather than stone. This is actually the only example of a theatre built by these materials. In its present condition most of the bricks are missing, taken out in order for the Roman buildings of the city to be constructed. The absence of the materials is more obvious above the 7^{th} row of seats and the retaining walls. It is still not clear how the bricks were positioned and whether the final finish of the koilon was brick or marble. There are also indications that the seats of honour were made of porous stone. There are four phases of the koilon: a) early Hellenistic, b) Hellenistic, c) Roman, with a narrow passage around the pipe and d) early Byzantine, limited to a small building at the north part of the koilon [Karadedos, 1986]. Figure 9.4.2b illustrates the present condition of the theatre of Dion with the parts that have remained from the different phases.

9.4.1.3 Skene-Building

Based on archaeological evidence, the skene-building was a typical Hellenistic structure, with a proskenion, two paraskenia and the main building [Karadedos, 1986]. The proskenion was 2.65m higher than the orchestra's level. The walls of the skene-building were made of marble and some part of porous stone, while the tiles of the roof were ceramic with inscriptions [Karadedos, 1986]. New excavations have revealed that the inside of the skene was 2.50m above the orchestra with a floor made of red soil [Karadedos, 1994]. Figure 9.4.3 shows the section of the theatre for the original and the present condition. It is noted that, since the material of the paraskenia was different than that of the main building, they were probably an addition of one of the phases, rather than part of the original construction.

Two big rectangular holes that were found parallel to the skene-building were the foundations of the columns that supported the stage wall, although more columns of smaller size were found in the same line. It has been mentioned by the archaeologists that the existence of the two major columns must have provided multiple possibilities for scenery, mechanical device applications, new staircases and platforms on the roof [Karadedos, 1994]. Furthermore, the big openings on the stage wall allowed the use of the ekkyklema, the platform that transported the actors and the scenery from the inside of the stage building to the proskenion, as described in Chapter 4.

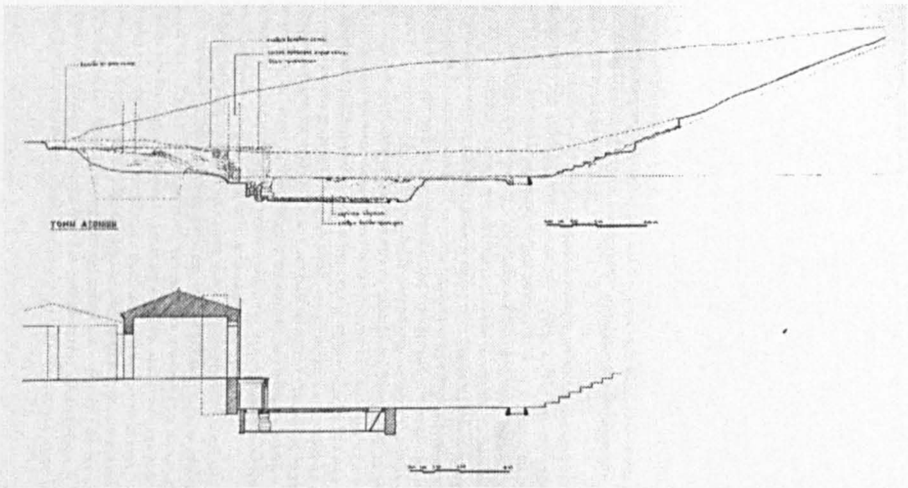


Figure 9.4.3. *Section of the present and the original condition of the theatre of Dion [source:Karadedos, 1994].*

9.4.2 Acoustic Simulation

This section presents the acoustic simulation of the theatre of Dion at four stages. First the theatre is simulated in its original condition, then the present condition, followed by the application of purposely-built scenery design and finally by a detailed calculation for a stage enclosure according to results from Sections 9.2 and 9.3.

The original condition of the theatre is simulated with two alternative sources, an actor standing at the orchestra (Source 1) or on the proskenion (Source 2). The present condition is simulated with the theatre koilon only, since the stage building is missing. This simulation is performed for comparison mostly, with two orchestra absorption coefficients, for soft and rough soil respectively. Moreover, purposely designed scenery is tested and adjusted in order for the audience to receive sound equally, and with improved energy responses.

The material of the koilon is brick, rather uncommon for a Greek theatre with absorption coefficients of 0.09 at 125Hz, 0.07 at 250Hz and 0.05 from 500Hz to 4k Hz [LMS Numerical Technologies, 2001]. The absorption coefficient of the skene-building, made of marble, is 0.01 for the third octave band from 125 to 4k Hz and of the orchestra is 0.34 at 125Hz, 0.55 at 250Hz, 0.60 at 500Hz, 0.42 at 1kHz, 0.55 at 2kHz and 0.56 at 4kHz. In Section 9.4.2.2 the absorption coefficient of rough soil is also simulated. Flat panel diffusion coefficients are applied to all surfaces, at 0.30 at 125Hz, 0.20 at 250Hz, 0.15 at 500Hz, 0.10 at 1kHz, 0.09 at 2kHz and 0.07 at 4kHz.

Source 1 is situated at a height of 1.80m above the orchestra level and Source 2 at 1.80m above the proscenium level, thus 4.45m above the orchestra floor. The simulation parameters are based on the investigation presented in Chapter 5 and the source's sound power is the same as in Section 9.2.4.

9.4.2.1 Antiquity

The whole theatre, including the skene-building is simulated for the original condition, during the Hellenistic period in antiquity. As mentioned above, two source positions are used and the results are compared. Figure 9.4.4 illustrates the plan of the theatre as used in the simulation with the positions of the sources, some typical receivers and the receiver line.

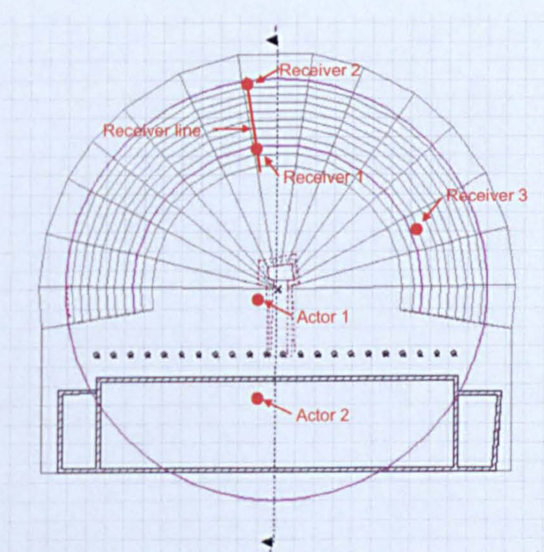
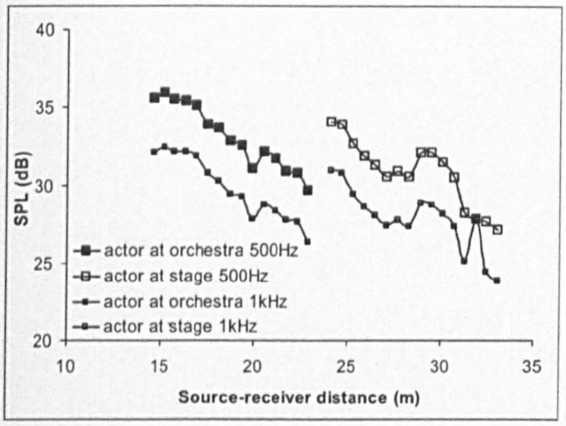


Figure 9.4.4. *Plan of the theatre of Dion as used in the simulation, with actors 1 and 2 and receivers 1-3.*

The results for the SPL are illustrated in Figure 9.4.5 for the receiver line at 500Hz and 1kHz. It can be seen that the difference in source position reflects on the SPL results, with differences at the range of 2.5-3.5dB. It needs to be noted that due to different source-receiver distances, it is rather difficult to compare the curves in Figure 9.4.5a. Hence, Figure 9.4.5b illustrates the receiver line according to the distance from the centre of the orchestra, irrespectively of the source's distance. It is clear that the SPL is related to distance, at satisfactory levels, from 64 to 36dB at a distance of 14.50m, but it can be seen that early reflections created when the actor is positioned on the stage building allow an increase in SPL at specific receiver points and balance the differences between the two source positions. This is possibly related to relative source-receiver heights.



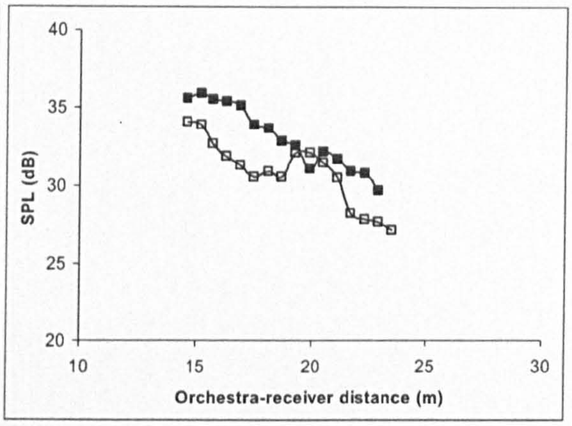


Figure 9.4.5. *SPL (dB) along the receiver line. a) Source-receiver distance at 500 and 1k Hz and b) Distance from the centre of the orchestra at 500Hz.*

There is no great alteration in RT30 values for the two sources at the receivers that are high in the koilon, with increased number of reflections, although for those closer to the orchestra the difference is around 0.20-0.30s. Figure 9.4.6 illustrates the RT30 for receivers 1 and 2 at 125-4k Hz and for the receiver line at 500Hz. The actor situated near the orchestra's centre produces a RT30 around 0.75-1.20s. However, the RT30 for the source on the stage building presents more variation, at 0.60-1.30s. It is noted that although the RT30 is rather long at specific receiver positions, considering that it is an outdoor space, the higher differences at 500Hz can be found at the front seats, due to variation in reflection patterns.

The EDT results, as shown in Figure 9.4.7a for the actor on the orchestra, correspond to the RT, although with reduced values (around 0.60-0.80s for 500Hz and 0.60-0.90s for 1kHz). Regarding the actor on the stage, EDT is very short, tends to decrease as the receiver is far from the source, up to 0.20s, due to the small number of early reflections usually found at the last rows of the koilon, confirmed by the energy responses shown in Figure 9.4.8. As expected, since there is no background noise applied, the STI is rather high, around 0.70 for both situations, with slightly improved conditions with the actor performing on stage. If in reality there was no background noise, these results would correspond to 'good' intelligibility, according to

Steeneken and Houtgast [1985]. Moreover, as seen in Figure 9.4.7c D50 is noticeably high for the source on stage, at 90-95%, while the results for the source on the orchestra are also good, at 70-80%. C80 has also been improved by the move of the actor from the orchestra to the stage.

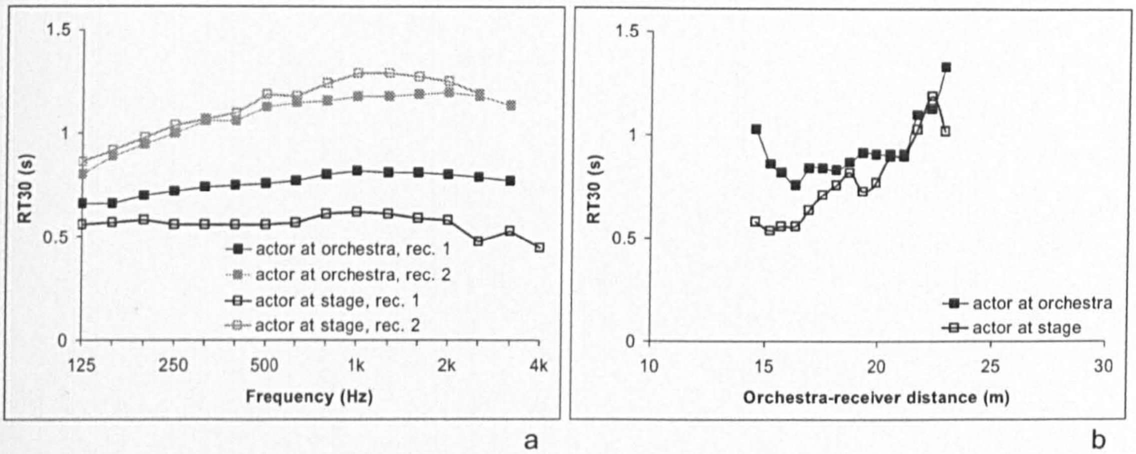


Figure 9.4.6. *RT30 (s). a) For receivers 1 and 2 across the frequency range and b) Along a receiver line at 500Hz.*

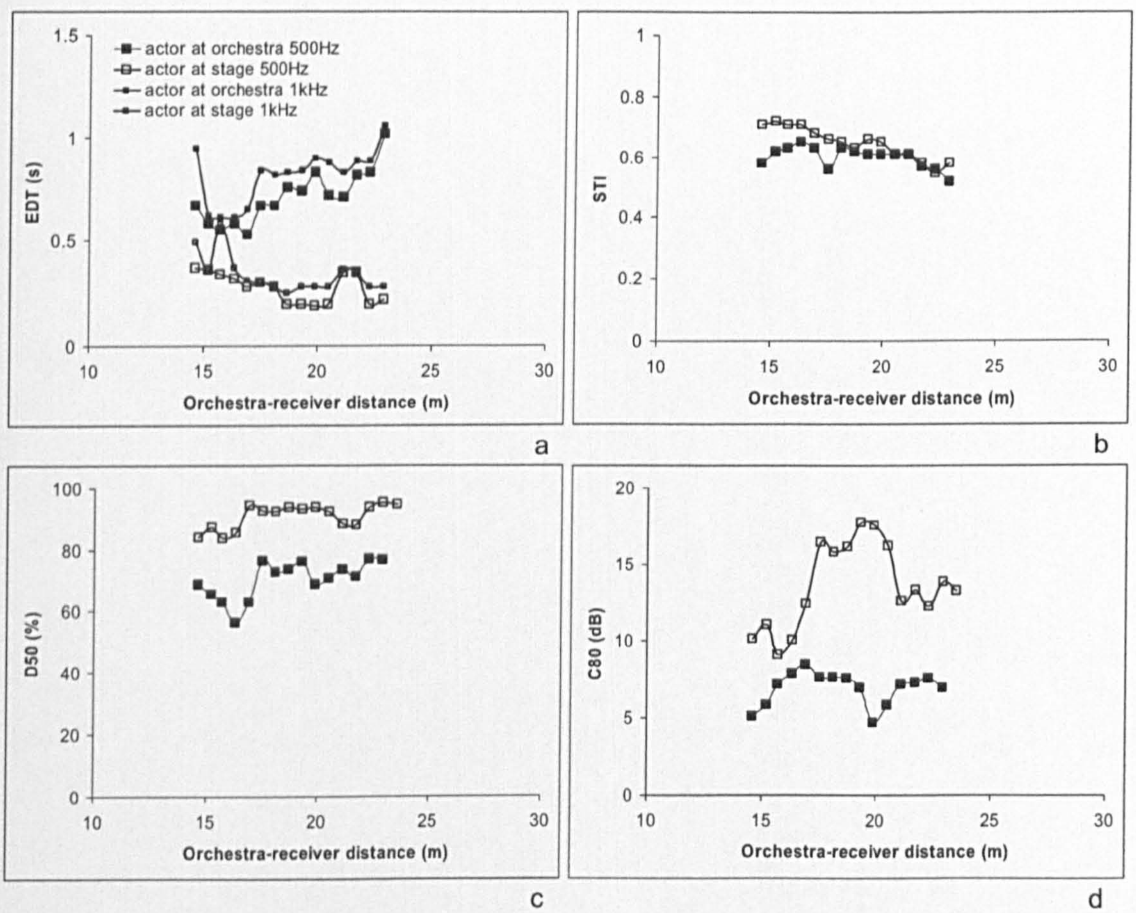


Figure 9.4.7. *Acoustic indices along a receiver line at 500Hz. a) EDT (s), b) STI, c) D50 (%) and d) C80 (dB).*

The energy responses for receivers 1, 2 and 3 are shown in Figure 9.4.8. It is clearly seen that when the actor is performing on the orchestra more reflections reach the audience. This corresponds to all receivers in the audience area. Also, there are important delay gaps in the energy responses of the stage performer (Figure 9.4.8b, d and f). This is easily explained by the reflection patterns relative to the source-receiver distance and can be explained as follows: When sound is reflected from the koilon back to the skene-building and then to the receiver, the distance it covers is much bigger when the actor performs on stage. Figure 9.4.9 shows a pattern that corresponds to the reflection after the delay gap in Figure 9.4.8d.

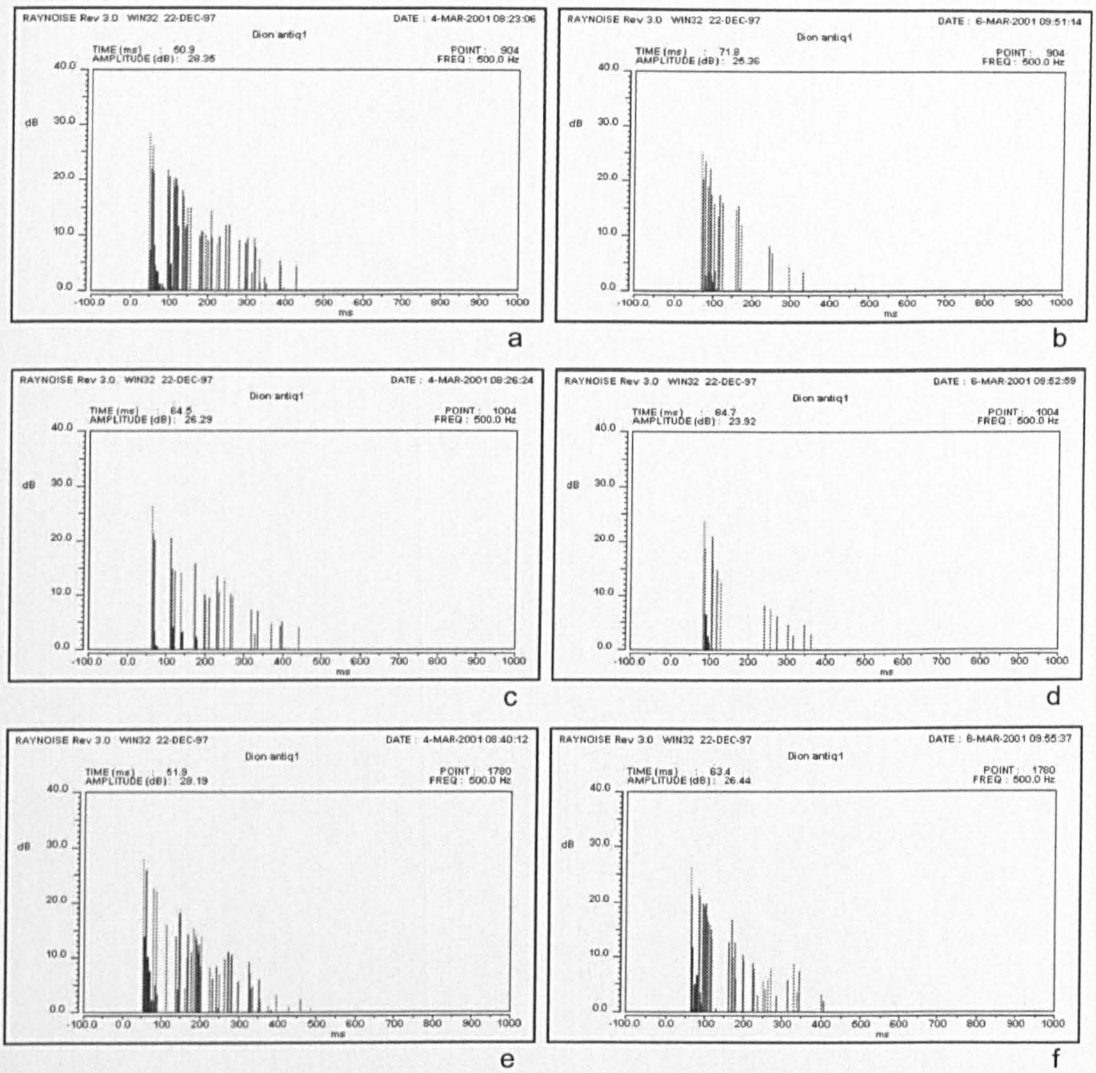


Figure 9.4.8. *Energy responses at three receiver points at 500Hz. a) Receiver 1 with actor on orchestra, b) Receiver 1 with actor on stage, c) Receiver 2 with actor on orchestra, d) Receiver 2 with actor on stage, e) Receiver 3 with actor on orchestra, f) Receiver 3 with actor on stage.*

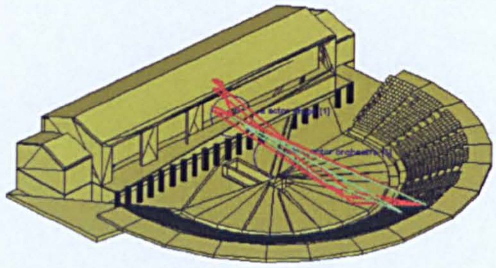


Figure 9.4.9. *Reflection pattern for receiver 2 corresponding to the energy response in Figure 9.4.8d. Red lines, first reflections; green line, reflection at 240ms.*

9.4.2.2 Present Condition

The present condition of the theatre of Dion is presented in this section not only to be briefly compared with the results from antiquity, but also to consider possible differences that can emanate from variable soil characteristics, presented by the archaeologists. It is discussed that the ancients stepped on the soil of the orchestra, in order to make it rougher. Also, in ancient historical notes, as mentioned in Chapter 2, there are references to the decrease of the chorus' voices in an ancient theatre when the orchestra was spread with straw, and to the reflection provided by the plaster on the walls [Hunt, 1978]. It is therefore clear that several materials could have been used for the specific needs of a performance, and possibly influenced sound distribution. Therefore two absorption coefficients have been alternatively simulated and presented. The absorption coefficient for the orchestra was calculated as 0.34 at 125Hz, 0.55 at 250Hz, 0.60 at 500Hz, 0.42 at 1kHz, 0.55 at 2kHz and 0.56 at 4kHz and as 0.15 at 125Hz, 0.25 at 250Hz, 0.40 at 500Hz, 0.55 at 1kHz, 0.60 at 2kHz and 0.60 at 4kHz for soft and rough soil respectively according to Egan [1988] and the parametric study in Chapter 7.

Figure 9.4.10a illustrates the SPL for the present condition of the theatre, which is only altered by less than 1dB between soft and rough soil in all frequencies, considering the difference in the orchestra's material. In general the results of the present condition are relatively low compared to antiquity, where the stage building was present. The difference is at the range of 2-3dB, depending on the distance to the source, and can be seen in Figure 9.4.10a. As expected, RT30 is very short compared to the original condition of the theatre of Dion in antiquity (0.10-0.30s as opposed to 0.66-1.31s), considering the missing reflective background surface the skene-building represented and the soft materials used in this theatre, not only for the orchestra but for the koilon as well. Figure 9.4.10b indicates that the soft soil produces RT30 around 0.10-0.20s for the range of frequencies, although the variation in rough soil coefficient is somewhat increased at low and decreased at high frequencies, at less than 0.10s.

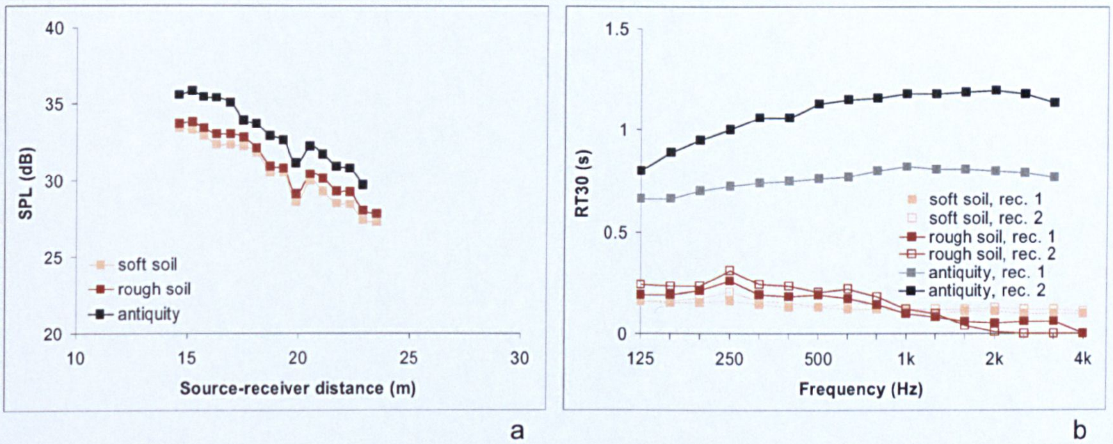


Figure 9.4.10. *Acoustic indices for the present condition of the theatre of Dion. a) SPL (dB) along the receiver line at 500Hz, b) RT30 (s) for receivers 1 and 2 for the frequency range.*

Since STI depends only on reverberation in these models, the results are approaching 1, with excellent intelligibility, although they don't particularly reflect on reality. There are also very close with both situations. The same observations apply to clarity and definition results. As it is generally retrieved, the orchestra's material doesn't particularly influence the acoustic indices. However, in this case, the present condition of the theatre was simulated, without any scenery or skene-building. The existence of another boundary that would provide additional reflections, as seen in Section 9.4.2.1 could alternate the amplitude of the reflection off the two materials, thus the acoustic environment of the whole theatre will be further investigated in Chapter 10 with the application of scenery.

9.4.2.3 Purposely-Built Scenery

The impact of scenery application in the ancient theatre of Dion is the main subject of this section. The scenery is purposely designed by the author, in order to provide important early reflections to the whole audience area, similarly to Section 9.3.3. The plan and section of the scenery can be seen in Figure 9.4.11. The material used is gypsum board, frequently used by stage designers. It is lightweight and easy to use, cut and handle, since one of the purposes is to be easily carried and adjusted in many theatres during one season. The absorption coefficients are 0.10 at 125Hz, 0.05 at 250Hz, 0.04 at 500Hz, 0.07 at 1 kHz, 0.09 at 2kHz and 0.05 at 4kHz [Egan, 1988].

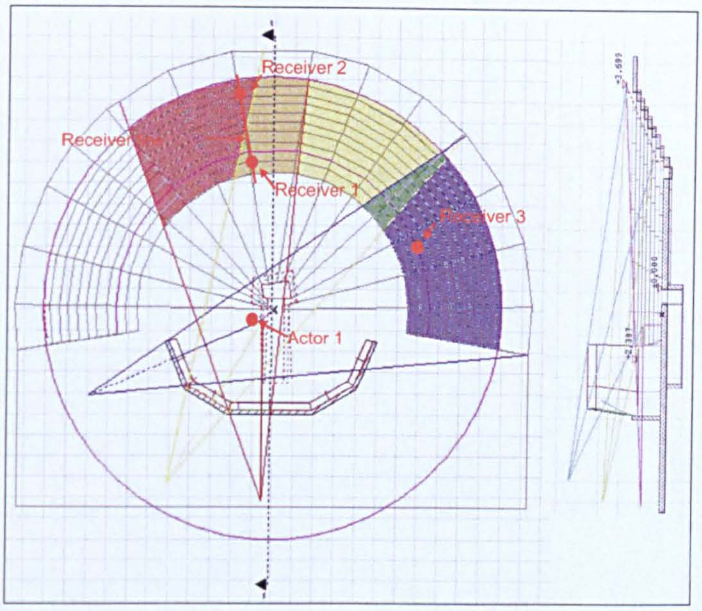


Figure 9.4.11. *The plan and section of the theatre of Dion with the scenery applied.*

All figures presented in this section include the values of both the theatre for the ancient and present condition (without the stage building) for the sake of comparison and to judge the effectiveness of the scenery design. Figure 9.4.12 presents the SPL for the scenery design, the stage building and the present condition. It can be seen that the theatre without any stage building or scenery is poor in sound distribution. The SPL is fairly increased, around 2dB, with the stage building of antiquity and by about 4dB with the especially designed scenery. The differences between the ancient and present conditions are around 2.5dB and around 3.2dB at low and high frequencies respectively, while between the latter and the scenery application are at 3.8 and 3.3dB respectively. It is hence indicated that the effectiveness of both the ancient stage building and the scenery is obvious for the frequency range, while the scenery's design to improve the acoustic conditions is also related to frequencies that correspond to human speech. Nevertheless, more indices need to be examined. It needs to be noted that although the values of SPL are affected, the curves in SPL regarding the source-receiver distance have the same tendency. The effects of both the stage building and the designed scenery can be seen in Figure 9.4.12b, where RT30 is illustrated for the three situations. They produce RT30 around 1s, which is rather long when compared to the 0.20s of the present condition. The scenery is more effective in terms of RT30 increase along the receiver line, providing stable values for the range of frequencies. However, in terms of EDT, the differences between the ancient stage building and the temporary scenery are around 0.20-0.60s, and show a clear distinction in terms of source-receiver distance, shown in their graphic representation in Figure 9.4.12c. EDT is reduced at large distances with the purposely-built scenery, compared to antiquity, which reflects its inefficiency in providing multiple early reflections to the high parts of the koilon. Definition depends exclusively on early sound and reverberation; hence the values of the empty theatre are approaching 100%, whereas in antiquity and in the present condition with scenery application they are 60-80% and 40-60% respectively.

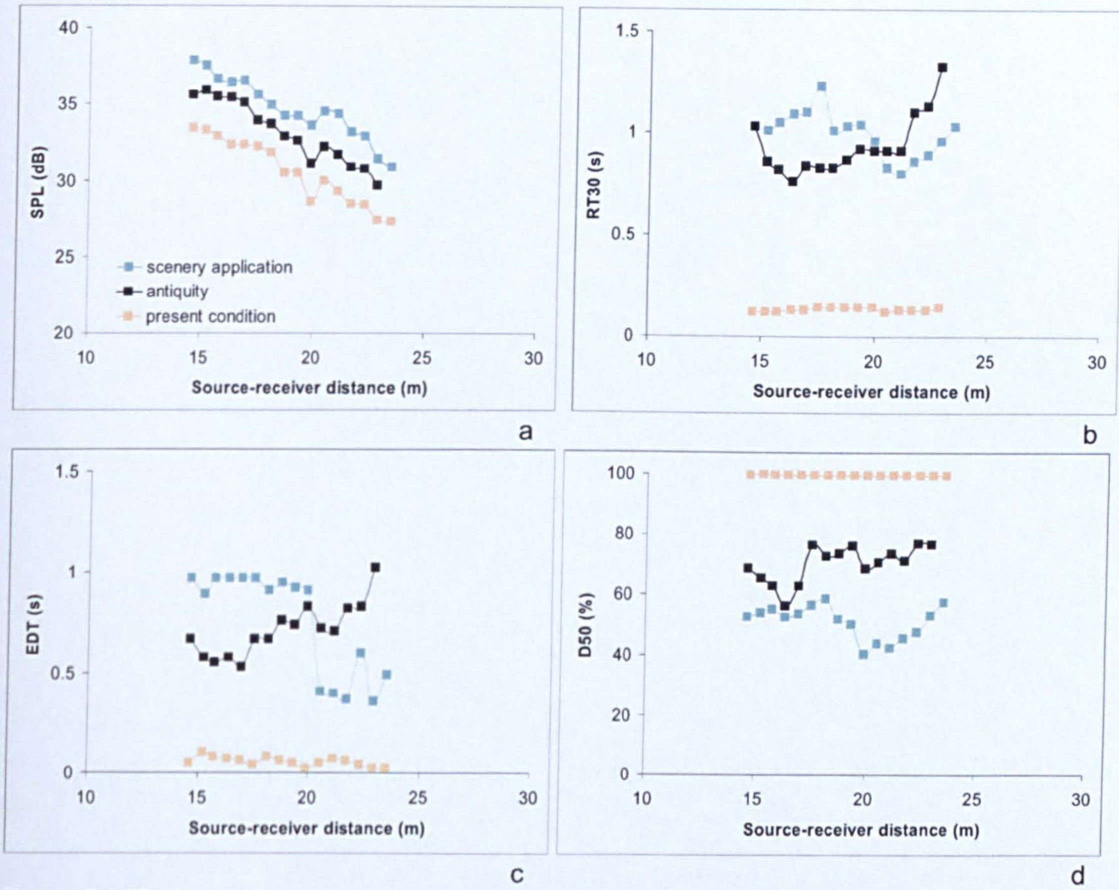
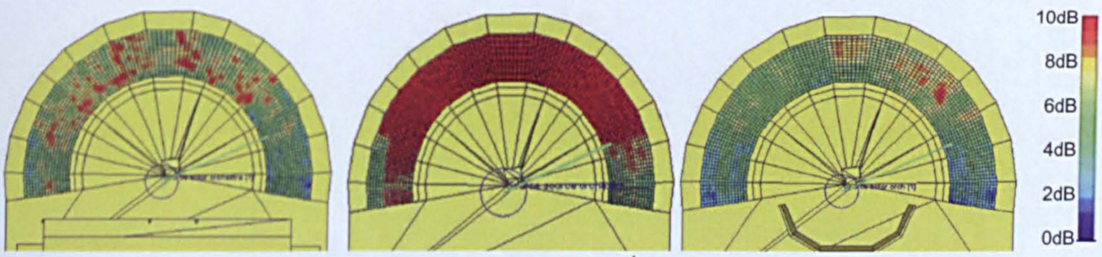


Figure 9.4.12. *Acoustic indices along a receiver line of the theatre of Dion with scenery application at 500Hz. a) SPL (dB), b) RT30 (s), c) EDT (s) and d) D50 (%).*

Clarity is shown in Figure 9.4.13 corresponding to D50 results, considering that the range is from 0 to 10. The long skene-building of antiquity provided multiple reflections, increasing C80 at some scattered points in the audience area. The scenery seems to provide focus on specific parts of the audience, with decreased values near the sides of the koilon.



a b c

Figure 9.4.13. *Colour maps of C80 (dB) at 500Hz for the theatre of Dion. a) Stage building of antiquity b) Present condition and c) Designed scenery.*

Figure 9.4.14 presents the energy responses for receivers 1 and 2, shown in Figure 9.4.11. They reveal that although the designed scenery provided important reflections to the whole audience area, the linear wall of the stage building seems to increase the number of reflections that reach the receivers and distributes them equally in time. These results correspond to the simulation of temporary scenery in Section 9.2.5, where the theatre of Mieza was tested, revealing that a linear wall, in similar layout as the ancient stage building, provided multiple reflections without noticeable delay gaps, with rather good values in reverberation.

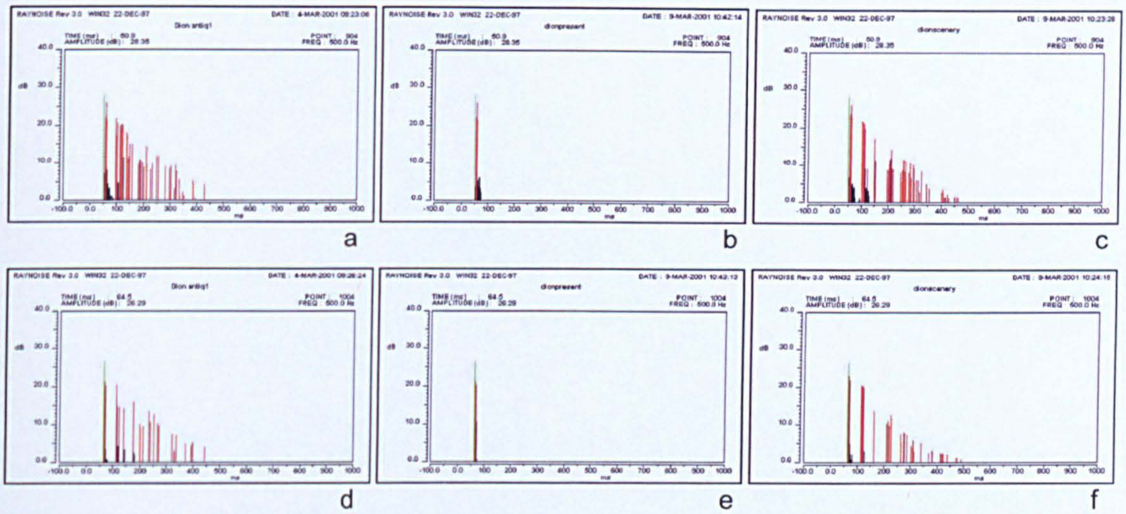
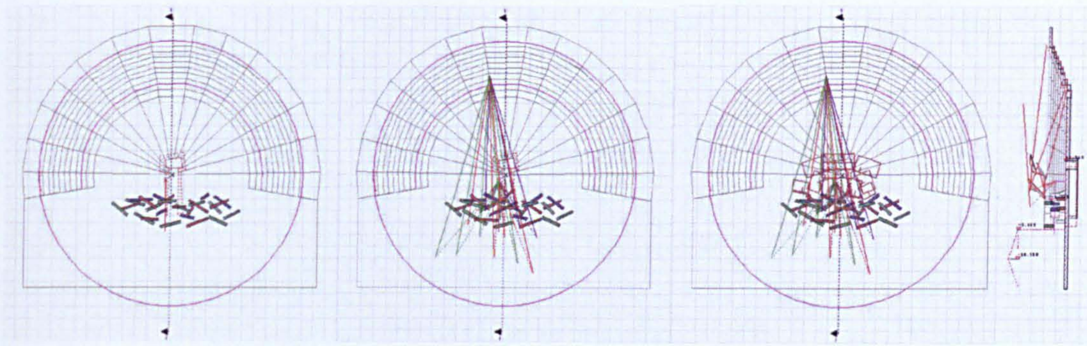


Figure 9.4.14. *Energy responses for three conditions at 500Hz. a) Receiver 1 in antiquity, b) Receiver 1 in present condition, c) Receiver 1 with designed scenery, d) Receiver 2 in antiquity, e) Receiver 2 in present condition, f) Receiver 2 with designed scenery.*

The same simulation for the scenery has been carried out with two alternatives, first by applying diffusion coefficients of 0.50 at 125 and 250Hz, 0.60 at 500Hz, 0. 70 at 1 kHz, 0.65 at 2kHz and 0.60 at 4kHz to the gypsum board of the scenery, simulating irregularities that can be adjusted to the panel and then by replacing the gypsum board with marble. As expected, diffusion in the form of decorations on the scenery surface caused a reduction in both SPL and RT30 by 2dB and 0.10-0.30s respectively, although the curves had the same tendency. As far as the energy responses are concerned, the specular reflections were reduced and the decay curves were shorter. However, the delay gaps that were the obvious drawback of the scenery design have not been reduced, due to the same specular reflection distribution.

9.4.2.4 Complex Scenery Design

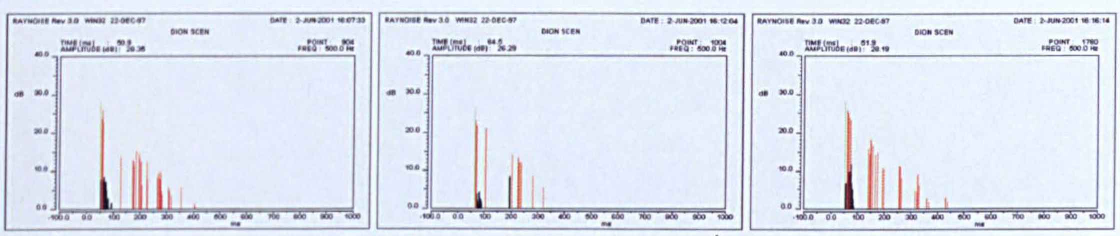
The same condition of the theatre has been simulated with a complex scenery design, using the same principles as Patsas' design [Patsas, 1995] that was previously applied to the theatre of Mieza and provided good acoustic conditions for the majority of the audience, as seen in Section 9.2, due to the angular layout. Hence, a similar layout has been created for the theatre of Dion in order to evaluate the acoustic condition, initially with no particular acoustic design, illustrated in Figure 9.4.15, namely Configuration 1. The scenery is designed at three levels/layers. The first from 0 to 1.5m above the orchestra's level, the second from 1 to 2.5m, and the third from 2 to 3.5m, represented by the red, the blue and the green colours respectively. From the pilot study some delay gaps were found and then Configurations 2 and 3 were created to overcome these problems, shown in Figures 9.4.15b and c respectively.



a b c

Figure 9.4.15. Layouts of three applied scenery designs in the theatre of Dion. a) Configuration 1, b) Configuration 2 and c) Configuration 3.

Figure 9.4.16 illustrates the energy responses for receivers 1, 2 and 3, shown in Figure 9.4.11, with Configuration 1. It is rather clear that the delay gaps are distinctive and can cause low speech intelligibility, with definition and clarity consequences. The delay gap for receiver 1 lasts 69.1ms, between a 2nd order reflection at 59.7ms off the orchestra and the koilon and a 5th order reflection at 128.8ms, off the scenery and the sides of the koilon. For receiver 2 the delay gap is 36.2ms and for receiver 3 it is 64.9ms. Therefore, it was decided that adjusting the scenery, with small changes in angles and lengths, will provide receiver 1 with additional reflections that would eliminate or at least shorten the delay gap.



a b c

Figure 9.4.16. Energy responses with Configuration 1 at 500Hz. a) Receiver 1, b) Receiver 2, c) Receiver 3.

Configuration 2, shown in Figure 9.4.15b, was created, as mentioned above, so that the scenery would contribute, with slight adjustments, to more reflections for receiver 1. The result was a replacement of the delay gap, at 85.1ms after the direct sound, between a 2nd order reflection from the scenery and the koilon and a 3rd order reflection that covers the distance from the actor to the koilon, the orchestra and the scenery, with a length of 71.2ms. This led to the addition of overhead reflectors, namely Configuration 3, shown in Figure 9.4.15c, placed above the orchestra area.

It would be enlightening at this point to briefly discuss the acoustic environment created and altered by the introduction and alteration of the scenery respectively. Figure 9.4.17 illustrates the SPL results for receiver 1 at the range of frequencies and the receiver line at 500Hz. It is clear that the purposely-built scenery presented in Section 9.4.2.3 was more effective in the SPL from the amplitude's viewpoint than the complex scenery of Configuration 1. However, the analysis of the early reflection patterns in Configuration 2 has shown that the conditions were improved, bringing the SPL amplitude at around 33-37dB. Between Configurations 1 and 2 there is a difference at the range of 2.5-5dB. Moreover, the decision of adding a ceiling to the scenery, one that would create an enclosure, and perhaps improve the acoustic environment has been proved effective. The SPL has increased by 2dB. It is important to take into account that the provision has been made especially for receiver 1, although it seems to have influenced the whole receiver line.

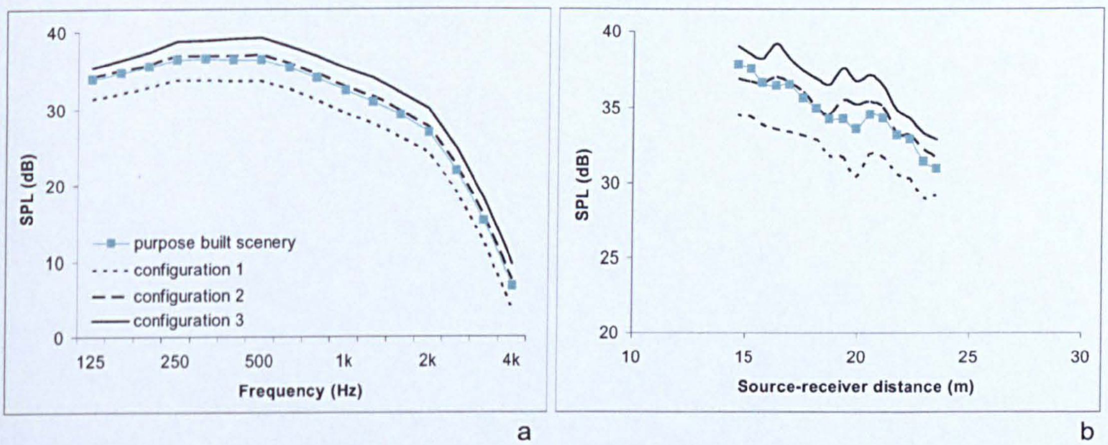


Figure 9.4.17. *SPL (dB) results at the theatre of Dion with scenery application. a) SPL from 125 to 4kHz for receiver 1 and b) SPL along the receiver line at 500Hz.*

Figure 9.4.18 illustrates RT30, EDT, STI and C80. Reverberation becomes shorter when initial reflections are added in Configurations 2 and 3, compared to the previous cases. RT30 is around 0.60-1.20s depending on the scenery condition, while EDT is 0.30s with the scenery adjustment and the overhead reflector. As expected, STI corresponds to reverberation results, as seen in Figure 9.4.18c. Clarity has also improved for receiver 1, from 7-9dB with the purposely-built scenery, to 10-12dB with Configuration 1, 8-13dB with Configuration 2 and 13-16dB with Configuration 3, since the ratio of the energy of the early sound to the late arriving sound was the aim of the design.

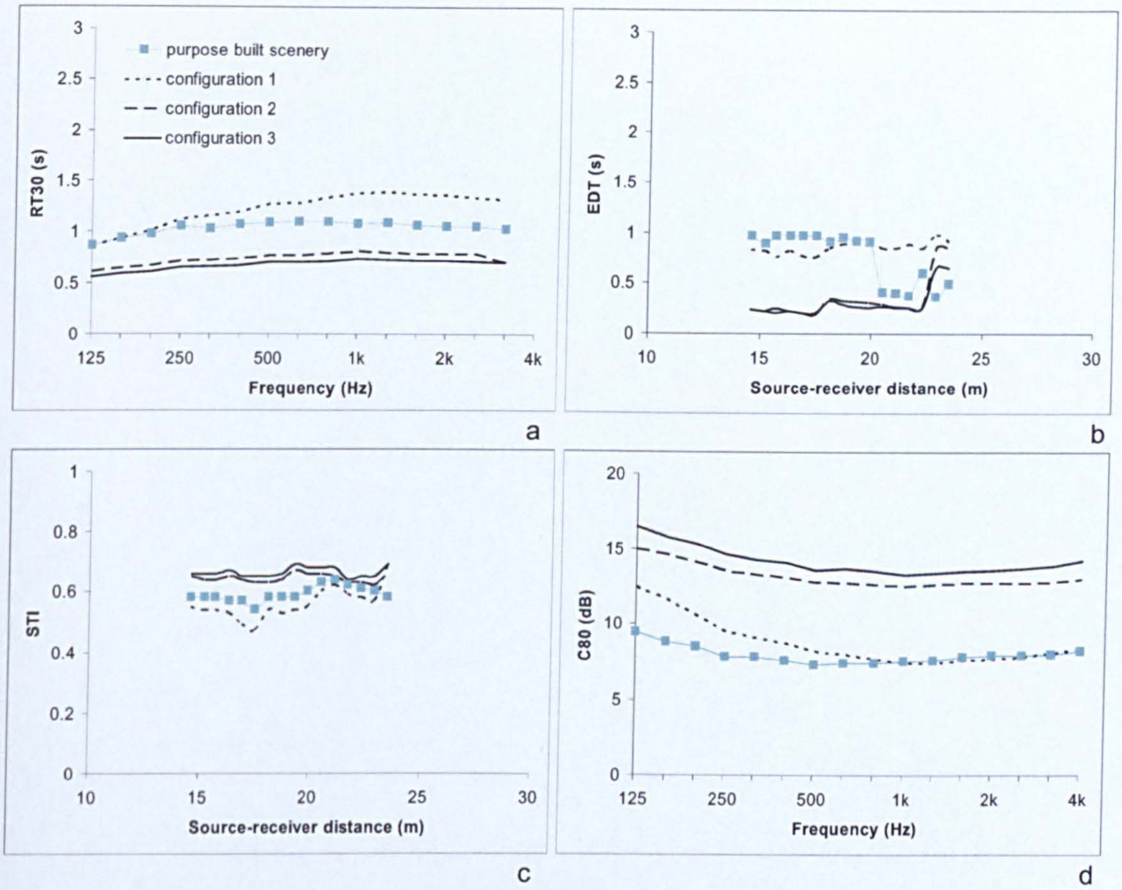


Figure 9.4.18. *Acoustic indices at the theatre of Dion with scenery. a) RT30 (s) from 125 to 4kHz for receiver 1, b) EDT (s) along a receiver line at 500Hz, c) STI along a receiver line at 500Hz and d) C80 (dB) for receiver 1 from 125 to 4kHz.*

The energy responses of receiver 1 in all configurations are shown in Figure 9.4.19. The early reflections in Configuration 2 are very important for the receiver, although the delay gap is not reduced. As expected, the maximum number of reflections is found in Configuration 3, when overhead reflectors are placed. The delay gap is substantially reduced in this way, since the ceiling provided an additional boundary in the theatre. Moreover, the duration of the delay gap with Configuration 3 is 23ms instead of 71.2 ms with Configuration 2. The overhead reflectors receive sound from the actor, allowing it to travel after multiple reflections to the receiver. Figure 9.4.20 illustrates the sound paths before and after the delay gap in Configuration 3.

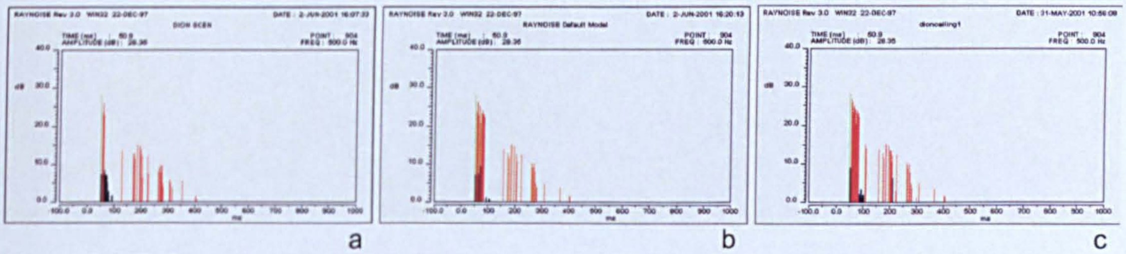


Figure 9.4.19. *Energy responses for receiver point 1 at 500Hz. a) Configuration 1, b) Configuration 2, and c) Configuration 3.*

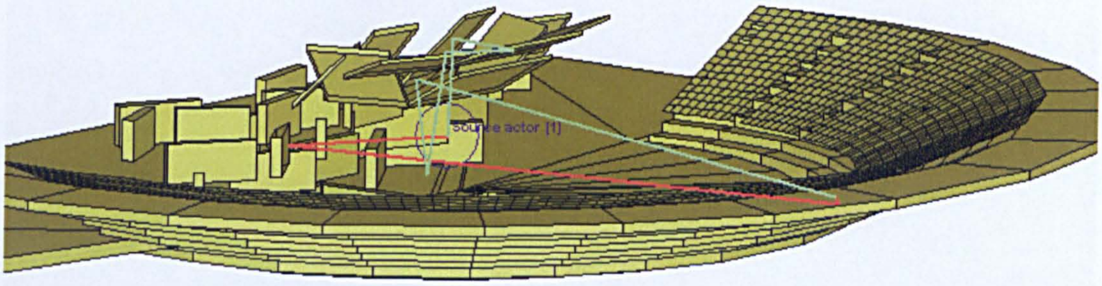


Figure 9.4.20. *Reflection paths for receiver point 1 in Configuration 3. Red line, sound path at 85.1 ms; green line, sound path after the delay gap, at 108.1 ms.*

9.4.2.5 Occupied Condition

Configuration 3 in Section 9.4.2.6, namely the theatre with the complex scenery design with calculated reflection patterns for receiver 1 and overhead reflectors, has been also simulated with audience absorption. The absorption coefficient for these simulations have been selected according to Chapter 7 as 0.28 at 125Hz, 0.40 at 250Hz, 0.78 at 500Hz, 0.98 at 1kHz, 0.96 at 2kHz and 0.87 at 4kHz. It has also been assumed, according to previous studies [Chourmouziadou and Kang, 2002], that the audience also functions as a diffuser, with diffusion coefficients of 0.30 at 125Hz, 0.20 at 250Hz, 0.15 at 500Hz, 0.10 at 1kHz, 0.09 at 2kHz and 0.07 at 4kHz.

The SPL results show a reduction in the region of 2-2.5 dB, although at high frequencies there is no effect of the audience. Figure 9.4.21 presents the SPL and RT30 along the receiver line. By comparing the SPL in the unoccupied theatre without the overhead reflectors and the occupied with them, it is clear that the results are at the same levels. Hence, it is preferable to have the additional reflections the overhead reflectors provide under the occupied condition. RT30 is around 0.35s, since reverberation is also reduced by the audience, by almost 0.40s compared to the unoccupied.

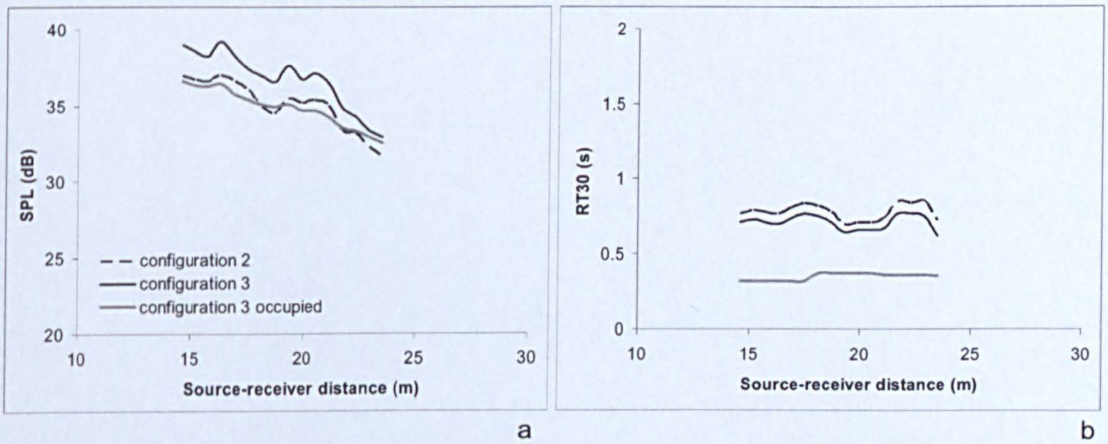


Figure 9.4.21. *Acoustic indices at the theatre of Dion. a) SPL (dB) and b) RT30 (s) along a receiver line at 500Hz.*

9.5 Comparison of the Theatres in Antiquity and Today

This section presents a short comparison of the three theatres, namely Dion, Mieza and Philippi, in their condition in antiquity, as well as the present condition (for Dion and Philippi) and the restoration proposal (for Mieza). These three were the major theatre constructions of northern Greece, used at the same periods. As mentioned before, they have not systematically been examined from the acoustic viewpoint before, hence this chapter allows for their evaluation in terms of performance conditions and acoustic importance as well. In general, it has already been noted that the original layouts of the theatres presented good acoustic conditions. However, due to their uniqueness, shapes, sizes and construction methods, it is useful to compare whether their present condition provides the same ranking, for the performance of ancient drama. It needs to be noted that the configurations compared in this section refer to the conditions with the actor performing in the orchestra. Figure 9.5.1 illustrates the SPL and RT30 for the original and present conditions of the theatres.

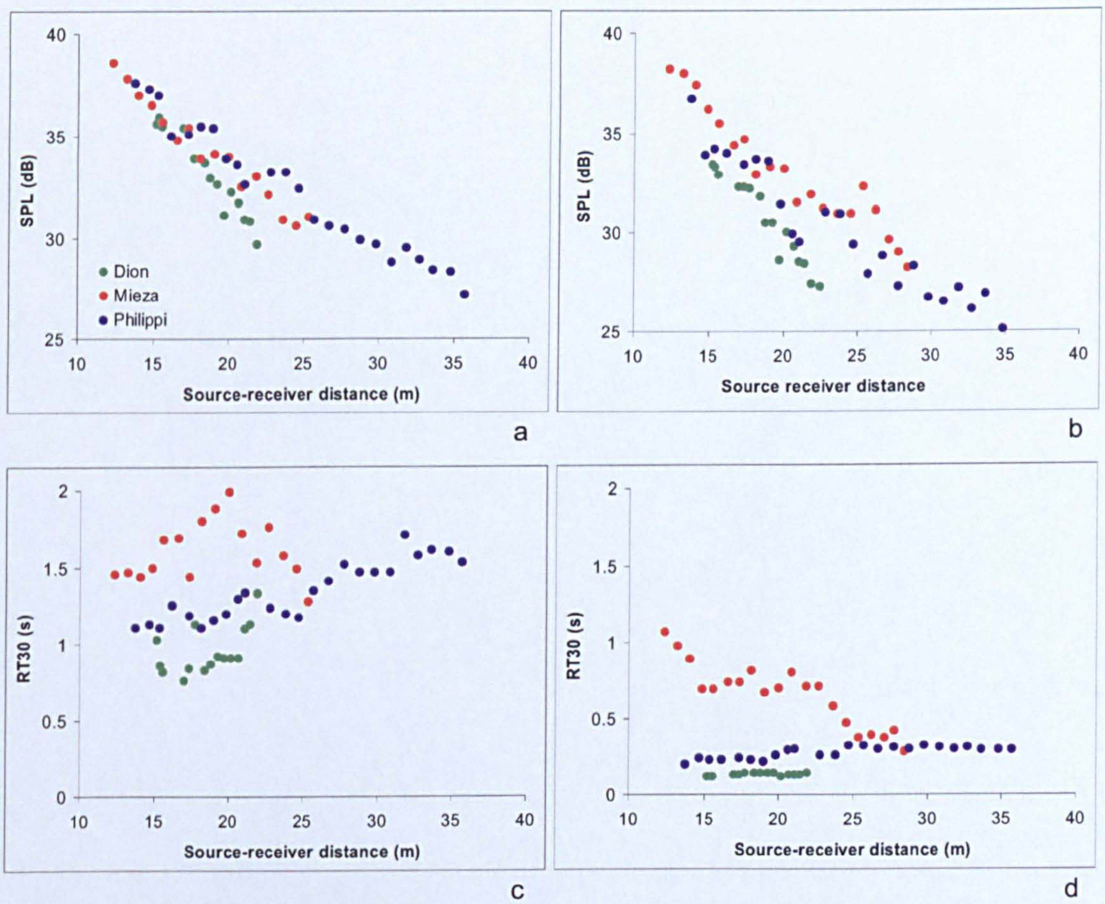


Figure 9.5.1. *Comparison between the theatres of Dion, Mieza and Philippi along the receiver line at 500Hz. a) SPL (dB) in antiquity, b) SPL (dB) today, c) RT30 (s) in antiquity and d) RT30 (s) today.*

SPL is shown in Figures 9.5.1a and b respectively. It can be clearly seen that the omission of the stage building during the calculations has resulted in decreased SPL values in the present condition, when compared to the original, especially for the theatre of Dion. In general, the values in antiquity were mostly depending on the direct sound, which is related to the source-receiver distance, and the reflections from the stage building. In the present condition however, the destroyed koilon and especially its material also play an important role, particularly in Dion, which has been simulated with brick, and in Mieza, where the extra seating area provide more reflections.

Greater differences can be found in the RT30 results between the two conditions, since the stage building provided many reflections, and multiple reflections between it and the other components of the theatres, namely the orchestra and the koilon. For Dion the average RT30 in antiquity is 0.96s and in the present 0.13s, for Mieza at 1.61s and 0.65s and for Philippi at 1.34s and 0.28s respectively. Hence, the average reductions are in the range of 0.83s, 0.96s and 1.06s respectively. Considering the sizes of the theatres, which are further discussed in Chapter 10, these reductions are expected. Figure 9.5.2 illustrates the STI and the D50 for the theatres in antiquity and today.

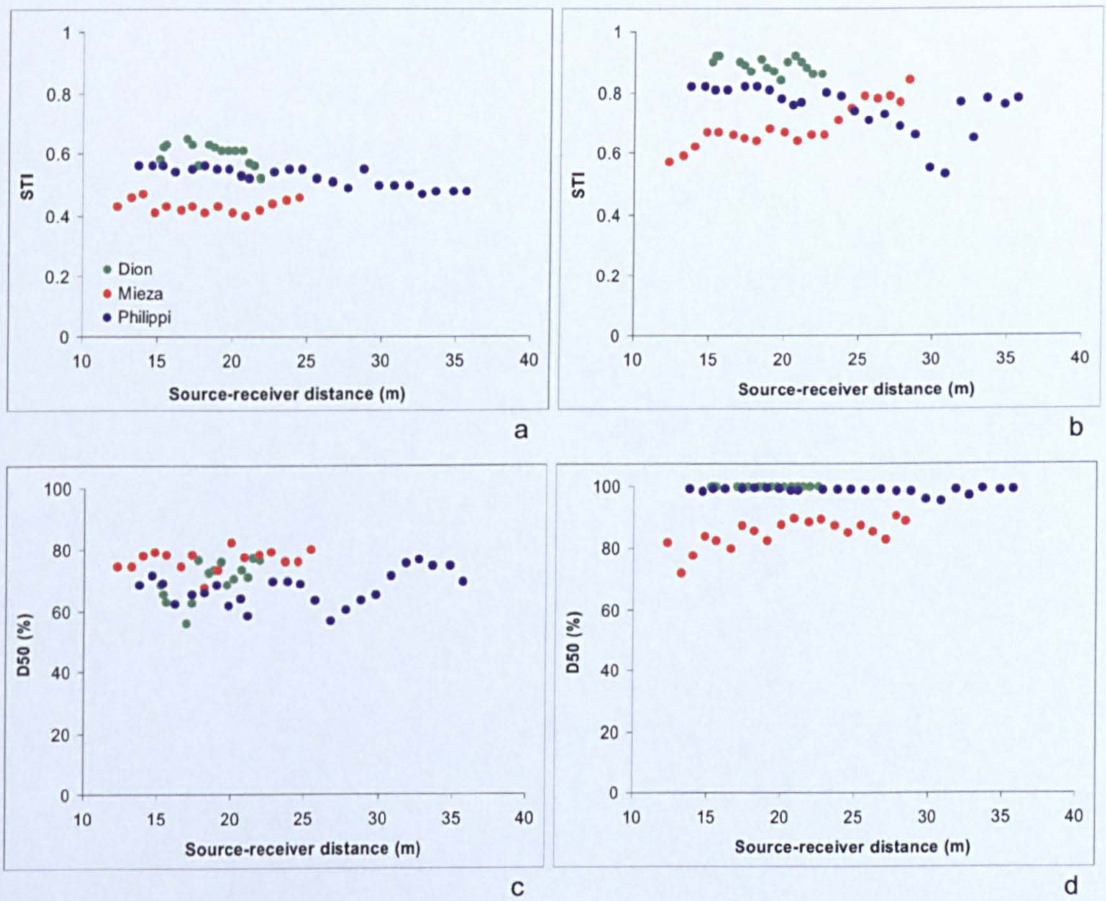


Figure 9.5.2. *Comparison between the theatres of Dion, Mieza and Philippi along the receiver line at 500Hz. a) STI in antiquity, b) STI today, c) D50 (%) in antiquity and d) D50 (%) today.*

Corresponding to RT30 results, STI is presented in Figure 9.5.2a and b. Although the order of the theatres from antiquity to today has not changed, rating Dion at the first place, followed by Philippi and Mieza, the STI values have been significantly increased due to the reduction in reverberation and the absence of background noise. It needs to be mentioned that, although the occupancy of the theatres is almost the same in antiquity and today, hence the audience noise is the same, the noise produced by other means, like traffic or mobile phones is new and will consequently decrease intelligibility. Therefore, STI results will most probably reach the same levels as in antiquity, at around 0.4-0.6. For definition the values are also increased in the present condition, but the theatre order has changed. This is due to the lower ratio of the energy of the early sound to the reverberant sound, which is smaller because of the comparatively long RT30 found in Mieza.

Overall the conditions in the theatres have changed due to the absence of an important component, the stage building, and the intervention through restoration proposals. In general, the theatre of Philippi presents the best conditions, since it balances the increased SPL, STI and D50 with low RT30. On the other hand, in Dion SPL and RT30 are rather low, with better results in STI and D50, while exactly the opposite conditions are found in Mieza. However, earlier in this chapter it was observed that RT30 can be increased with the addition of scenery design, which will also be the subject of Chapter 10.

9.6 Conclusions

The results of the three theatres presented in this chapter have demonstrated the importance of these structures for the performances of ancient drama in Northern Greece, during the years that the family of Alexander the Great ruled the significance of each construction both in antiquity and today, and the ranking of the theatres in terms of acoustics. An important contribution of this chapter was that it linked the previous analysis of general theatre types, presented in Chapter 7, with specific theatres with individual layouts, while it compared and related the ancient and present conditions of the theatres, in order to introduce appropriate solutions for their present use. Hence, the effect of the stage building and temporary scenery design for the acoustic quality as well as the usefulness of acoustic simulation for the revival of ancient performances was also established.

For the theatre of Mieza, the original stage building contributed to rather long RT30, of about 1s. The restoration proposal, which is of particular interest, has been proved to be generally successful, especially in terms of definition. Corresponding to the restoration proposal, the effectiveness of six scenery designs has been examined, and the importance of scenery for the acoustic conditions has been demonstrated. The purposely-designed sceneries increase the SPL and, in cases where the scenery has been purposely-built, distribute sound energy evenly to the audience area. A simple linear wall has similar effects with the original stage building and also contributes to relatively long RT30. With the other scenery shapes including convex, concave and dome, the SPL distribution is not even in the audience area, since some create focus areas, and the reflection/energy response patterns are uneven, although the RT30 may appear to be long. It is suggested that when the scenery consists of several small objects instead of one simple generic shape, it is easier to improve/adjust the acoustic environment. This case will be further investigated in Chapter 10. The simulation also shows that surface diffusion causes a slight decrease in SPL as expected.

For the theatre of Philippi the condition of the Roman times was better than today's, with the stage building providing useful early reflections, increasing RT30 and SPL. The temporary scenery, in the form of a stage enclosure carefully designed for the specific theatre, increases the SPL and RT30 for the actor source, and reduces traffic noise. It also contributes to providing a more even reverberation distribution throughout the audience area, and a more uniform reflection/energy response pattern. Overall, with strategically designed sceneries in terms of shape as well as surface absorption and diffusion, the soundscape of the contemporary use of ancient theatres can be much improved.

Regarding the theatre of Dion it is noted that the condition in antiquity provided higher levels of SPL, RT30, although with lower values of clarity and definition compared to the present. Moreover, the variation in orchestra materials has shown that, when no scenery or stage building is involved, there is no impact on the acoustics of the theatre. The application of purposely built scenery design has indicated that by careful and appropriate design the conditions can be improved. It is worth mentioning that delay gaps, which are a common characteristic of the energy responses in ancient theatres due to large reflection paths, can be 'filled' with adequate acoustic design. This can be achieved by placing overhead reflectors that will reduce the reflection paths and provide additional reflections where needed.

Overall, this Chapter linked the previous hypotheses that hard materials improved the acoustic environment of the theatres of the Classic and the Hellenistic times with scenery design and it concentrated on specific cases instead of general layouts. The aim was to connect the original and contemporary conditions of the theatres with their function when using temporary scenery design. Additionally, effects of background noise were taken into account. It was indicated that appropriate scenery design is necessary for optimum acoustic conditions in ancient theatres, through carefully designed reflection patterns to improve definition, lateral efficiency and create intimacy. Apart from a purposely-built stage enclosure, this can be accomplished by the use of sceneries composed by many small objects that can be moved and adjusted according to the desired effect. Also, overhead reflectors are very practical to redirect sound to the audience area and reduce delay gaps. Their usefulness in the occupied condition has also been demonstrated, since they provide early reflections to compensate for those lost due to audience absorption. The parameters an architect/scenery designer should consider when creating temporary scenery are further investigated in Chapter 10.

CHAPTER 10

CLASSIFICATION OF SCENERY DESIGN AND INVESTIGATION OF THEIR ACOUSTIC EFFECT

10.1 INTRODUCTION

This chapter illustrates several generic scenery layouts, based upon the classification carried out in Chapter 4, where several forms of past and contemporary sceneries were illustrated. It has been suggested in previous studies that the missing skene-building of the present condition of ancient theatres has led to a decrease of reflections with short time delays [Shankland, 1973], stressing the importance of the orchestra floor and the 'stage house' in ancient Greek theatres rather than Roman, and at the same time resulted in acoustic problems, like in the case of the theatre of Epidaurus [Schubert and Tzekakis, 1999]. Therefore the use of appropriate scenery designs is vital, to compensate for this inefficiency. The aim of this chapter is to identify the optimum forms of scenery design to be used to improve the acoustic environment of ancient theatres for their current use, especially types from the Hellenistic times that survived through the centuries and are used for the revival of ancient drama, as well as for modern drama.

As mentioned in Chapter 9, the theatres selected for this study are representative examples of Hellenistic theatres of Northern Greece, varying in sizes, koilon inclinations and materials. Therefore, in this chapter the theatres of Philippi, Mieza and Dion are used for the investigation of the scenery's effect.

Initially the characteristics of the theatres selected for this part of the study will be presented briefly, following their detailed description in Chapter 9. The second part of the chapter will be the categorisation of the sceneries and a brief discussion of the simulation procedure and the methods used. The simulation results of each category will be then presented to identify the preferred layouts for each theatre. Additionally, ways of simplifying the representation of complicated sceneries, maintaining the acoustic characteristics of each performance, will be examined, according to the methodology of Chapters 5 and 6. Moreover, because the actors rarely stay at the same position during the play, although in ancient drama most of the positions were predefined, as seen in Chapter 4 (for example the king was always entering the stage from the central door of the skene-building), simulations for several actor's positions have been compared. Finally, the acoustic effects of the combination of 2 or 3 categories of sceneries will be briefly discussed.

10.2 ARCHITECTURAL CHARACTERISTICS OF THE SELECTED THEATRES

Three theatres have been selected for this part of the study. The theatres were described in detail and compared in Chapter 9, so this Section will mainly focus on the characteristics that encouraged this choice. None of these theatres has been thoroughly examined in terms of acoustics before. The detailed characteristics of the theatres are shown in Table 10.1. The variables examined are:

Size

The theatres of Dion and Mieza are almost at the same size, occupying about 1430m^2 [Karadedos, 1986; Karadedos *et al*, 2001] while the theatre of Philippi is comparatively larger, at 2350m^2 [Koukouli-Chrysanthaki and Karadedos, 2001].

Table 10.1. *Detailed characteristics of the theatres used for the scenery classification simulations.*

	Dion	**Mieza**	**Philippi**
Overall dimensions (m^2)	1429.142	1428.655	2348.867
Length (m)	49.97	48.171	65.154
Width (m)	28.6	29.658	36.051
Diameter (m)	47.977	56.449	65.928
Radius (m)	24.857	28.224	32.964
Angle in plan (°)	161	90	153
Orchestra's radius (m)	13.141	11	12.796
Height of the koilon (m)	3.10	6.66	11.070
Inclination of the koilon (°)	25	22	25 below 27 above
No of rows	8	19	8 below 13 above
Material	brick	limestone	marble

Shape

When looking at the plans, the angle of the audience area varies at each theatre. The angle of audience area is quite important for the distribution of sound due to the directivity of the human voice. Therefore, narrow angles that resemble the horizontal directivity of human speech are usually preferred. In this case, at the widely used theatres of Dion and Philippi the angle of the koilon is 161° and 153 ° respectively, quite wide when compared to the 90° of the theatre of Mieza.

Materials

The materials used for the theatres' construction usually dominate, especially from the viewpoint of acoustics, as seen in Chapter 7. The materials in the ancient theatres of Dion, Mieza and Philippi are brick, porous stone, and marble respectively. Consequently, the absorption coefficients are different, especially in the unoccupied conditions.

Location

The locations and the surroundings of the theatres also affect the overall soundscape, as briefly discussed in Chapter 9. Except for Philippi, the theatres are situated in archaeological sites, far from urban and traffic noise, although there are sources producing background noise during a performance, like people, cicadas, animals and occasionally cars and motorbikes. The theatre of Philippi is located next to a major motorway connecting two cities, thus the conditions are not ideal during the performances.

Condition

Excavations are still carried out in all theatres. The excavation and restoration projects are mainly focused on the skene-buildings of the theatres of Dion and Philippi, and on whole area of the theatre of Mieza. It needs to be noted that for the latter, the restoration proposal plans are used for the application of scenery designs.

10.3 Classification and Generic Design of Scenery

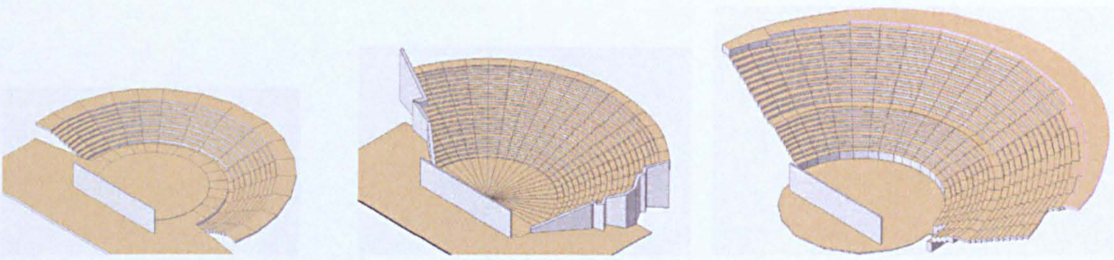
After examining the sceneries that have been created in ancient theatres for the performances of ancient drama in the 19^{th} and 20^{th} centuries in Greece, the categories identified for the scenery designs in Chapter 4 are the following four, divided into subcategories according to the variables examined [Chourmouziadou and Kang, 2007b].

10.3.1 Category 1: Background wall

In this category the generic scenery is basically composed of some kind of a boundary, namely a wall that is situated in the orchestra, usually in front of the ancient skene-building, bearing in mind that, in terms of contemporary sceneries, nothing is allowed to be constructed on top of the ancient ruins, since they are listed and still studied. This is a commonly used scenery layout, as seen in Chapter 4, and has been used for the performances of 'Prometheus Bound' and 'Iketides' in 1930 by Kontoleon, 'Ekabi' and 'Oresteia' in 1955 by Klonis, 'Oedipus Tyrant' in 1985 by Aggelis [Kontogiorgi, 2000], 'Bacchai' in 1983 by Patsas [Patsas, 1995], the recent 'Iphigenia en Taurois' by Toutsi in 2006 and many more. After the study carried out in Chapter 9 for the variety of wall layouts for the theatre of Mieza, only the linear wall will be the subject of this Chapter's investigation. The variables that will be further examined discussed below. It needs to be noted that the important difference between this section and the analysis in Chapter 9 is the examination of contemporary scenery forms in relation to the theatre layouts, and the detailed investigation of scenery layouts that would 'function' acoustically when adapted to many open-air theatres.

10.3.1.1 Theatre Layout

In this case the physical characteristics of the wall will be constant, like height (5m), length (20m), width (0.10m) and materials (marble), while for the surrounding space the three theatre layouts will be used.



a b c

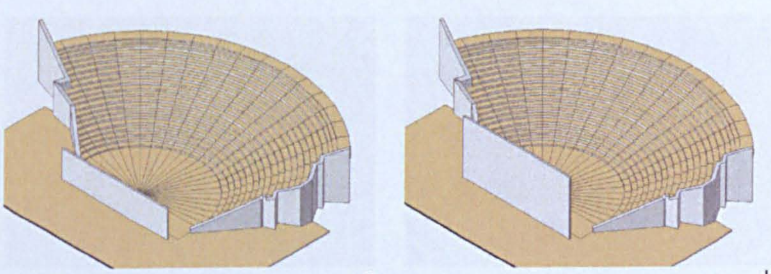
Figure 10.3.1. *The theatres with 5x20m background wall. a) Dion, b) Mieza and c) Philippi*

10.3.1.2 MATERIALS

For this part of the study the simulation will be carried out for three materials, marble, gypsum and textile, reflecting at different absorption coefficients, to check the final result in terms of acoustic indices and energy responses. The materials were selected based on previously constructed sceneries, like the examples of Chapter 4. Also, the variety of the material coefficients allows a wider range in the acoustic indices' results. The theatres of Dion and Mieza have been chosen for this section, due to the different materials used for their construction that will consequently affect the overall result.

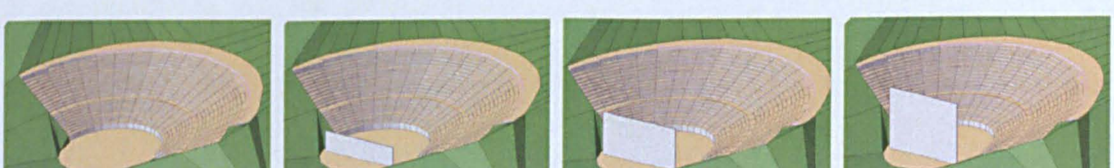
10.3.1.3 HEIGHT

The height of the scenery is of importance, when its materials are rather hard. This will allow strong reflections between the scenery wall and the audience area, and may create unwanted acoustic effects, like flutter echoes. Due to the different layouts and heights of the selected theatres, the theatres of Mieza and Philippi have been used in this section, with walls measuring 5 and 10m for the former and 5, 10 and 15m for the latter. Figures 10.3.2 and 10.3.3 show the configurations used. The theatre without any scenery installed, has also been calculated for comparison. The material of the wall is marble in all configurations.



a b

Figure 10.3.2. *The theatre of Mieza with the background scenery walls. a) 5m and b) 10m.*



a b c d

Figure 10.3.3. *Configuration used for the theatre of Philippi. a) No background wall, b) 5m, c) 10m and d) 15m background wall.*

10.3.1.4 SHAPE OF SCENERY WALL

As seen in Chapter 9, in the theatre of Mieza, four shapes of the background wall have been installed [Chourmouziadou and Kang, 2004; 2005], to examine their effect on the acoustic indices. These are a linear, a convex, a concave wall, and a dome.

10.3.1.5 AUDIENCE

In the theatre of Philippi the occupied condition of the theatre is compared to the unoccupied, when a 10m wall is installed. These two conditions are also simulated without the presence of a wall for comparison and to show the effect of the scenery, with absorption coefficients as seen in Table 10.1.

10.3.2 CATEGORY 2: LARGE ORCHESTRA OBJECTS

This category involves objects that are placed in the orchestra as the main architectural components used for the performance. The first scenery created in the 20^{th} century that belongs in this category was the rock used for 'Prometheus Bound' in the celebrations in Delfoi in 1927, shown in Chapter 4, while there were many cases where one object was used. These objects partly create a background and provide a space for the actor to hide or exit the main performance space, without interfering with the surroundings.

Four basic geometric shapes have been used for these calculations: a cube, a sphere, a cylinder and a pyramid, illustrated in Figure 10.3.4. Particularly for the cube and the pyramid the shapes were derived from actual sceneries, as seen in Chapter 4, created for the performances of 'Oedipus Tyrant' in 1987 by Photopoulos [Photopoulos, 1987], 'Prometheus Bound' in 1927 by sculptor Phoskolos and 'Ekabi' in 1927 by Kontoglou [Kontogiorgi, 2000], recent examples like 'Eleni' by Kakridas in 2006, while the rest have been used to examine sound distribution in different patterns. Due to the nature of these shapes, it is expected that the impact on the acoustic indices will be different in each case. The flat panel diffusion coefficients were applied to the surfaces of all the objects and a detailed 3D representation of their shapes allowed additional diffusion due to surface size, especially for the curved surfaces. The theatre of Philippi has been used as a basis for all the calculations, since it is of medium size with a rather open angle in plan.

a b c d

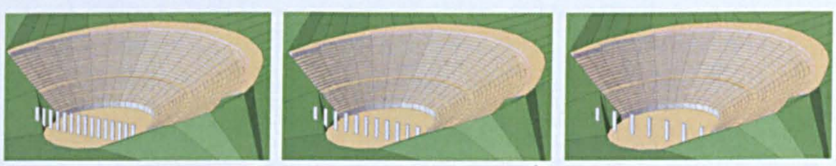
Figure 10.3.4. *Generic scenery in the theatre of Philippi. a) Cube, b) Sphere, c) Cylinder and d) Pyramid.*

10.3.3 CATEGORY 3: SMALL ORCHESTRA OBJECTS

The 'props' used in modern theatre performances are all the small objects that are necessary for a performance to take place, like tables, chairs and other furniture and equipment. The small objects in this study are panels placed on the orchestra, forming a line or even scattered. It is common practice, especially in recent performances, to use this kind of scenery, because it doesn't distort the visual impact of the ancient theatre and its surroundings and at the same time provides a reference to the play. Because of the complexity and the variability of the positioning, the size and the shape of the objects, there are several variables simulated. Examples of this category are the sceneries for 'Iketides' in 1964 by Pappas [Greek skenographers, costume designers and ancient drama, 1999] and 'Ecclesiazousai' in 1993 by Patsas [Patsas, 1985]. The theatre of Philippi is used.

10.3.3.1 DENSITY

One of the major decisive factors for the acoustic effect of the small objects is their density. Several studies have been carried out regarding the density of reflectors in indoor spaces, like theatres and concert halls and some of the principles used can be applied in this case. Regarding the density of the objects used in this case, panels of 1m width and 5m height were positioned in a line with a spacing of 1, 2 and 4m. The generic sceneries used for this category can be seen in Figure 10.3.5.

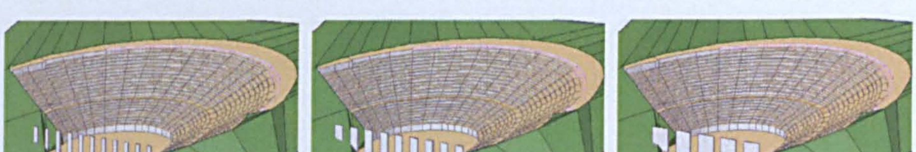


a b c

Figure 10.3.5. *The theatre of Philippi with 1x5m panels with a spacing of a) 1m, b) 2m and c) 4m.*

10.3.3.2 SIZE

Due to the variability in sizes mentioned above, simulations were carried out for a line of panels of 5m height, positioned every 2m. These had widths of 1m, 2m or 4m, as shown in Figure 10.3.6.

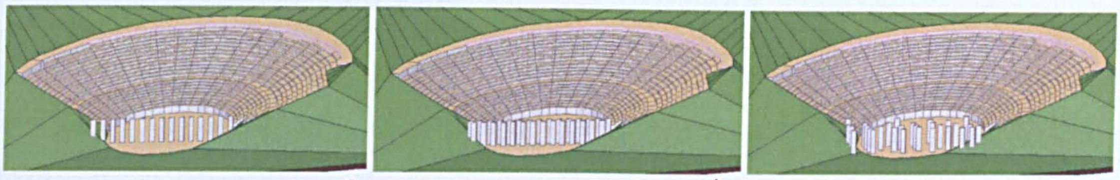


a b c

Figure 10.3.6. *The theatre of Philippi with a) 1m, b.)2m and c) 4m wide panels with a spacing of 2m.*

10.3.3.3 DISTRIBUTION

The placement of the panels in the orchestra can either provide the effect of the wall, or be randomly placed. In this study the panels were distributed evenly in one row, two rows (to provide a more dense background) or scattered in the orchestra, to examine possible variations. Figure 10.3.7 presents the panels of 1m width and 5m height in the three arrangements.



a b c

Figure 10.3.7. *Panels measuring 1x5m. a) Distributed in one row, b) Distributed in two rows and c) Scattered in the orchestra.*

10.3.4 CATEGORY 4: ORCHESTRA

This category is rarely scenery on its own, but usually in relation with small orchestra objects or any other category. Covering the orchestra was common in antiquity and, as mentioned in Chapter 2, the ancients were aware of the effect on the sound environment. The theatre used for this part of the simulation is Dion.

10.3.4.1 MATERIALS

Similarly with Section 10.3.1.2, the material of the orchestra are a major factor in determining sound, since reflection amplitudes are closely related with sound absorption and diffusion. Previous studies support that the first reflection in the ancient theatre is off the orchestra's floor [Barron, 1993]. More recent research has shown that in some cases the risers of the koilon provide the first reflection, followed by the reflection from the orchestra [Chourmouziadou and Kang, 2002; Vasilantonopoulos *et al*, 2004]. Therefore, since the orchestra contributes to the overall acoustic environment by providing early reflections, both SPL and RT30 are formed accordingly. Previous scenery designs have used several materials to cover the orchestra, like straw, in the performance of 'Ploutos' in 1985 by Photopoulos [Photopoulos, 1987], or plastic in 'Thesmophoriazousai' by Mizicov in 2003 [Chourmouziadou and Kang, 2006b]. The materials used for this part of the study include reflective ones, like marble, and gypsum, as well as rough soil, and absorptive ones, like grass. Also, to enable multiple reflections, a 5m high background scenery wall is used. According to Chapter 6, flat panel diffusion coefficients are applied to the surfaces. The effects of glass, water and plywood are also discussed in this section.

10.3.4.2 HEIGHT

The height of the orchestra's floor can influence sound distribution, similarly to the height of the stage. Past sceneries have used raised orchestra floors, like 'Electra' in 2003 by G. Patsas [Chourmouziadou and Kang, 2006b]. In previous research it was indicated that the raised stage in the evolution of ancient theatres has resulted in improved acoustic conditions. Therefore, the simulation has been carried out with 3 orchestra levels, 0m, 0.30m, 0.60m and 0.90m.

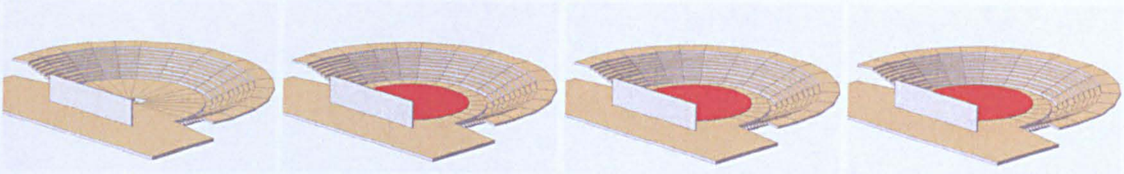


Figure 10.3.8. *Several orchestra levels at the theatre of Dion. a) 0m, b) 0.30m, c) 0.60m and d) 0.90m.*

10.4 ACOUSTIC EFFECT OF GENERIC SCENERY DESIGN

Figure 10.4.1 illustrates the receiver positions for the calculations at the theatres of Dion, Mieza and Philippi. Table 10.2 shows the absorption coefficients for the materials used for the simulation.

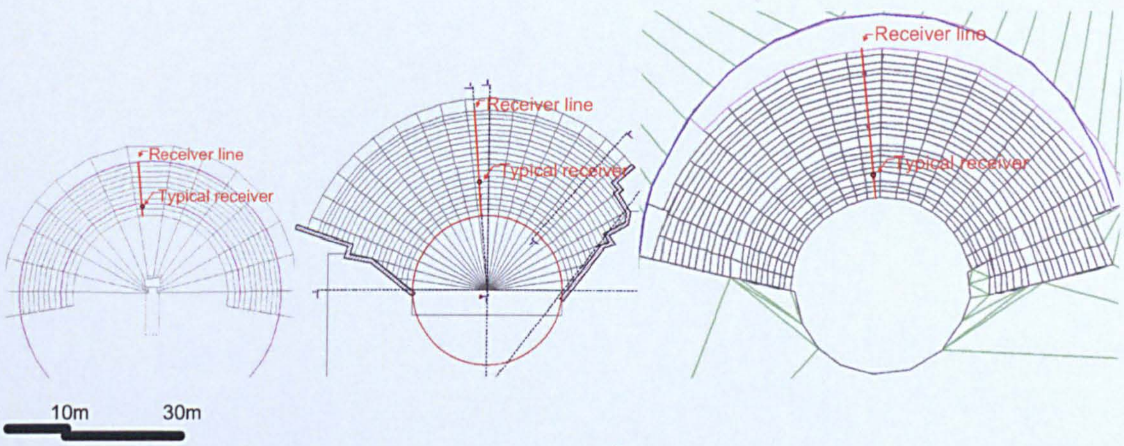


Figure 10.4.1. *Position of the typical receivers as well as the receiver lines. a) Dion, b) Mieza and c) Philippi.*

Table 10.2. *Absorption coefficients of the materials used in the simulation.*

ABSORPTION COEFFICIENTS (Hz)	**125**	**250**	**500**	**1k**	**2k**	**4k**
Audience [Beranek, 1998]	0.35	0.38	0.41	0.38	0.33	0.26
Brick [LMS, 2001]	0.09	0.07	0.05	0.05	0.05	0.05
Grass [Egan, 1988]	0.11	0.26	0.6	0.69	0.92	0.99
Gypsum board 1/2" thick [Egan, 1988]	0.1	0.05	0.04	0.07	0.09	0.05
Limestone (measured, Chapter 8)	0.01	0.01	0.052	0.071	0.087	0.085
Marble [LMS, 2001]	0.01	0.01	0.01	0.01	0.01	0.01
Reflector [LMS, 2001]	0.14	0.11	0.10	0.06	0.05	0.05
Rough soil [Egan, 1988]	0.15	0.25	0.40	0.55	0.60	0.60
Textile [Egan, 1988]	0.12	0.14	0.60	0.70	0.73	0.85
Water [Egan, 1988]	0.01	0.01	0.01	0.02	0.02	0.03

The following results are presented according to the classification of Section 10.3 and the sub-categorisation. All simulations have been carried out with 10.000 rays. The reflection order is

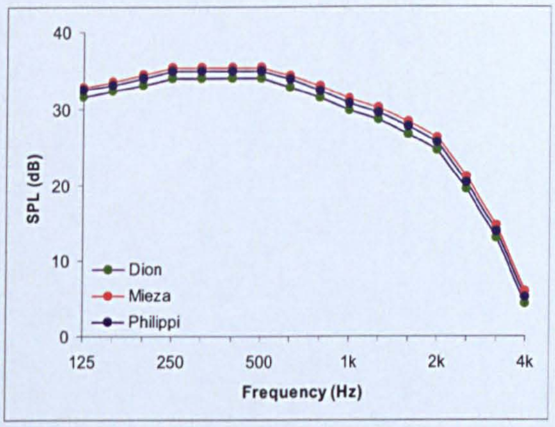
10, the time window is 2000ms, the dynamic range at 90dB, while flat panel diffusion is always calculated for the theatre surfaces at 0.3 at 125Hz, 0.2 at 250Hz, 0.15 at 500Hz, 0.1 at 1kHz, 0.09 at 2kHz and 0.07 at 4kHz.

10.4.1 Category 1: Background wall

10.4.1.1 Theatre Layout

The results of this part of the simulation correspond to the three theatres involved, with the exact material characteristics as in the current condition of Dion and Philippi and in the restoration proposal of Mieza, described in Chapter 9. The height of the scenery wall is 5m. For the sake of convenience the theatre of Dion is represented by the green circle, the theatre of Mieza by the red and the theatre of Philippi by the blue.

Figure 10.4.2 illustrates the SPL for the typical receiver at around 17.3m from the source, as well as for the receiver line at 500Hz. The results regarding the range of frequencies, seen in Figure 10.4.2a, are almost at the same levels at the three theatres, since the receivers chosen are at the same distances from the source. The SPL values at the theatre of Dion are the lowest, 1.2-1.7dB lower than Mieza and 0.8-1dB lower than Philippi, due to its brick construction, when compared to the harder materials of the other two, namely porous stone and marble. Consequently, Mieza presents SPL by 0.3-0.7dB higher than Philippi, possibly caused by the smaller size that allows early reflections to reach the receiver with high amplitudes. However, in Figure 10.4.2b it is shown that there is higher attenuation at the SPL curve for the theatre of Dion, compared to the others, due to the softer material.



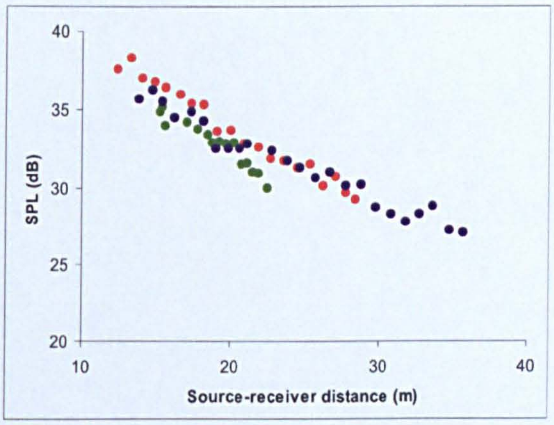


Figure 10.4.2. *SPL (dB) results for the three theatres. a) Typical receiver at the range of frequencies and b) Receiver line at 500Hz.*

More interesting are the results regarding reverberation. The higher values, at 0.93-1.2s at mid-frequencies, are presented in the theatre of Dion, although it is of smaller size and is made of brick, a soft material. This could possibly be explained by the wider layout of Dion, which is 161°

in plan, allowing reflections between opposite surfaces of the koilon, compared to 153° of the theatre of Philippi and 90° of the theatre of Mieza. However, in order to characterise the whole theatre it is important to check the results regarding the receiver line and the whole audience area. For the former in the theatre of Philippi the RT30 is 0.44-1.27s due to the large size and the wide layout, while the theatre of Mieza has RT30 at 0.76-0.98s. It is shown in this way that, although the curves for the typical receiver are smooth for the frequency range, for the receiver line the theatres of Mieza and Dion have a more even distribution of RT30, compared to Philippi. The changes in the acoustic environment of the three theatres reveal that, considering the effect of the specific scenery (background wall, 5m high), it is possible to allow for adaptability when designing scenery, considering the layouts of the theatres that will accommodate it. This is the major difference between this chapter and Chapter 9, which mainly focused on purposely-built sceneries, used by one theatre only.

Nevertheless, specular reflections can determine the RT30 considerably and present significant differences between two adjacent points, due to the amplitude of specular reflections and the software's feature to translate the decay curves of the energy responses into reverberation. This was further explained in Chapters 2 and 5. Moreover, the energy responses in Figure 10.4.4 reveal that for the theatre of Dion the reflections are less compared to Mieza and Philippi, leaving some delay gaps as well, which is a contradiction to the long RT30 found at the typical receiver point.

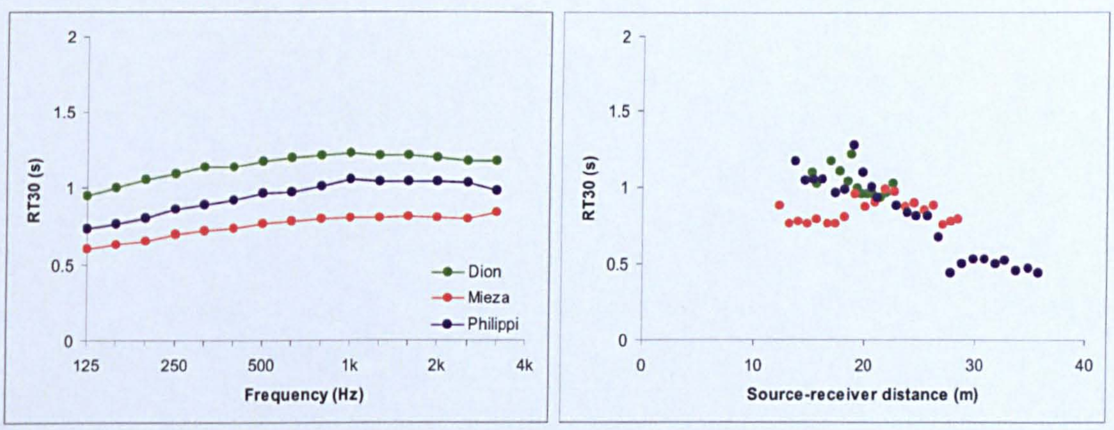


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Figure 10.4.3. *RT30 (s) results for the three theatres. a) Typical receiver at the range of frequencies and b) Receiver line at 500Hz.*

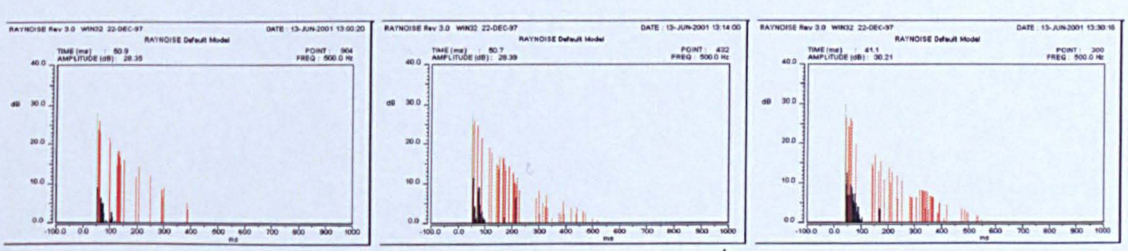

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Figure 10.4.4. *Energy responses. a) Theatre of Dion, b) Theatre of Mieza and c) Theatre of Philippi.*

Corresponding to Figure 10.4.3, Figure 10.4.5 illustrates the colour maps of RT30 of the theatres, revealing the variation in reverberation in the theatre of Philippi. This is also related to the height of the background wall, as will be seen in Section 10.4.1.3.

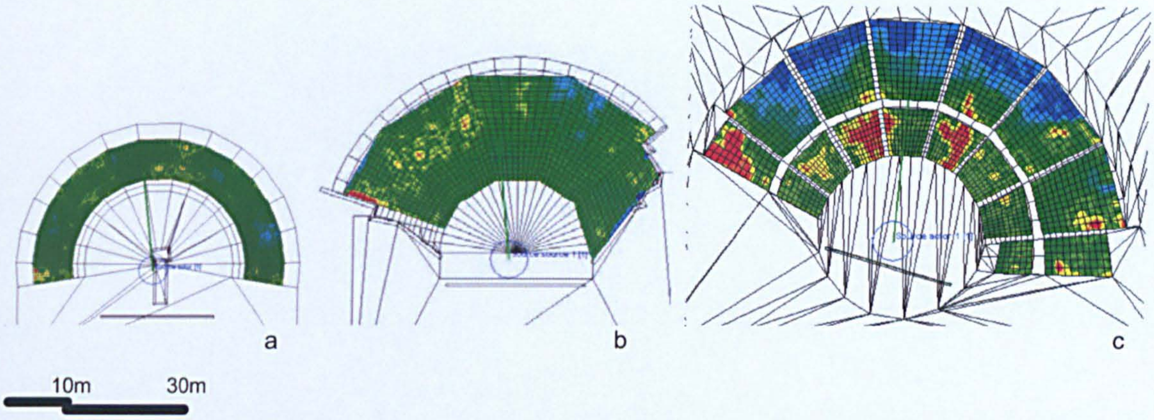


Figure 10.4.5. *RT30 (s) colour maps. a) Theatre of Dion, b) Theatre of Mieza and c) Theatre of Philippi.*

Figure 10.4.6 illustrates the results for STI and C80. Corresponding to reverberation the results of STI show that the best speech intelligibility conditions can be found in Mieza with STI around 0.6 as long as there is no background noise from the surrounding area. All the theatres present similar results regarding clarity, as can be seen in Figure 10.4.6b, with C80 between 5 and 10dB. The bigger variation can be found in the theatre of Philippi between the low and the high part of the audience area. The former is around 4-6dB while the latter around 8-11dB. Due to the relationship between early and later arriving sound, C80 and RT30, small number of reflections to the high part of the koilon produces short reverberation time and increases clarity. This is possibly a result of the relatively low background wall, which, although it is efficient for producing relatively long RT30 at the lower audience areas of the theatres of Dion and Mieza, as seen in Figure 10.4.3, seems inefficient for the theatre of Philippi.

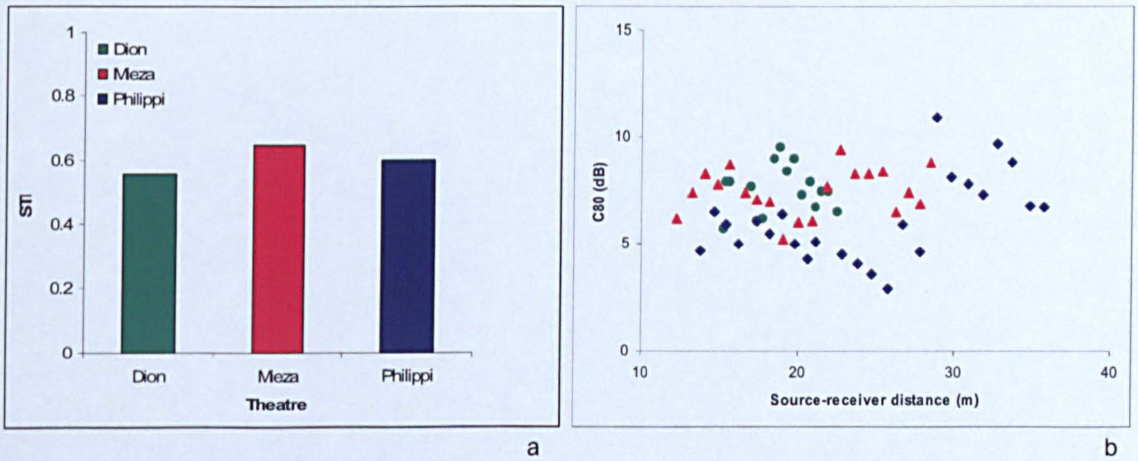


Figure 10.4.6. *Acoustic indices for the three theatres for a) STI for the typical receiver and b) C80 (dB) for the receiver line at 500Hz.*

10.4.1.2 MATERIALS

The absorption coefficient of marble is 0.01 for the range of frequencies. Gypsum has higher absorption coefficients while textile is even more absorptive, as shown in Table 10.2. It is noted that especially high coefficients were selected for textile, corresponding to folded curtains, to indicate extreme conditions. For marble and gypsum flat panel diffusion coefficients have been applied to the surfaces. Figure 10.4.7 illustrates the SPL, RT30 and STI for the theatre of Dion.

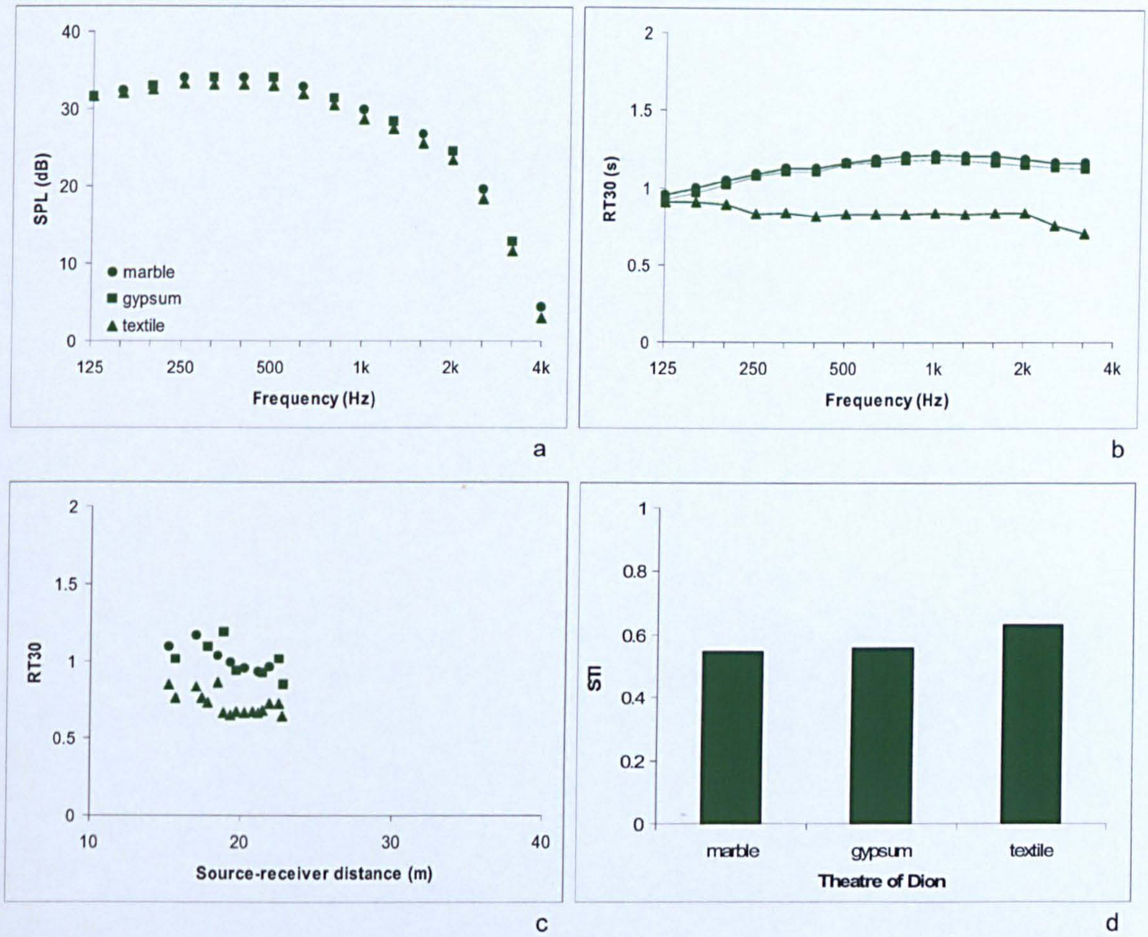


Figure 10.4.7. The theatre of Dion with three materials for the 5m background wall. a) SPL (dB) for the typical receiver at the range of frequencies, b) RT30 (s) for the typical receiver at the range of frequencies, c) RT30 (s) for the receiver line at 500Hz and d) STI for the typical receiver.

Figure 10.4.7a shows the SPL for the typical receiver, revealing the trivial effect of the change between marble and gypsum for the scenery wall. The differences between the two materials are around 0.1dB, whereas when replaced by textile the differences are at the scale of 0.3-1.3dB, the larger indicated at high frequencies. For RT30 the results between marble and gypsum have the same effect as in SPL, with variations of about 10-30ms. The absolute RT30 values are around 0.90-1.20s. By comparing marble with textile, the RT30 becomes shorter by an average of 0.33s for the frequency range, at about 0.75-0.90s. The effect is more obvious at high frequencies. By examining Figure 10.4.7c, namely the RT30 at mid-frequencies for the receiver line, it is shown that the curve is fairly smooth, following the same line for all the materials. The STI results are around 0.55 for the hard and 0.63 for the soft materials, which correspond to 'fair to good' intelligibility, assuming that there is no background noise.

More simulations have been carried out for the ancient theatre of Mieza, with the same wall height and materials, as in the theatre of Dion. Figure 10.4.8 illustrates the acoustic indices. Similar to the theatre of Dion are the results of SPL, with the marble and the gypsum wall having the same effects. The values are reduced with the textile by an average of 1dB for the receiver line at 500Hz and with similar effect on the other frequencies. The same applies to reverberation, where the marble and gypsum produce 0.60-0.84s from low to high frequencies and the textile 0.60-0.63-0.48s. It can be seen that the highest differences can be found at high frequencies, where the absorption of textile is increased, as seen in Table 10.2.

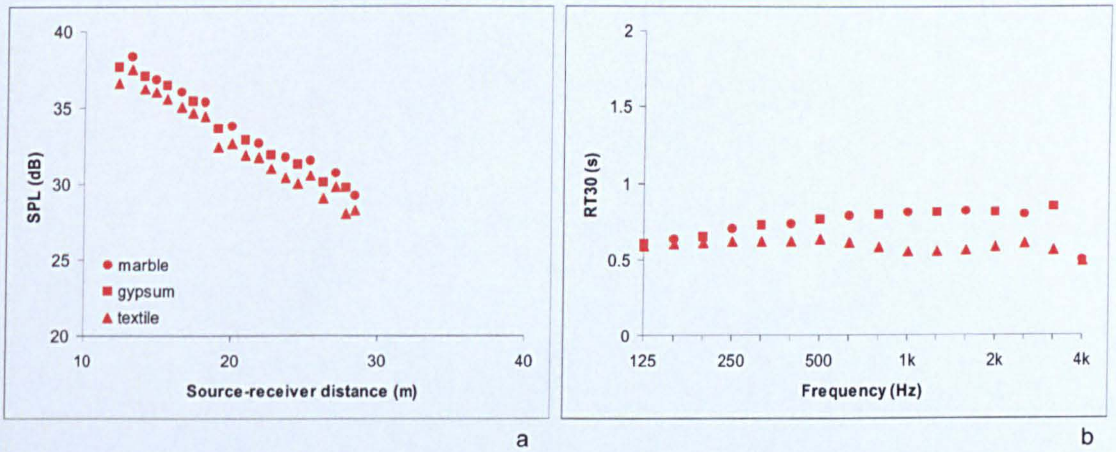


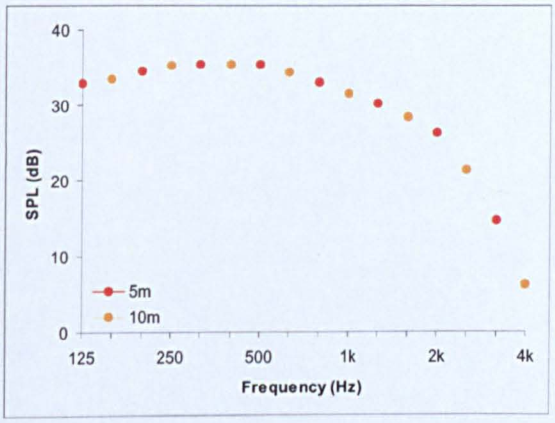
Figure 10.4.8. *The theatre of Mieza with three materials for the 5m background wall. a) SPL (dB) for the receiver line at 500Hz and b) RT30 (s) for the typical receiver at the range of frequencies.*

10.4.1.3 Height

For the theatre of Mieza, with the highest row of the koilon at 6.66m, two heights have been considered for the background wall, of 5 and 10m. The reason for that is that above a specific height the sound paths cannot reach the receivers, because the specular reflections are sent to the sky. Similarly, the positioning of the wall is the same, since the closer the wall is to the source and the audience, the less height is needed for the sound to be reflected effectively.

The simulation for the theatre of Mieza has shown that there is no particular impact of the wall height on the SPL, with less than 0.3dB variation. This can be seen in Figure 10.4.9a. Figure 10.4.9b reveals that for RT30 the differences are just noticeable, at a maximum of 0.20s, found at the rear seats, where the longer RT30 is found, around 0.75-1.0s. These phenomena are explained by the relation between the height of the theatre and the scenery height, as far as the specular reflections are concerned, and is further clarified in Figure 10.4.10, where the colour maps representing the RT30 for the whole audience area at 500Hz and a cross section of the theatre are shown.

It is shown that the distribution pattern is not significantly altered between the two scenery heights. The cross section of the theatre illustrates that specifically for specular reflections the higher reflection point on the wall is at 2.20m, as shown by the blue path. Above that it is mostly diffuse reflections that form the RT30. Therefore, although the reflection path from the highest point of the 5m high wall leads sound to the sky, for most of the receivers seated high in the auditorium the reverberation has increased from around 1s to 1.25-1.50s, suggesting reflections due to the diffusion applied to the high scenery wall.



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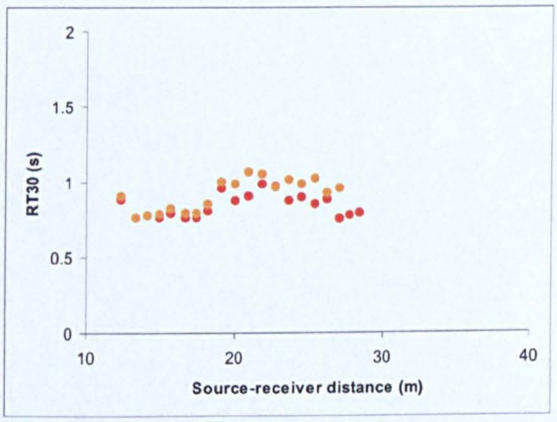


b

Figure 10.4.9. *The theatre of Mieza with background wall of 5 and 10m height. a) SPL (dB) for the typical receiver at the range of frequencies and b) RT30 (s) for the receiver line at 500Hz.*

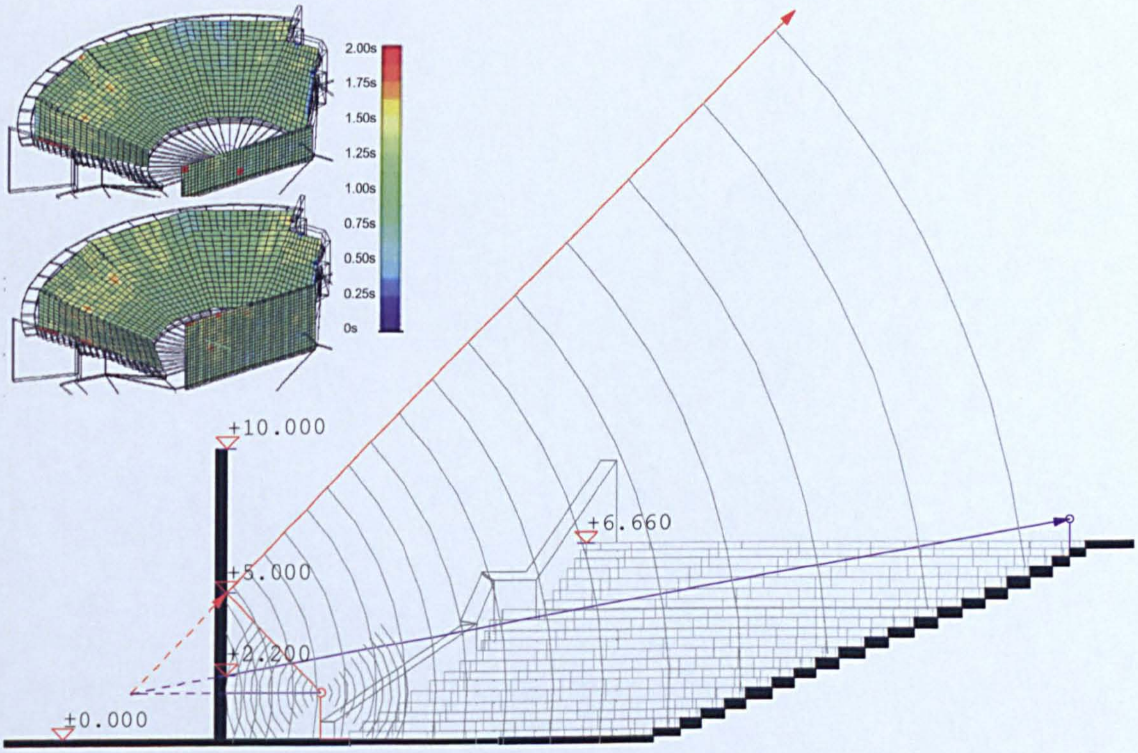


Figure 10.4.10. *The theatre of Mieza. Colour maps with background wall of 5m and 10m height and cross showing the reflection paths.*

For Philippi the height of the scenery follows the increased height of the auditorium (11.07m). Therefore the background wall has been calculated with 5, 10 and 15m height. Figure 10.4.11 illustrates the acoustic indices for the theatre of Philippi for the three wall heights, as well as without any scenery installed. Compared to no scenery the 5 and 10m wall add 1.7-3.1dB to the SPL, while the 15m wall further increases SPL by 0.4-1.5dB. This proves the efficiency of the specific type of the generic scenery in increasing the SPL at the audience area. The absolute values of the SPL are at an average of 36dB for the receivers close to the source, decreasing at 27dB for the ones seated at the highest parts of the koilon.

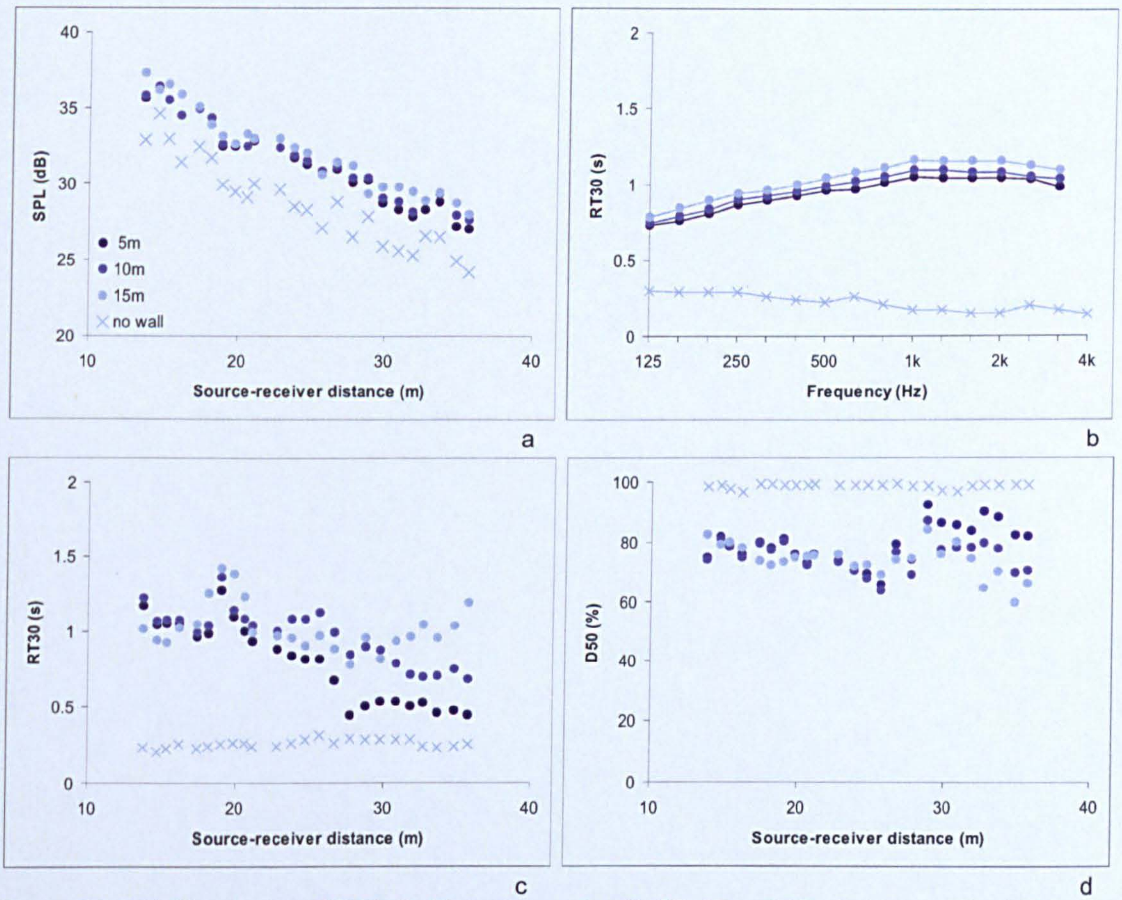


Figure 10.4.11. *The theatre of Philippi with background wall of 5, 10 and 15m height. a) SPL (dB) for the receiver line at 500Hz, b) RT30 (s) for the typical receiver at the range of frequencies, c) RT30 (s) and d) D50 (%) for the receiver line at 500Hz.*

The results regarding reverberation are similar, showing that the scenery's presence increases RT30 by up to 1s with maximum differences between the different wall heights by 0.20s at high frequencies. By examining the RT30 at mid-frequencies it is shown that far from the source the variation between the three conditions increases. From 5 to 10 the difference for the receivers seated at more than 30m from the source is 0.25s and additionally 0.25s from 10 to 15m wall. In general the RT30 is between 0.50 and 1.40s, depending on the scenery's height. The definition for the theatre with no scenery approaches 100%, while the decrease with the scenery is by 5-35%.

From the simulation it is suggested that the effective scenery height is related to the height of the audience area in an ancient theatre, while it is also affected by the proximity to the source. Therefore for Mieza a wall of 2.20m is needed to provide the minimum number of useful specular reflections to the audience (seated from 0 to 6.65m height near the axis of the theatre), when this is situated at almost 4m behind the source. For Philippi background walls situated at 2m, 4m and 8m behind the source need to be 2.20m, 2.50m and 3.50m high respectively, although to consider the whole audience area, as well as to provide diffused sound, higher walls are needed. In particularl, the higher part of the scenery affects mostly the receivers seated high at the auditorium.

10.4.1.4 Shape of Scenery Wall

As seen in Chapter 9 and in the previous research, a simple linear wall has similar effects to the original skene-building and also contributes to relatively long RT30. With the other scenery shapes including convex, concave and dome, the SPL distribution is not even in the audience area, since some create focus areas, and the reflection/energy-response patterns are uneven, although the RT30 may appear to be long.

10.4.1.5 Audience

As seen in Section 10.4.1.3 the 10m wall increases SPL by 1.7-2.6dB compared to the theatre with no scenery applied. Figures 10.4.12a and b illustrate the SPL for the typical receiver at the range of frequencies and the receiver line at 500Hz respectively.

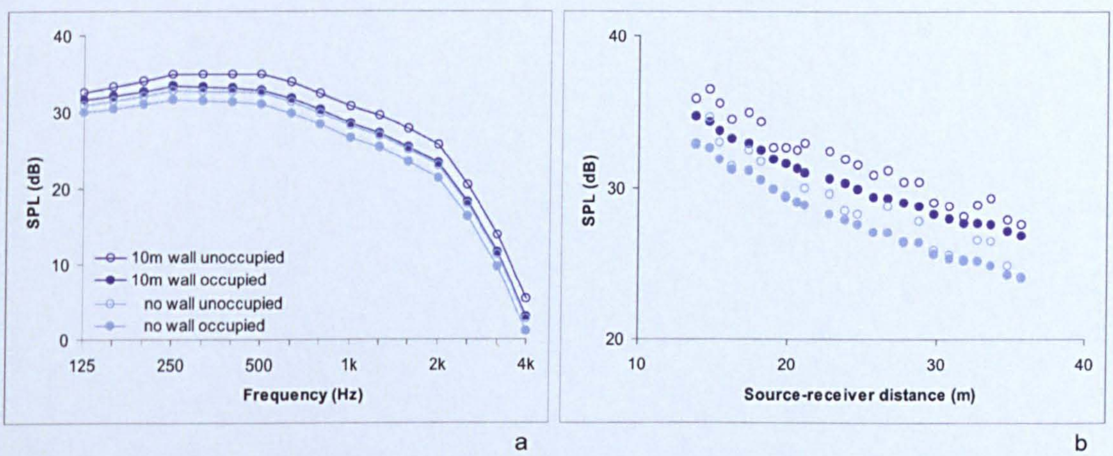


Figure 10.4.12. *SPL for the occupied and unoccupied condition of the theatre of Philippi. a) SPL (dB) for the typical receiver at the range of frequencies and b) SPL (dB) for the receiver line at 500Hz.*

As expected, for the occupied theatre the difference between no scenery and 10m background wall is reduced due to the audience's absorption by 1.6-2dB. In general, the occupied condition reduces SPL by 1-2.3dB compared to the unoccupied when a 10m scenery wall is installed and by 0.9-1.6dB when there is no scenery. Therefore, even for the occupied condition the scenery significantly increases SPL, as seen in Figure 10.4.12. Regarding the source-receiver distance the occupied condition creates a smooth SPL curve, distributing sound more evenly. This can be also seen in the colour maps of Figure 10.4.13.

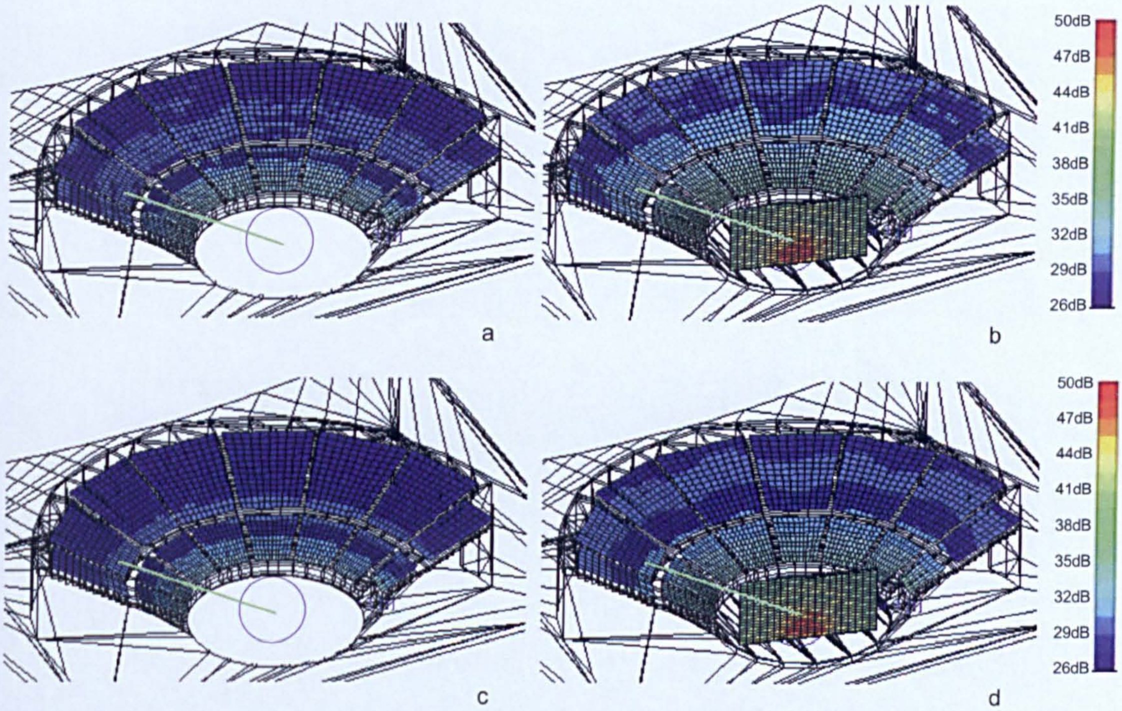
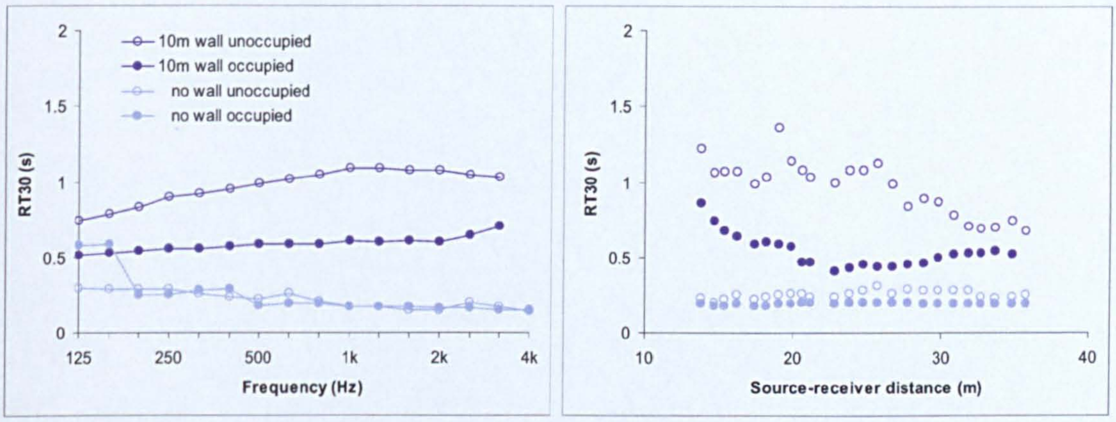


Figure 10.4.13. *Colour maps for the SPL (dB) distribution for the occupied and unoccupied condition of the theatre of Philippi. a) No scenery unoccupied, b) 10m wall unoccupied, c) no scenery occupied and d) 10m wall occupied.*

The reverberation in the theatre reaches its highest values when the scenery wall is applied and no audience is present (0.74s at low-to-mid frequencies and 1.09s at high frequencies). Obviously, the occupied theatre has shorter RT30, while its values are almost equal for the whole frequency range, at an average of 0.55s. More interesting are the RT30 values for the theatre with no scenery. It is noted that RT30 is almost indistinguishable between the occupied and unoccupied conditions, at 0.15-0.30s, with the exception of low frequencies, where the difference is around 0.30s, thus 0.59s for the unoccupied and 0.29s for the occupied condition. This is particularly important for the theatre practitioners, on the one hand because it shows the importance of scenery in reverberation, since it increases it by 0.40s even when the theatre is fully occupied and on the other because it reveals that the audience absorption is less important – if not at all – when there is no scenery.

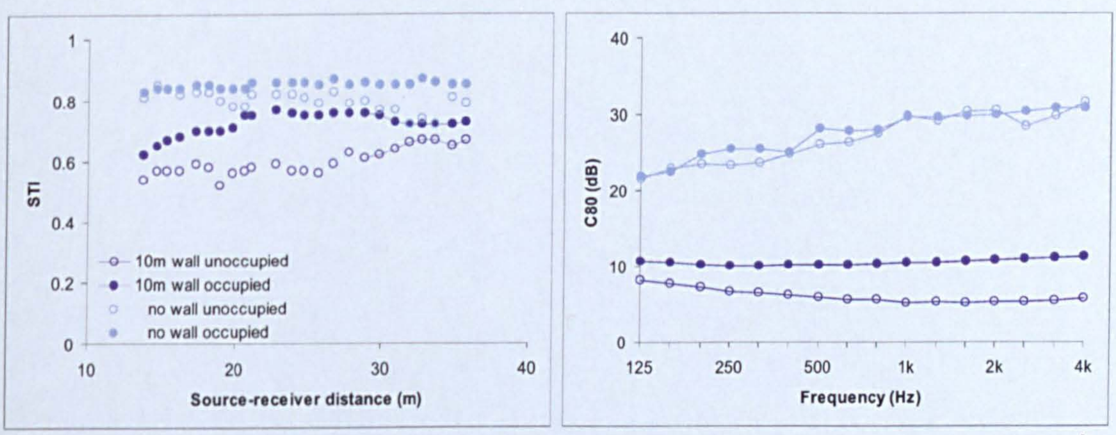
From Figure 10.4.14 the RT30 for the receiver line demonstrates that the audience absorption reduces RT30 significantly, balancing the differences between the different receiver positions on the receiver line. Especially at distances between 20 and 30m, the RT30 for the unoccupied condition is 1.10-1.30s and for the occupied at around 0.45-0.50s. Based on reflection patterns between opposite sides, the specific area is located at a height of 5.30-9.40m, where multiple reflections between the koilon and the wall become low in amplitude in the occupied condition. In opposition to this, the receivers close or far from the source had a reduction in RT30 at around 0.45 and 0.20s respectively.



a b

__Figure 10.4.14.__ Occupied and unoccupied condition of the theatre of Philippi. a) RT30 (s) for the typical receiver at the range of frequencies and b) RT30 (s) for the receiver line at 500Hz.

Corresponding to RT30 values at 500Hz the STI is almost the same for both conditions of the theatre, when the scenery is not present, while the differences between the two conditions with the scenery wall present the maximum values for the middle part receivers. From Figure 10.4.15 it is shown that generally the STI corresponds to 'fair to good' and 'good' speech intelligibility for the unoccupied and occupied condition respectively when the wall is installed and excellent when there is no scenery [Steeneken and Houtgast, 1985]. Clarity is around 6 and 10dB in the unoccupied and occupied condition with the wall respectively and around 22-30dB for the same conditions with no scenery.



a b

__Figure 10.4.15.__ The theatre of Philippi in the occupied and unoccupied condition. a) STI for the receiver line at 500Hz and b) C80 (dB) for the typical receiver at the range of frequencies.

10.4.2 Category 2: Large Orchestra Objects

The four basic geometric shapes that have been used for these calculations are attributed with flat panel diffusion, since it is assumed that the surfaces are rather smooth. For comparison, a sphere with Sröeder diffusion has also been simulated. Figure 10.4.16a illustrates the SPL for the receiver line shown in Figure 10.4.1c. Compared to the theatre without scenery, the SPL increase with the geometric objects varies from 0.2-0.7dB that corresponds to the cube, to 1.6-4.8dB that corresponds to the sphere. Looking at the different shapes, it is clear that the cube and the pyramid affect the least, followed by the sphere and the cylinder. This is explained by the early reflection patterns that, for the case of the circular objects, distribute sound to the audience, while for the cube and pyramid, send the reflections to particular audience areas and the sky, where it is absorbed. Particularly for the cube, one can rotate it accordingly, in order to send reflections to a specific area of the koilon, while in order for the whole audience area to be benefited, different shapes or sizes should be used. Normally the SPL values are in the range of 33.4-37.7dB for the receivers close to the source, and 24.4-29.1dB for the last rows of the koilon. Nevertheless it is clear that for most of the shapes there is an improvement in the SPL conditions compared to the condition of the theatre with no scenery, or to minimised scenery types, like small furniture.

As far as reverberation is concerned, Figure 10.4.16b demonstrates the geometric shapes for the typical receiver at the frequency range. It reveals the high effect of the cylinder, which increases the RT30 to 0.75s at low and 1.18s at high frequencies, given that it is a contribution of the convex shape and the detailed representation that allow specular reflections to reach the receiver areas, due to reflection patterns in addition to the reflection order. This corresponds particularly to high frequencies, possibly due to the wavelengths associated with the cylinder segments. The cube and the sphere produce RT30s at almost the same levels, at an average of 0.45 and 0.47s respectively, although the sphere has an even result for the frequency range. Regarding the cube, as mentioned previously for the SPL results, the fact that its edge is towards the audience, as shown in Figure 10.3.4, allows reflections mostly at the sides of the koilon, as seen later in Table 10.3. Even lower are the values of the spherical diffuser, at 0.31s, while the pyramid has no effect on reverberation due to the high number of lost reflections. Of course, for an imaginative scenographer it would be possible to turn the pyramid upside down and adjust the inclination in order to make the best of the early or the higher order reflections. Such an intervention could possibly lead to a stage enclosure, as shown in Chapter 9, but for the moment it should be left to the designer's creativity. Generally speaking, the RT30 values are quite short compared to the previous scenery category, namely the background wall. Since it is an outdoor theatre, no optimum values for RT30 can be suggested, although flutter echoes should always be avoided. Obviously, the high background wall that resembles the layout of the ancient theatre in terms of the skene-building, forming an enclosed space and producing comparatively long RT30 values, may contribute to the feelings of intimacy and warmth. In any case, there have been suggestions of optimum RT30 values for the indoor 'intimate' theatre, at 0.90-1.10s [Egan, 1988], which could possibly be achieved with appropriate scenery design.

There is however a drawback in the use of the cylinder. The long RT30 values, shown in Figure 10.4.16b, lead to comparatively low STI values, as seen in Figure 10.4.16c. As a result, speech intelligibility in this case is 'fair to good' according to Steeneken and Houtgast [1985]. The best values can be found at the theatre with the pyramid or with no scenery. However, it is indicated that as long as no background noise is applied to the theatre, the STI values will always depend exclusively on reverberation, thus the results will not be realistic. As far as clarity is concerned, compared to indoor spaces all C80 values are far higher, from 5-7dB for the cylinder, to 11-12dB for the sphere, either diffusive or not, 13-14dB for the cube and 21-30dB for the pyramid, as seen in Figure 10.4.16d, which reveals that the ratio of early sound to the late arriving sound is quite important for open-air theatres and can be achieved when less reverberant sound is produced.

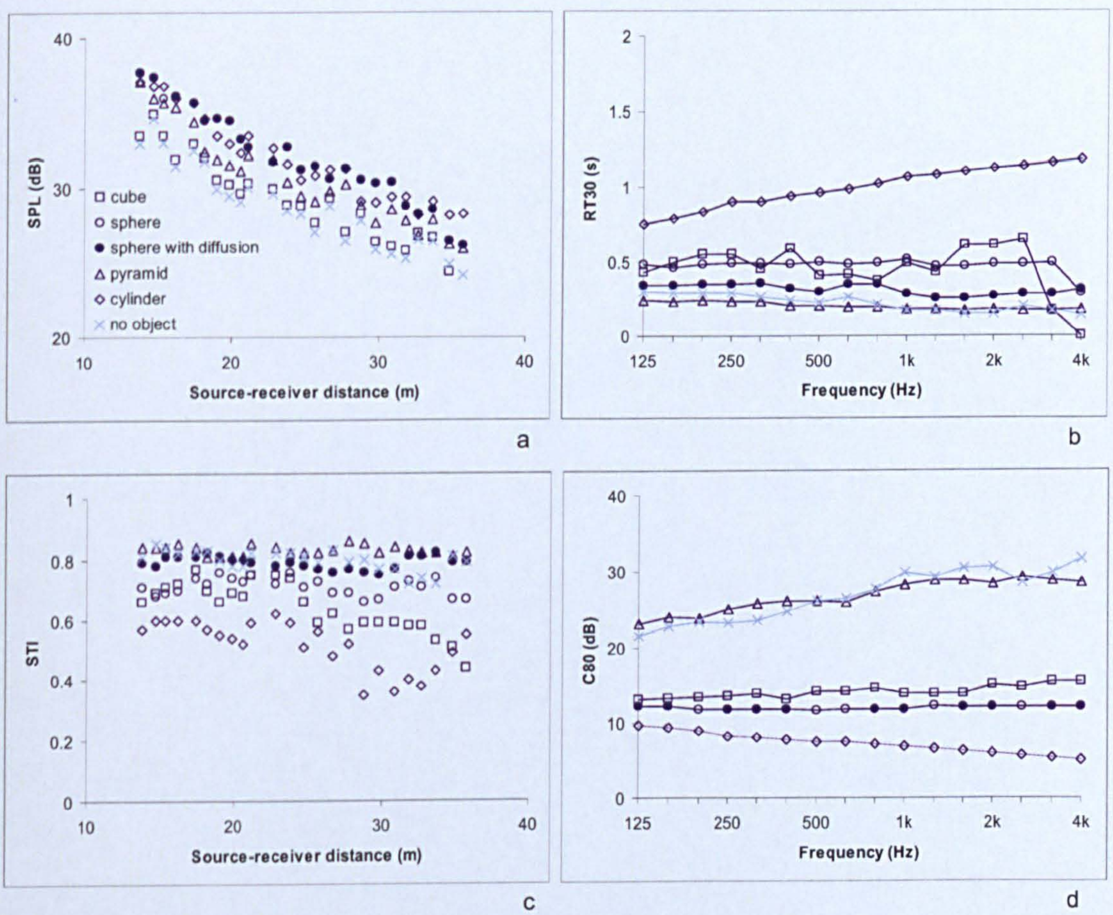
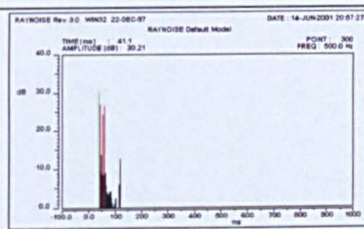
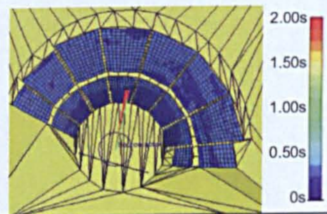
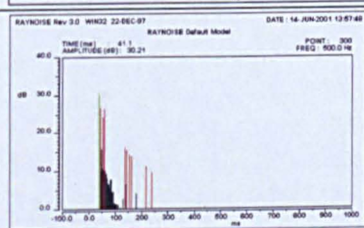
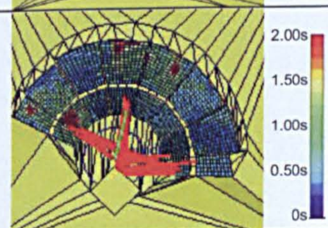
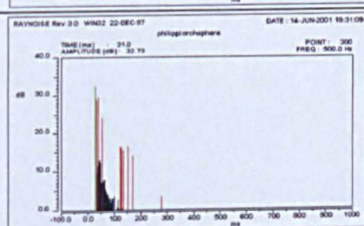
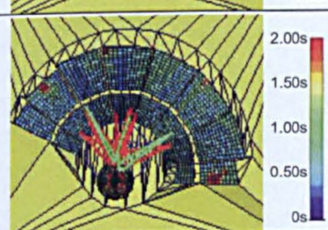
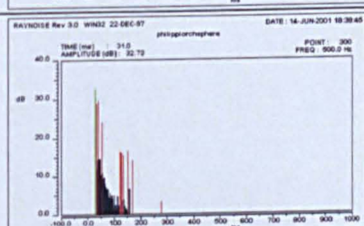
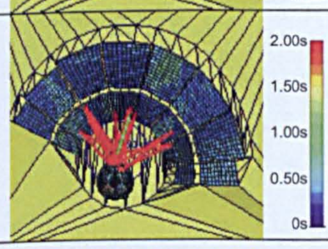
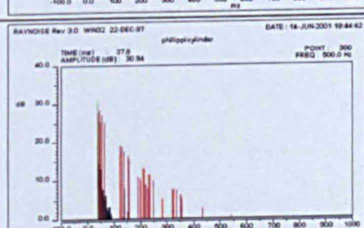
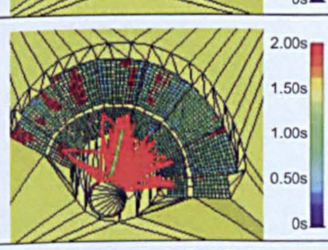
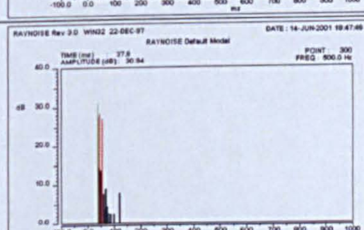
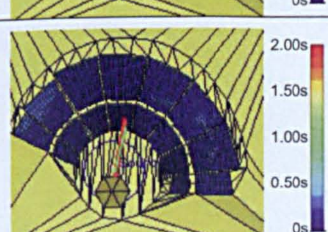


Figure 10.4.16. *Geometric shapes applied as scenery objects in the theatre of Philippi. a) SPL (dB) for the receiver line at 500Hz, b) RT30 (s) for the typical receiver at the range of frequencies, c) STI for the receiver line at 500Hz and d) C80 (dB) for the typical receiver at the range of frequencies.*

Table 10.3 illustrates the energy responses, the corresponding reflection paths and the colour maps for the RT30 for all geometric shapes. Clearly, the cylinder provides the maximum number of reflections, as shown in the form of the reflection path. It is noted that the red lines indicate the reflections while the green line corresponds to the direct sound. Due to the nature of the objects, the cylinder uses most of its surface area to provide reflections, combined with the koilon, illustrated in the energy response as well.

Table 10.3. *Energy responses, RT30 (s) colour maps and reflection paths at 500Hz, for all geometric shapes applied as scenery objects in the theatre of Philippi.*

Object	Energy Response	Reflection Paths and RT30
NO SCENERY		
CUBE		
SPHERE		
SPHERE DIFFUSION		
CYLINDER		
PYRAMID		

Although the cube assists as a shape in increased reflection number, its position and angle in the orchestra determine the reflection points. In this case, it is demonstrated that most reflections come from its two sides, from and towards the sides of the audience area. The sphere follows with better reflection distribution, while the additional diffusion increases the scattered energy, indicated by the black lines in the energy response. In terms of RT30 and reflection distribution the poorest shape is the pyramid, as explained earlier, almost similar to the theatre with no scenery installed. However, it needs to be noted that the scenery, regardless of its shape, usually creates better conditions in terms of reverberation than the condition of the theatre with no scenery. Provided that the aim of the performance is usually to bring the actor closer to the audience and to create intimacy, RT30 conditions seen above contribute to this.

10.4.3 Category 3: Small Orchestra Objects

Although it is most probable that one or two small scale 'props' used for the performances cannot significantly alter the acoustics of the theatre, when these are positioned in large numbers in a line or even scattered in the orchestra, the indices should be influenced. The material of the objects is reflector with absorption coefficients of 0.14 at 125Hz, 0.11 at 250Hz, 0.10 at 500Hz, 0.06 at 1kHz, 0.05 at 2kHz and 0.05 at 4kHz, as seen in Table 10.2, mostly to allow average absorption because of the variety of materials that could be used. It is not the intention of this section to examine the material characteristics of the panels, but rather to investigate their effect in terms of their position in the orchestra. Diffraction has also been considered in the simulation, both to allow the distribution of sound to areas behind the panels and to provide reflections from their edges, based on the methodology discussed in Chapter 6.

10.4.3.1 Density

The objects that will be used in this part of the study are rather narrow, 1m wide and 5m high. The variable that is examined in this case is density, thus the spacing between them is 1, 2 and 4m. Figure 10.4.17 illustrates the SPL, RT30 and C80 for the theatre of Philippi.

Figure 10.4.17a shows the SPL curve for the typical receiver at the frequency range, indicating that the density does not affect the results. All the values are at the same range, at around 31dB and 3dB at low and high frequencies respectively, while there is a peak at 400Hz at 33.1dB. Examination of the receiver line at 500Hz shows the same results. The solid and dashed lines represent the theatre with no scenery and the 5m scenery wall respectively, shown in Section 10.3.1.3. Therefore it is indicated, as for most of the scenery layouts that the dense objects do not contribute to higher SPL compared to the theatre with no scenery, as expected, due to the fact that SPL depends mostly on the direct sound and the early reflections. Nevertheless, the full sized wall (20m by 5m) increases SPL by 1-2dB at low-to-mid frequencies, while at higher frequencies the dense objects (every 1m) are more effective, most probably due to diffraction and edge diffraction, which were accounted for in the simulation. This was achieved by selecting the edges of the panels for diffraction to be automatically calculated during the simulation and by applying flat panel diffusion coefficients, according to the methodology in Chapter 6 respectively.

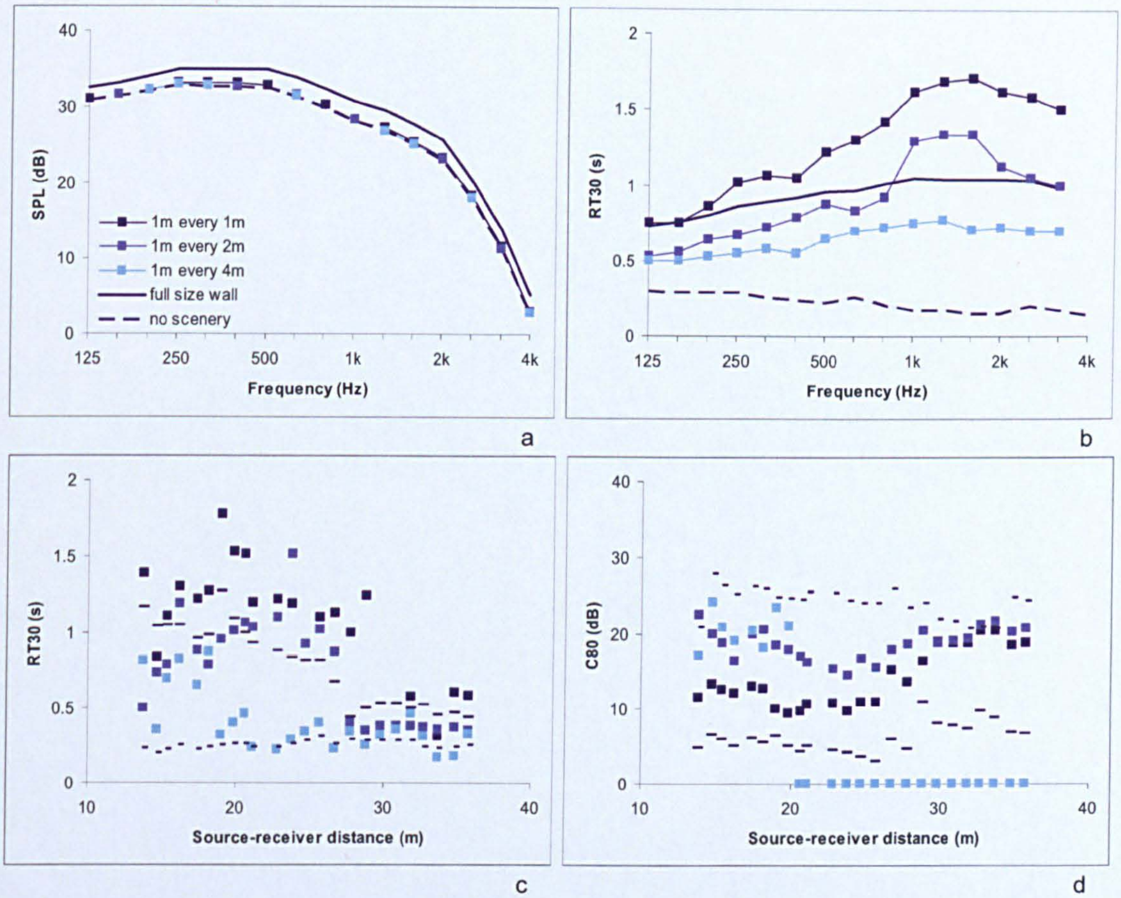


Figure 10.4.17. *Small sized objects (1m width and 5m height) arranged in a line in the orchestra of the theatre of Philippi. a) SPL (dB) and b) RT30 (s) for the typical receiver at the range of frequencies, c) RT30 (s) along the receiver line and d) C80 (dB) for the receiver line at 500Hz.*

RT30 is demonstrated in Figure10.4.17b. It is clearly indicated that the dense objects contribute to an increase in reverberation, because of repeated reflections between the koilon and the scenery. Still, the objects that are arranged with 1m spacing present higher RT30 values than the full sized wall, namely 1.22s instead of 0.96s at 500Hz, due to the additional reflections caused by edge diffraction. This phenomenon is more obvious at high frequencies. By comparing the three conditions in terms of density it is shown that the 2m distance allows for a decrease in RT30 at an average of 0.36s and the 4m distance at an additional 0.21s. However, it needs to be mentioned that the sparsely distributed scenery panels cause almost the same levels of reverberation for the whole frequency range. Focusing on 500Hz, Figure 10.4.17c shows that sound is hardly evenly distributed along the receiver line. Naturally, an effective way of even distribution would be to install surfaces to provide diffusion. Clarity is shown in Figure 10.4.17d, with good results for the 1m and 2m spacing, especially regarding the whole receiver line. When the ratio of the solid to the void is 1:4 the results are around 20dB for the receivers close to the orchestra and is approaching zero at 20m from the source and towards the end, while for 1:2 it is at an average of 18.6dB, with less fluctuation and for 1:1 it is 14dB. As expected, the best conditions in terms of clarity are found in the empty theatre.

The colour maps of the three conditions, illustrating the whole audience area, are shown in Figure 10.4.18. It is demonstrated that all conditions result in almost the same distribution in terms of reverberation, with shorter RT30, by 0.50s, for the receivers at large distances from the source. Also, the koilon wedges that present shorter reverberation are the same in all conditions, possibly due to the scenery panels' angle. Similarly, the sides of the koilon present long RT30, with particularly great differences compared to the rest of the koilon with the 1m and 2m distances.

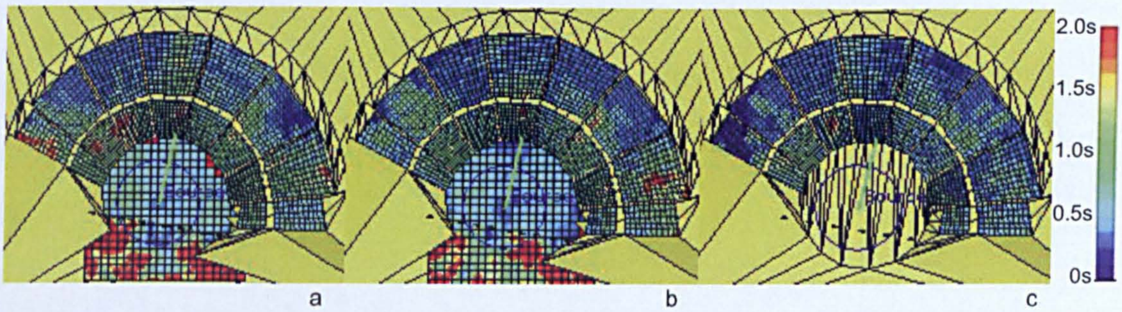
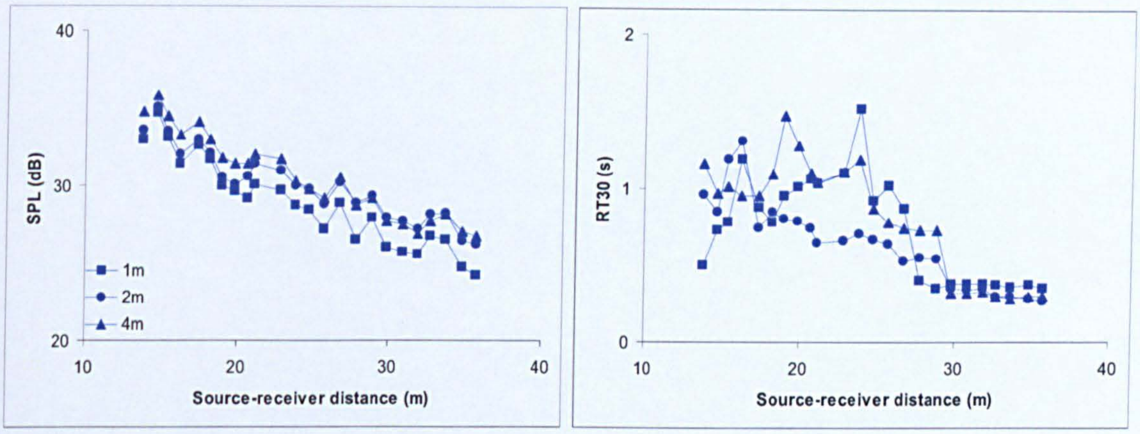


Figure 10.4.18. *RT30 (s) colour maps for the theatre of Philippi with 1mx5m objects. a) 1m distance, b) 2m distance and c) 4m distance.*

10.4.3.2 Size

The panels that have been simulated in this section are 5m high, with a spacing of 2m. They are 1m, 2m and 4m wide. Figures 10.4.19a and b illustrate the SPL and RT30 for the receiver line at 500Hz. For the SPL it is evident that the increase in panel width results in an increase in SPL. From 1 to 2m width the difference is lower at receivers closer to the source, around 0.5dB, because it is determined by the direct sound, and higher at distances more than 20m from the source, from 1.3-2.4dB, due to the early reflection contribution. The 4m wide panels bring additional increase for the receivers close to the source, at around 1dB, tending to approach the layout of the solid background wall of Category 1.

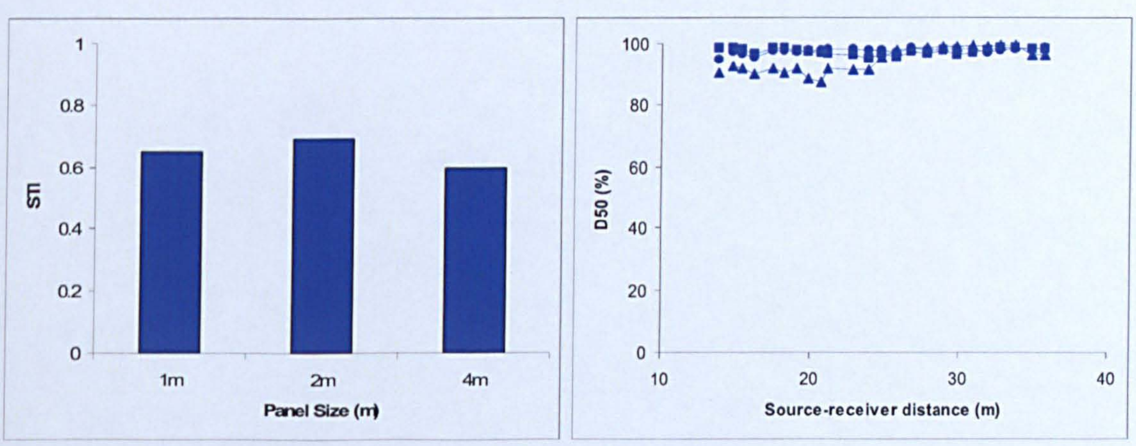
For RT30 the receivers at the high part of the koilon present almost the same values for all panel widths, mostly because the low-height panels do not particularly 'function' acoustically, due to the relative source-reflection point-receiver positions and the reflection distribution patterns, as discussed in Section 10.4.1.3. On the other hand, for the ones situated closer than 30m from the source, the higher values are encountered when the width of the panels is 4m or 1m, at 1.03 and 0.92s respectively, followed by the 2m panels with average RT30 below the 30m source-receiver distance at 0.79s. Diffraction from the panel edges and multiple reflections between parallel surfaces are the major factors that determine reverberation at this point. Thus, due to the larger areas of reflective surfaces, the 4m wide panels generate more specular reflections, although with more RT30 fluctuation between receiver positions. In opposition to this, smaller width panels allow for less specular reflections, with more edge diffusion and, consequently, shorter but more even RT30. However, considering the range of frequencies, the smaller size panels increase RT30 substantially between 630Hz and 2kHz. As indicated in previous studies, sound reflections are attenuated due to scattering effects caused by the size of the reflectors. Also, it has been suggested that many small reflectors should be preferred to few large reflectors, to give efficient sound in a wide range of frequencies [Rindel, 1991].



a b

Figure 10.4.19. Three object sizes, 1m, 2m and 4m wide at a distance of 2m in the orchestra of the theatre of Philippi. a) SPL (dB) and b) RT30 (s) for the receiver line at 500Hz.

Based only on reverberation for STI, the medium size panels provide 'very good' intelligibility. As seen in Figure 10.4.20a the values are at around 0.67 for the 2m wide panels, followed by 0.65 and 0.60 for the 1m and the 4m wide panels respectively. D50 is illustrated in Figure 10.4.20b with high values in general, in particular for the two sets of narrow objects, where the values are at 96.7-99%. The average reduction between these and the 4m wide panels is at 5.7%.



a b

Figure 10.4.20. Three object sizes, 1m, 2m and 4m wide at a distance of 2m. a) STI for the typical receiver and b) D50 (%) for the receiver line at 500Hz.

10.4.3.3 DISTRIBUTION

The distribution of 1m wide and 5m high panels is random, because the intention in this section is to examine the effect of scattered or lined up objects. For this reason it is rather the position and not the number of panels that is of interest at this point. Figure 10.4.21 illustrates the SPL and RT30. Generally the SPL values are at the same range for all situations, slightly increased for the two-row distribution and the randomly scattered panels, by 1-1.7dB. The same differences apply to the whole receiver line at 500Hz. On the contrary, the RT30 values are highly affected, since the distribution in two rows produces RT30 at around 0.65-0.94s, compared to 0.75-1.71s of the one row, since energy is trapped in between panels, creating 'energy clusters', acting as resonance, and does not reach the audience. The wider range and the scattered panels present a high variability in results (from 1.69s to 0.28s), especially for frequencies close to the wavelength of the panels. For 500Hz the random distribution produces shorter RT30 than the other two cases, at 0.20-0.09s, with maximum values appearing closer to the source. STI, C80 and D50 correspond to reverberation.

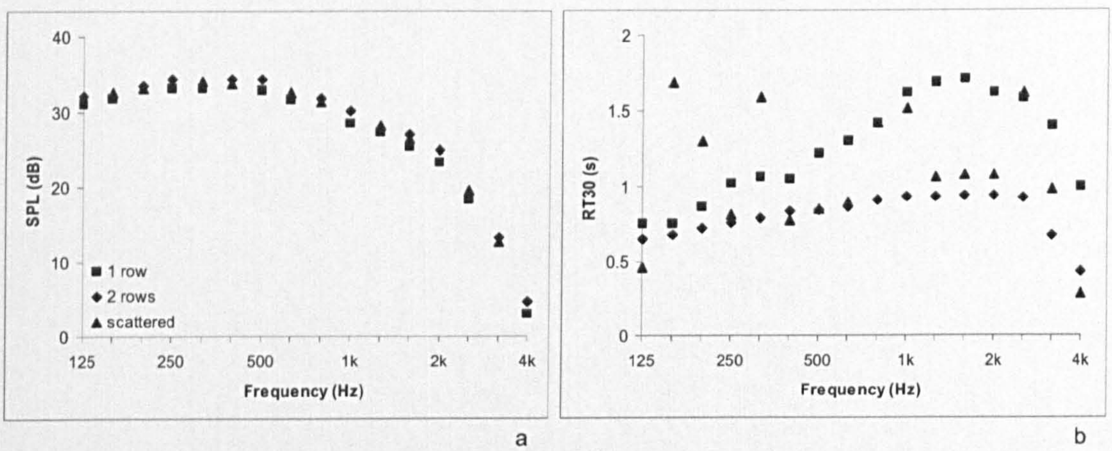


Figure 10.4.21. Distribution of 1m width panels in 1 and 2 rows. a) SPL (dB) and b) RT30 (s) for the typical receiver at the range of frequencies.

10.4.4 CATEGORY 4: ORCHESTRA

The parameters investigated for this category are the materials from which the orchestra is made and the heights of the orchestra level. The latter covers the cases when the scenery designer uses a material to increase the orchestra floor, when this is part of the skenography.

10.4.4.1 MATERIALS

The materials used here are marble, gypsum board, grass and rough soil, with absorption coefficients as illustrated in Table 10.2 [Egan, 1988; LMS, 2001]. Figures 10.4.22a and b illustrate the SPL and RT30 for the receiver line at 500Hz respectively. It is shown that none of the two indices is significantly influenced by the change of materials, although the absorption coefficients at the specific frequency are 0.01, 0.04, 0.4 and 0.6 for marble, gypsum board, rough soil and grass respectively. From marble to gypsum board the decrease in SPL is 0-0.1dB, then up to 0.8dB to the rough soil and additional 0.3-1.5dB to the grass. Overall, the maximum difference is at the range of 0.9-1.8dB, from marble to grass. However, these results apply to 500Hz. For the sake of comparison the theatre without any scenery applied has been simulated and presented in Figure 10.4.22a, showing the same effects. This reveals that regardless of the scenery's presence, the effect of the change of orchestra materials is similar. Consequently, the application of an absorptive or reflective material on the orchestra's floor can substantially influence the acoustics. Less variation can be found at low frequencies, while at high frequencies the maximum difference is at 2.8dB. As expected, the SPL curves decrease as the distance from the source increases.

For reverberation the values along the receiver line are almost at the same levels, 1-1.20s for all materials. Beyond all expectations, and although the materials should influence results in RT30, the differences are trivial, up to 0.20s only at specific receiver locations. This can be explained by the fact that: a) the reflections from the orchestra's floor are less in number than the ones from the koilon, b) they are mostly early reflections that only contribute to SPL and c) the change in materials is irrelevant to the reflection pattern, which would alter RT30 values. Corresponding to the absorption coefficients, the variations are more distinct at high frequencies. However, when comparing the two conditions of the theatre, namely with and without the scenery wall, the variation is approaching 1s. Despite this, in the absence of the wall, reverberation is not subject to the material change, because the reflections are decreased in number. STI, C80 and D50 can hardly be distinguished between the materials.

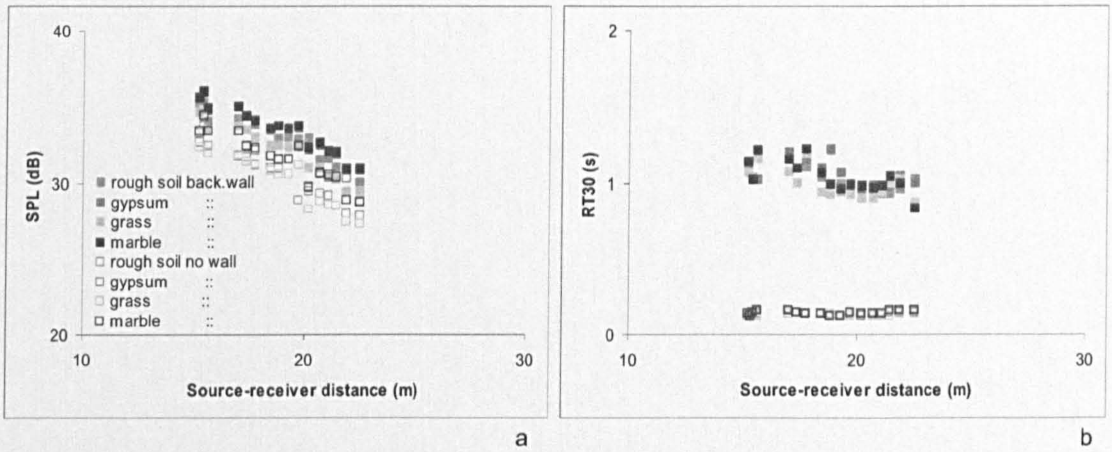


Figure 10.4.22. *The orchestra of the theatre of Dion simulated with four materials. a) SPL (dB) and b) RT30 (s) for the receiver line at 500Hz.*

Due to the fact that different orchestra conditions in terms of materials have resulted in small variations in SPL and RT30, it is expected that glass and water, being less diffusive while smoother, will provide less diffuse sound than specular reflections. The strong specular reflections would be profound in the energy responses and consequently in the overall impression. Figure 10.4.23 compares two highly reflective materials, namely marble and water.

The coefficients are similar as shown in Table 10.2, but the simulation has been carried out for still water, like it is found in ponds in the old Chinese Opera houses [Chourmouziadou, 2002; Chourmouziadou and Kang, 2003]. It is assumed that the wind is so trivial that the water surface is totally flat. Figure 10.4.23a shows the SPL for the typical receiver at the frequency range. It reveals that the water provides slightly increased SPL values compared to marble, by 0.1-0.5dB in both situations, with higher differences at low frequencies. Consequently, the differences are greater when water is compared with softer materials, namely gypsum board, rough soil and grass, examined earlier. Also, as before, when the scenery wall is absent the values are decreased. Similarly, for reverberation the water brings a small difference, thus the RT30 is at an average of 1.18s when the scenery wall is installed, instead of 1.15s with marble, while 0.11s instead of 0.13s respectively for the absence of the scenery wall.

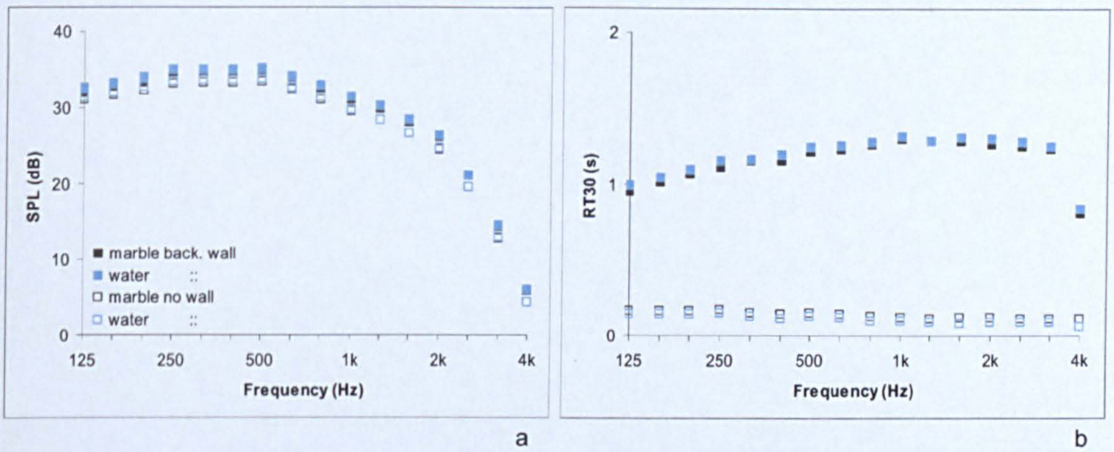


Figure 10.4.23. *Marble and water applied to the orchestra of the theatre of Dion, with and without background scenery wall. a) SPL (dB) and b) RT30 (s) for the typical receiver at the frequency range.*

10.4.4.2 HEIGHT

The height of the orchestra's floor presents much more flexibility to a designer, since it can influence the acoustic indices. As mentioned in Chapter 7, the raised stage in the late Classic and the Hellenistic theatres had increased RT30. The heights for which the simulation has been carried out are 0m, 0.30m, 0.60m and 1m. For comparison, all the orchestra materials are gypsum board, although one could possibly use different materials and influence the results accordingly, as shown in Section 10.4.4.1. Also, simulations have been carried out with and without a background scenery wall.

Figure 10.4.24 presents the acoustic indices for the typical receiver at the theatre of Dion across the frequency range. Contrary to the material simulation, as far as the orchestra level is concerned the distribution pattern determines the results. Although the increase in height brings a decrease in the SPL values, with maximum difference at 3.3dB, the effect in reverberation is opposite. RT30 is at the range of 0.95-1.28s for the original orchestra floor, decreases when the floor is raised at 0.30 and 0.60m above the original level, at 0.9-1.2s and 0.8-0.92s respectively, but increases substantially at 0.9m, at 1.14-1.68s. For comparison, simulation has also been carried out for the theatre with no background scenery wall. It is noted that for SPL the maximum differences are at 3.5-4.7dB, while for RT30 the variation is much less comparatively, at a maximum of 0.12s. Still, the RT30 has the tendency to be increased with raised orchestra floors. The energy responses in Figure 10.4.25 show the reflection distribution for the four cases, for a typical receiver.

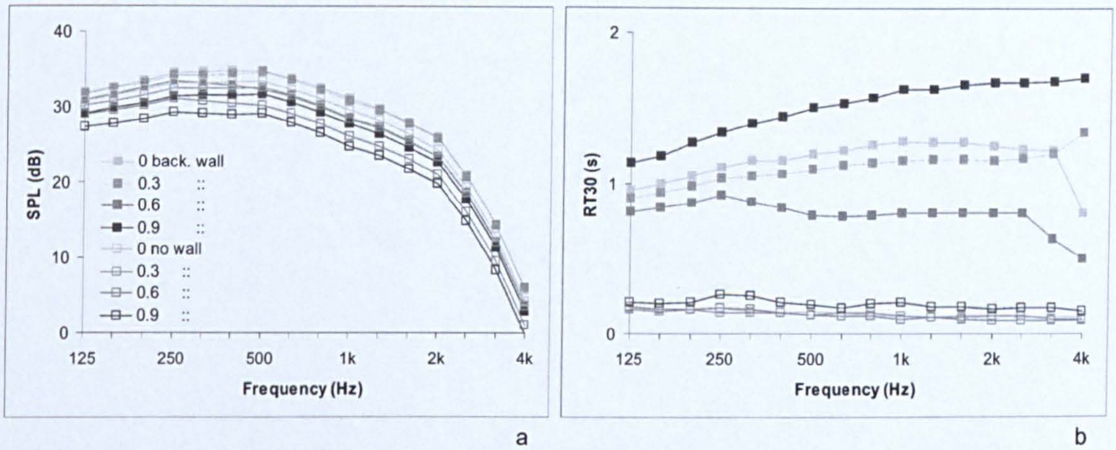


Figure 10.4.24. *Comparison between four levels of the orchestra of the theatre of Dion, above the original orchestra floor. a) SPL (dB) and b) RT30 (s) for the receiver line at 500Hz.*

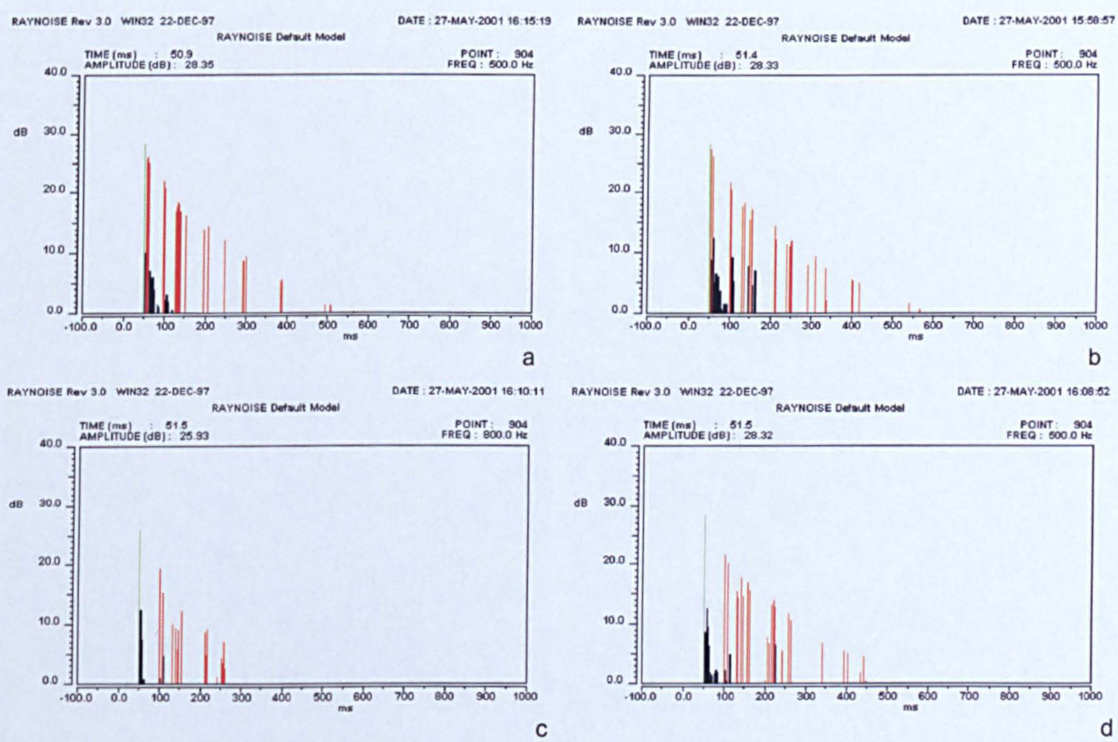


Figure 10.4.25. *Comparison between four levels of the orchestra of the theatre of Dion, above the original orchestra floor, with scenery installed. a) 0m, b) 0.30m, c) 0.60m and d) 0.90m.*

From Figure 10.4.25 it is clear that when the orchestra's floor is raised at 0.60m from the original level the reflections are reduced significantly, with obvious consequence in reverberation. The same applies to 0.30m although the effect is not as clear. Also, the additional reflections found in the energy response of 0.90m are the reason for the significant increase in RT30. Therefore the height of the orchestra can obviously be handled by a stage designer to provide the desirable effect. As in previous cases, it is mostly the position of the actor in the whole layout of the theatre that determines the acoustic indices, due to relative heights, source-receiver positions, multiple reflection paths and high reflection orders. Moreover, the imaginary decay lines of the energy responses are steeper at the first three cases, with the smaller found in 0.60m.

10.5 SCHEMATISATION OF THE SCENERY WALL

After examining the results for each parameter of Category 1, namely the theatre layout, the materials, the height of the wall, and the occupancy of the theatre, it is important for a designer to be able to provide several shapes, *schemata*, for the background wall. Although aesthetically important, the schema could work for the soundscape as well. From the viewpoint of acoustics, despite the fact that the shape of the wall has been predefined as rectangular, one can calculate the part of the wall that is beneficial in terms of reflection paths and re-shape the scenery without changing the distribution pattern.

The theatres of Dion, Mieza and Philippi have been used for this part of the analysis, where the field point mesh, the area for which the indices are calculated, has been applied in front of the scenery wall, to identify sound distribution on the wall. 5m, 10m and 15m high walls have been applied to the theatres, as shown in Sections 10.3.1.3 and 10.4.1.3.

The colour maps for the 5m high scenery wall in the theatre of Dion are shown in Figures 10.5.1a and b, demonstrating the direct sound and the SPL. The high SPL on the scenery walls in the theatres of Mieza and Philippi is shown clearly with the yellow and red colours in Figures 10.5.1c and d and Figures 10.5.1e and f respectively. Apart from the direct sound that is evenly distributed on the scenery wall, the reflections off the orchestra and the koilon allow for rather uneven distribution. It is in this way evident that the yellow and red areas are most probably the ones that will provide the highest amplitude reflections.

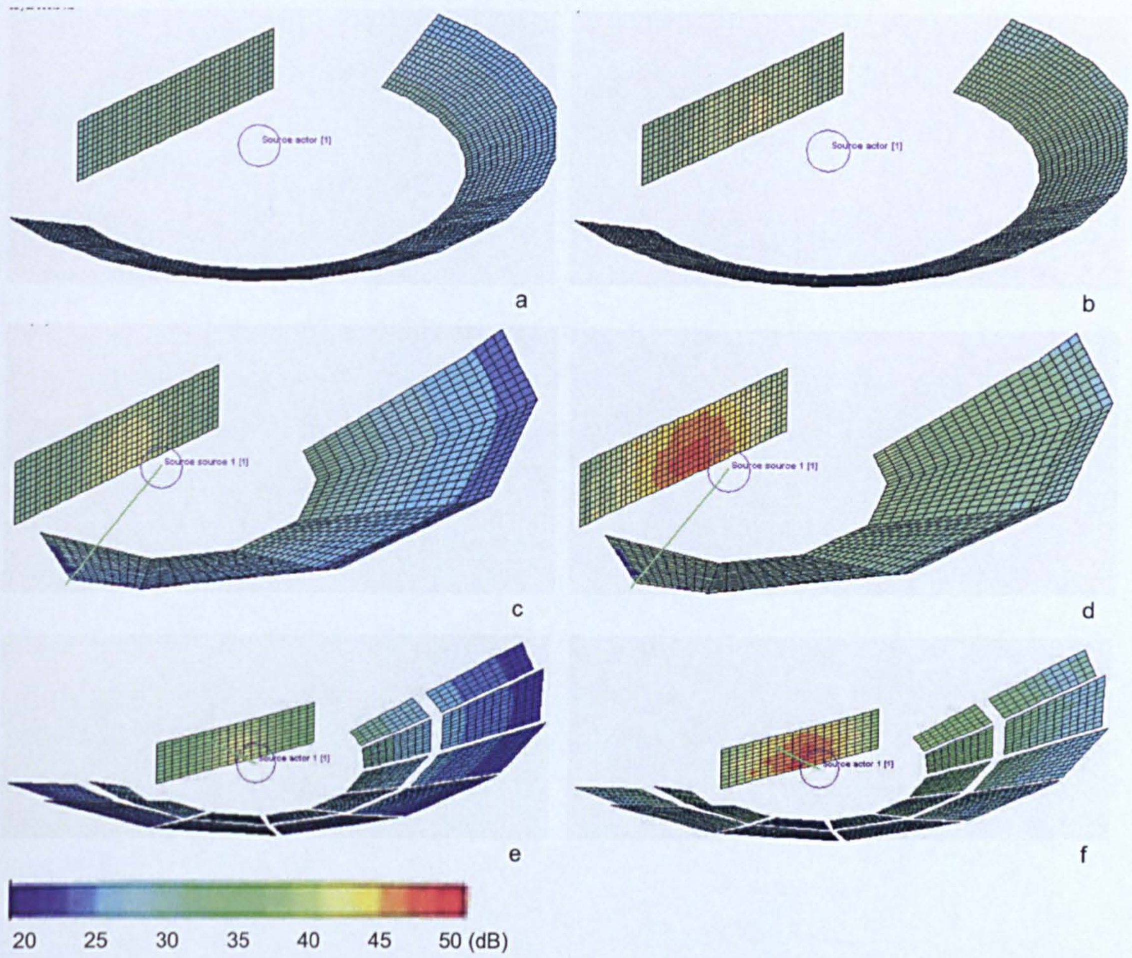


Figure 10.5.1. *Scenery colour maps with 20mx5m wall. a) Direct sound (dB) for the theatre of Dion, b) SPL (dB) for the theatre of Dion, c) Direct sound (dB) for the theatre of Mieza, d) SPL (dB) for the theatre of Mieza, e) Direct sound (dB) for the theatre of Philippi and f) SPL (dB) for the theatre of Philippi.*

The colour map for the SPL in the theatre of Mieza with 10m high background wall is shown in Figure 10.5.2a. In Figure 10.5.2b the reflection paths for a selection of 10 receivers at the koilon, both at the lower and the upper part, as well as the central part and the sides is illustrated. The area that is most effective in terms of reflection points is clearly indicated. Obviously, the selected areas are efficient in this case for the specific source position. Changing the source would alter the reflecting areas of the wall. This is also important when the actors' positions are predefined, which is rather common in ancient drama performances, because the scenery can be adjusted to the required position in terms of the acoustics. Figure 10.5.2c demonstrates the final schema of the wall, after the unnecessary parts have been cropped. This schema can be also preserved with other shapes of the scenery wall, like the examples shown in Figure 10.5.2d and e.

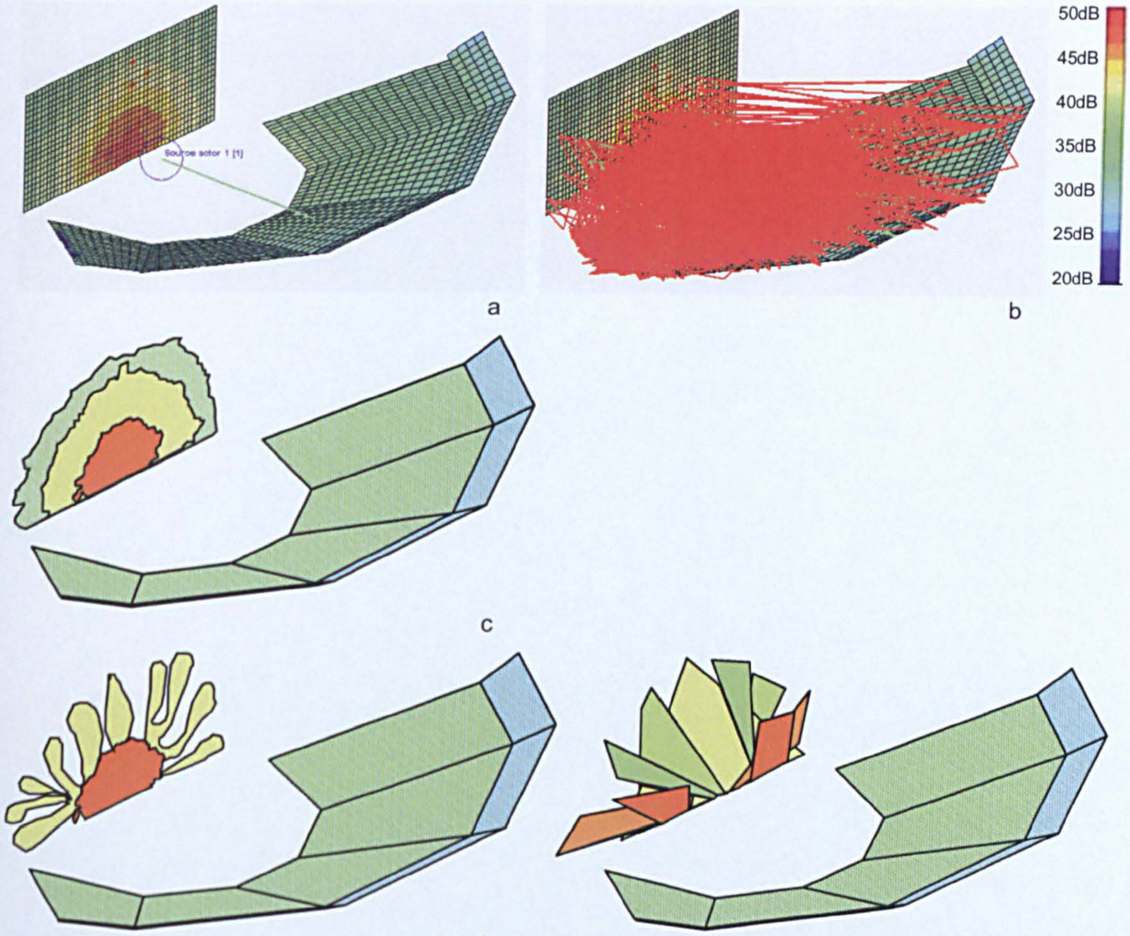


Figure 10.5.2. Scenery colour maps at the theatre of Mieza. a) SPL (dB), b) Reflection paths for 10 receivers at different areas of the koilon, c) Optimum shape of the scenery wall, d) and e) Examples of scenery that retains the optimum shape.

The same procedure can be followed in any ancient theatre. Combining the results of the examination of the effect of the wall height and the optimum wall schema, the reflection distribution of the energy responses for four points on a line of the 15m scenery wall of theatre of Philippi are illustrated in Figure 10.5.3, showing the effect of sound distribution on the scenery wall, emphasising on the significance of the optimum shape of the scenery wall, with more reflections at the points positioned lower, in the yellow area.

Similar calculations have been carried out for a cylinder, placed in the theatre of Mieza, like the one described and calculated for Category 2 in Section 10.4.2. Figure 10.5.4 illustrates the results in a three-dimensional colour map. It shows the height of the cylinder that receives a lot of reflections and could be used to re-distribute them to the audience. In fact, the thymele, the altar dedicated to gods that was in most cases placed at the centre of the orchestra, described in Chapter 4, resembles the effective area of the cylinder. Hence, apart from its religious function it could have been an additional reflector that redirected the focused sound back to the audience. Likewise, the material for the orchestra floor can be used, shown in Figure 10.5.4, as discussed in Section 10.4.4 for Category 4. It is noted that in this simulation the original condition of the theatre was used, as described in Chapter 9.

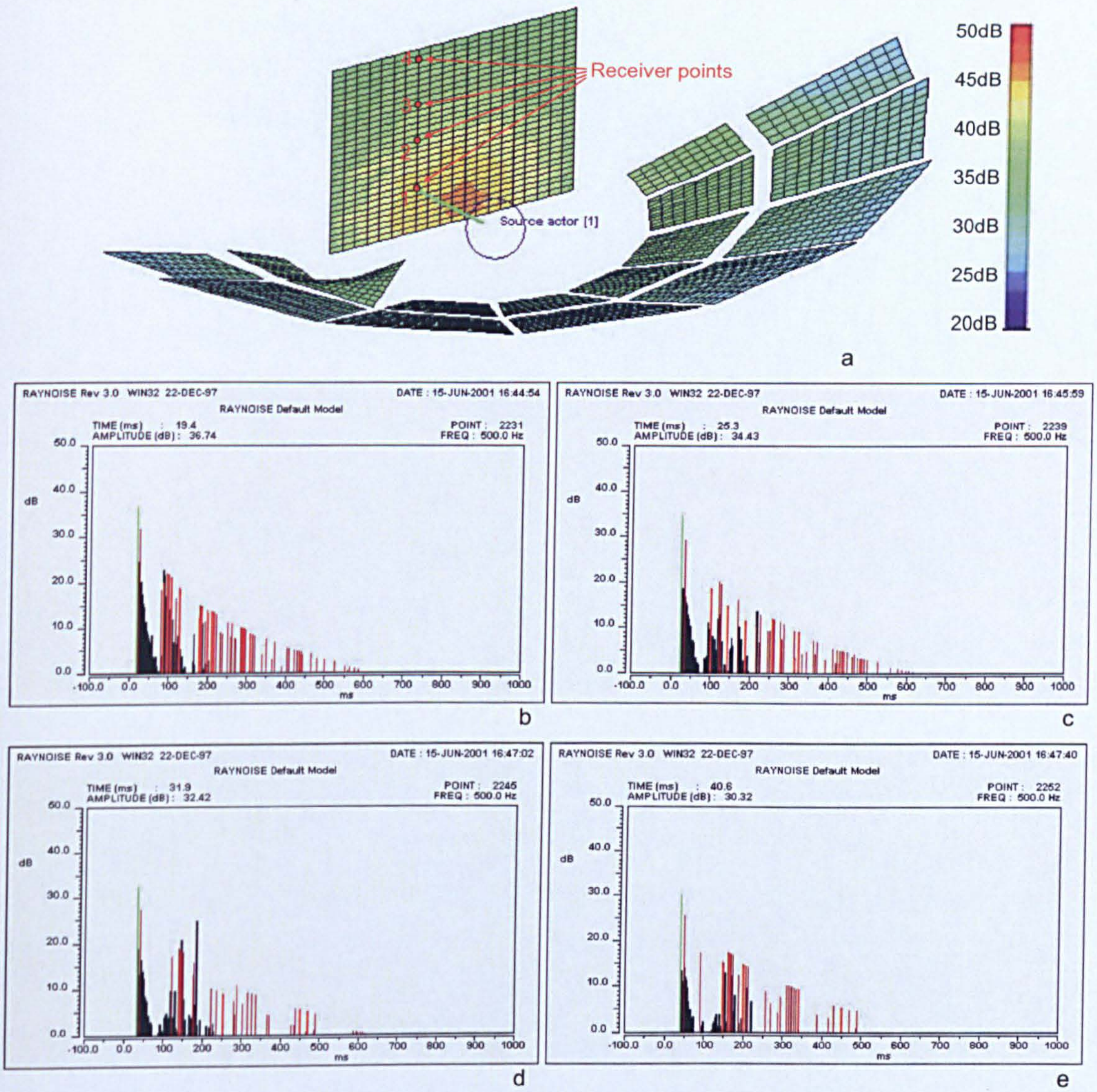


Figure 10.5.3. *The theatre of Mieza. a) SPL colour map and energy responses for scenery points, b) 1, c) 2, d) 3 and e) 4.*

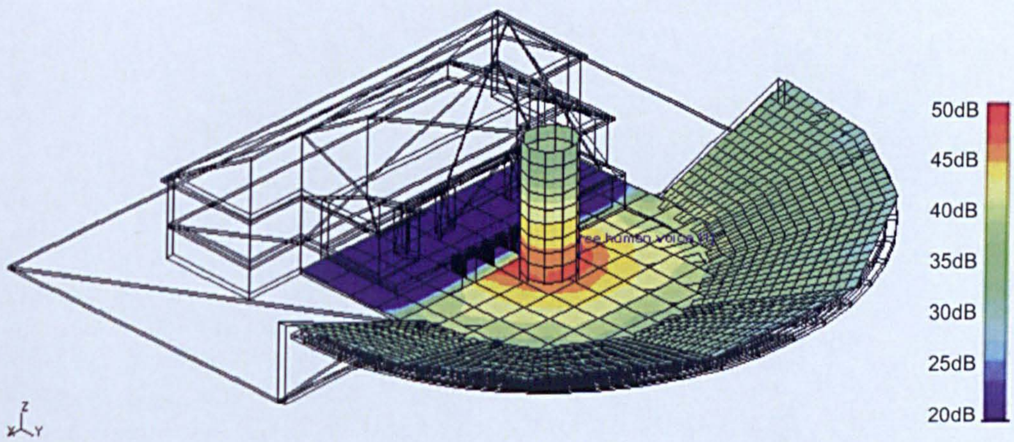


Figure 10.5.4. *SPL colour map for the theatre of Mieza showing the use of a cylinder to redirect sound.*

10.6 SIMPLIFICATION OF SCENERY DESIGN

The designer/acoustician can simplify the representation of the scenery design, in order to test the acoustic environment of the theatre with a quick calculation. Since the plain walls of Category 1 are the simplest representation of the scenery design, it is essential to test different ways of representing the scenery panels of Category 3 for the sake of the designer's convenience. The procedure followed in this section corresponds to the methods used in Chapter 6.

For the simplification of the scenery design from the viewpoint of acoustics two cases from Section 10.4.3 are used. The 1m wide scenery panels every 1m and every 4m, as illustrated in Figure 10.3.5 a and c. The simplification involves the application of a combined absorption coefficient α, as well as a diffusion coefficient d.

For the calculation of the combined absorption coefficient five methods are used. Method A is the realistic representation of the scenery panels, like in Section 10.4.3.1. Method B involves replacing the panels by a solid wall, divided into the same areas of solid and void and applying the absorption coefficients α_1 and α_2 of reflector and air respectively.

In Method C the scenery panels are replaced by a solid wall, although the absorption coefficient is a combination of reflector and air. The absorption coefficient in this case was derived from equation 10.1. Table 10.4 illustrates the characteristics of the scenery panels, as well as the proportions of solid and void.

$$a = \left(a_1 \frac{solid}{total} \right) + \left(a_2 \frac{void}{total} \right) \tag{10.1}$$

Table 10.4. *Characteristics of the scenery panels*

Calculation of Absorption Coefficient α	1m wide every 1m	1m wide every 4m
Length (m)	29	31
Height (m)	5	5
Panel surface (m^2)	145	155
Void area (m^2)	70	120
Solid area (m^2)	75	35
Void/Total	0.483	0.774
Solid/Total	0.517	0.226

According to equation 10.1 the final absorption coefficients for the representation of the scenery panels using Method C are 0.64 at 125Hz, 0.59 at 250 Hz, 0.56 at 500Hz, 0.53 at 1 and 2kHz and 0.52 at 4kHz and 0.84 at 125Hz, 0.82 at 250 Hz, 0.81 at 500Hz, 0.80 at 1kHz and 0.79 at 2 and 4kHz for the 1m wide panels with a spacing of 1m and 4m respectively. The flat panel diffusion coefficients are used.

In Method D the panels are realistically represented, while the diffusion coefficient is calculated by Method 2 in Chapter 6, based on Christensen and Rindel [2005a; 2005b]. For this calculation the procedure followed in Chapter 6 is used, as shown in Table 10.5, for two receiver groups, seated at 0° and 45° degrees from the axis of the theatre of Philippi, at rows 4, 9 and 18. In this way the average of the values of the two angles is calculated for every frequency. The final combined diffusion/scattering coefficients s_r are: 0.86 at 125Hz, 0.68 at 250 Hz, 0.52 at 500Hz, 0.43 at 1kHz, 0.30 at 2kHz and 0.08 at 4kHz.

Finally, in Method E the simplified representation of the panels was used, with the same absorption coefficients as in Method C, and combined diffusion coefficients *d*, according to Chapter 6, at. 0.64 at 125Hz, 0.57 at 250 Hz, 0.52 at 500Hz, 0.43 at 1kHz, 0.30 at 2kHz and 0.08 at 4kHz. The surface characteristics of the above methods are used to simulate the theatre with the scenery installed, as seen in Table 10.6.

Table 10.5. *Calculations used for the combined diffusion/diffraction coefficient of Method 10.3 at 500Hz.*

Formula\Angle (°)	**0**			**45**		
Row	**4**	**9**	**18**	**4**	**9**	**18**
$d_{incidence}$ **(m)**	4.015	4.012	4.012	4.711	4.853	4.979
$d_{reflction}$**(m)**	20.204	27.456	1.72	18.33	25.262	32.427
angle β (°)	2	8	12	5	9	12
cos (β °)	0.99	0.99	0.98	0.99	0.99	0.98
angle δ (°)	3	2	2	31	34	37
cos (δ °)	0.99	0.99	0.99	0.86	0.83	0.80
Width (m)	1	1	1	1	1	1
Height (m)	5	5	5	5	5	5
s_r	0.513	0.513	0.513	0.522	0.524	0.526

Table 10.6. *Absorption and diffusion coefficients of Method A-E.*

Method/Frequency (Hz)		**125**	**250**	**500**	**1k**	**2k**	**4k**
A (original)	**Absorption**	0.14	0.11	0.10	0.06	0.05	0.05
	Diffusion	0.30	0.20	0.15	0.10	0.09	0.07
B (wall)	**Absorption α_1**	0.14	0.11	0.10	0.06	0.05	0.05
	Absorption α_2	1	1	1	1	1	1
	Diffusion	0.3	0.20	0.15	0.10	0.09	0.07
C (wall combined α)	**Absorption**	0.64	0.59	0.56	0.53	0.53	0.52
	Diffusion	0.3	0.2	0.15	0.1	0.09	0.07
D (combined *d*)	**Absorption**	0.14	0.11	0.10	0.06	0.05	0.05
	Diffusion	0.86	0.68	0.52	0.43	0.30	0.08
E (wall combined α +*d*)	**Absorption**	0.64	0.59	0.56	0.53	0.53	0.52
	Diffusion	0.64	0.57	0.52	0.43	0.30	0.08

According to previous results it is expected that the change of coefficients will not affect SPL significantly. Figure 10.6.1 illustrates the acoustic indices for the five methods.

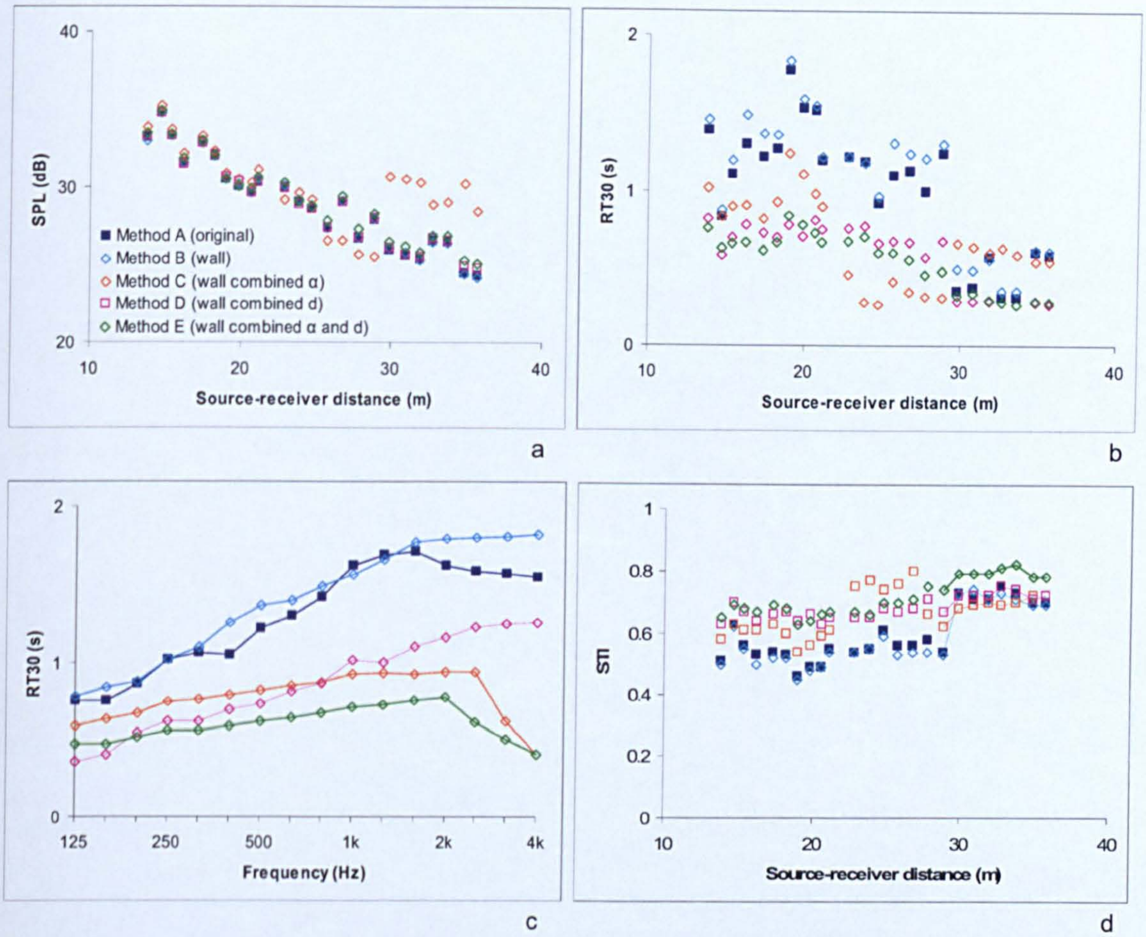
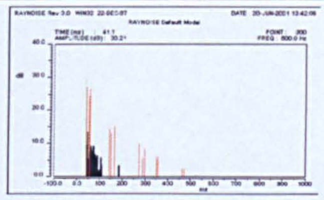
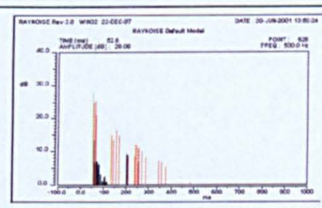
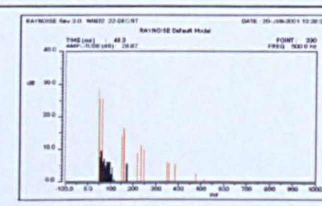
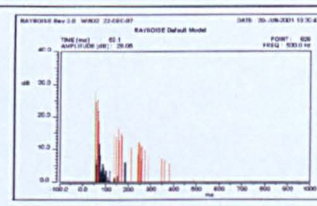
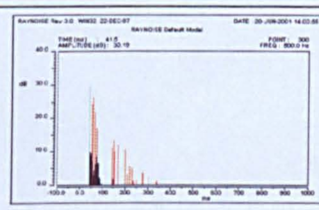
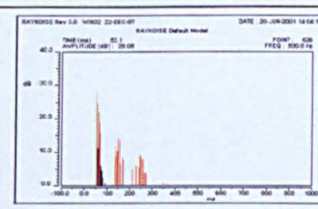
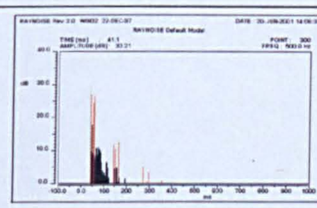
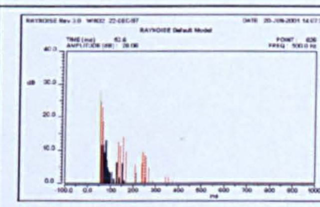
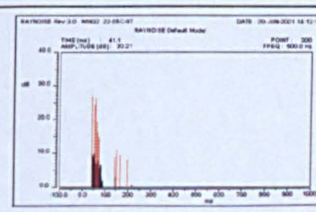
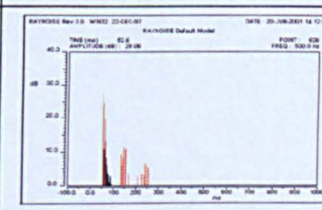


Figure 10.6.1. *Comparison between five methods of simplified representation of scenery in the theatre of Philippi. a) SPL (dB) and b) RT30 (s) for the receiver line at 500Hz, c) RT30 (s) and d) STI for the typical receiver at the range of frequencies.*

As seen in Figure 10.6.1a the values are almost equal for the majority of receivers. The maximum differences can be found at the receivers seating high at the koilon, at the range of 2.9-5.8dB, especially between Method C and the other methods. This is expected since in Method C the diffusion of the wall was not carefully selected to represent the change from the panels to the solid wall, namely the edges. The variations between the other methods are far less, at 0-0.5dB. However, in order to have the most effective simplification it is important to match all the acoustic indices of the selected method with the original scenery representation. In Figure 10.6.1b and c the RT30 for the five methods is demonstrated. It is shown that Method B, namely the replacement of the scenery panels by a whole wall, divided into equal segments of solid and void, where the corresponding coefficients of the scenery surface and air have been applied respectively, presents almost identical results with Method A. The RT30 differences are 0-0.15s. Methods C, D and E, with the combined absorption coefficient, the diffusion coefficient or a combination of these respectively, result in a rather decreased RT30 for the range of frequencies by 30-60%. Naturally the STI results, based mostly on RT30, present the same relationships between the methods. The differences in STI are at a maximum of 0.1, encountered at frequencies around 1kHz.

The energy responses of two points, near the axis and the side of the koilon are shown in Table 10.7. It is clear that the energy responses of Methods A and B are almost identical, which explains the results in both SPL and RT30 seen above. In Method C both the specular and diffused sound has been reduced with the increase of absorption and the minimisation of edge diffraction because of the scenery's representation. Moreover, Method D presents an increase in diffused sound because of the high diffusion coefficient, while Method E has further decreased reflections.

Table 10.7. *Energy responses of three receiver points for five methods of scenery simplification.*

Method / Energy response	Point 300	Point 626
A (original)		
B (wall)		
C (wall combined *α*)		
D (combined *d*)		
E (wall combined *α* +*d*)		

Therefore it seems that for calculations where the RT30 is of major concern, the most effective method of representing the scenery design is by replacing it by a simple wall, while the absorption coefficients are applied with the same proportions of solid and void of the original scenery. On the other hand, if SPL is of concern then most of the methods are characterised by the same results.

10.7 Combination of Categorised Sceneries

This chapter presented the analysis of the four categories of generic scenery design types, according to the classification of Chapter 4. Each category was examined separately, so that the effect of the variables would be clearly presented. However, in real cases a combination of two or more categories is used for the scenery creation, as seen in previous studies [Chourmouziadou and Sakantamis, 2006]. Therefore, based on the skenographer's ideas, a designer/acoustician should consider the effects of a combination of categories for the acoustic analysis of the performance, discussed in this section.

10.7.1 Categories 1 and 2

The combination of categories 1 and 2 would involve some kind of a background wall and a geometric shape in the theatre. This is not very common as one can see in the scenery examples of Chapter 4. Hypothetically speaking, a scenery created by a background wall and a sphere would provide a high number of both specular and diffused reflection, while the wall would complement for the low reverberation the sphere creates, or *vice versa*. The selection of materials and height would also be very important. A highly absorptive wall would not affect the acoustic environment when combined with any other scenery category. On the other hand the disadvantages of the pyramid will be compensated for by a high background wall made of hard materials.

10.7.2 Categories 1 and 3

This is a rather rare combination because it creates the same visual effects and is not therefore preferable. In case this is created, low density and hard background would provide long reverberation and relatively high SPL. However, if the panels are created by a soft and absorptive material, the reflections from both categories would be eliminated and an absorptive environment would be the result, with low amplitudes in SPL and short RT30. Clarity, definition and STI would be at the optimum values.

10.7.3 Categories 1 and 4

This is one of the most common combinations in skenography, especially in the ancient theatres. Based on historical notes scenery designs have been created where the orchestra was either covered or heightened and the background represented a house, palace temple or something abstract. In this case the impact of both categories can be maximised due to the reflection patterns. Highly absorptive orchestra materials do no allow for high amplitude reflections, while the height and the material of the background wall would mostly determine each acoustic index. Similarly, when the height of the orchestra level is increased in relation with the hard material of the wall, then the result would be a reverberant space.

10.7.4 Categories 2 and 3

Density is the most important variable in this case, since the rest of the conditions would be the same like in the combination of categories 1 and 2. The less dense objects would not affect the environment significantly, although they would provide a lot of edge diffraction that will result in short RT30 values.

10.7.5 Categories 2 and 4

This is a combination of a large orchestra object and the alteration of the orchestra's material or height. The results can be discussed from the viewpoint of the effect of Category 4 and previous analysis of Category 2. It is shown that both the SPL and the RT30 will be reduced when the orchestra's material becomes absorptive, like straw or fabric, although the conditions will be improved if the floor of the orchestra is heightened, more than 1m.

10.7.6 Categories 3 and 4

The results are similar with Section 10.7.5. From another point of view, by placing a number of panels on the orchestra, one can have a variety of results. An absorbing orchestra can be enhanced by the addition of reflecting panels, especially if they are dense.

10.8 Variation in Actors positions

Throughout this chapter the position of the actor in the orchestra was predefined, at coordinates (x=-1, y=-1, z=1.6), except for Section 10.4.4.2, where the height of the source was changed due to the orchestra's repositioning. However, as mentioned before, although the actors' positions are usually predefined, they can also move into different positions during the play. Therefore this section presents a comparison between three source positions in the simulation, to examine their effect particularly on SPL, RT30 and the energy responses. The sources in the theatre of Dion are located at (-1,-1), (-1, -7), and (-1, 9), as illustrated in Figure 10.8.1, to indicate possible variations due to the proximity to either the audience or the background scenery wall. Figure 10.8.2 illustrates the SPL, RT30, C80 and D50.

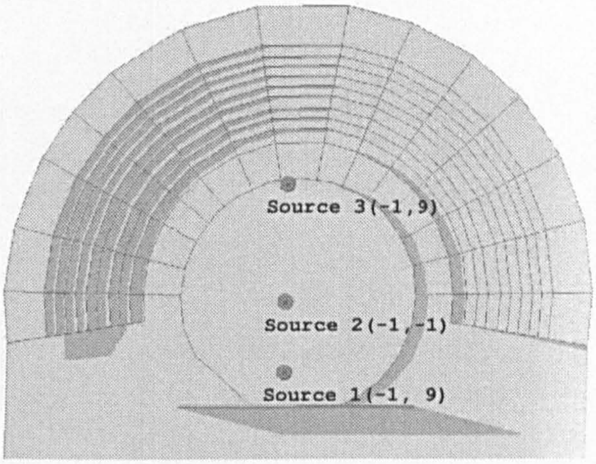


Figure 10.8.1. *Three source positions in the theatre of Dion.*

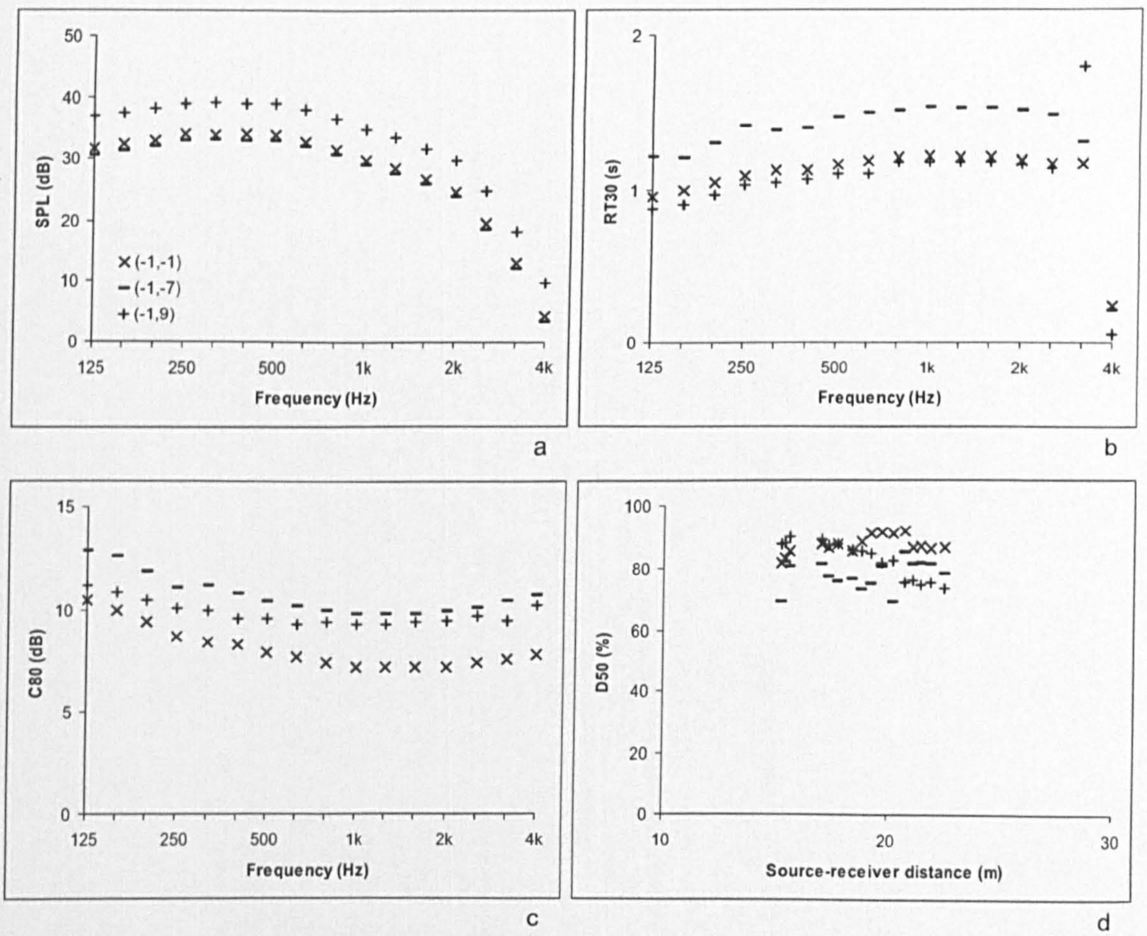
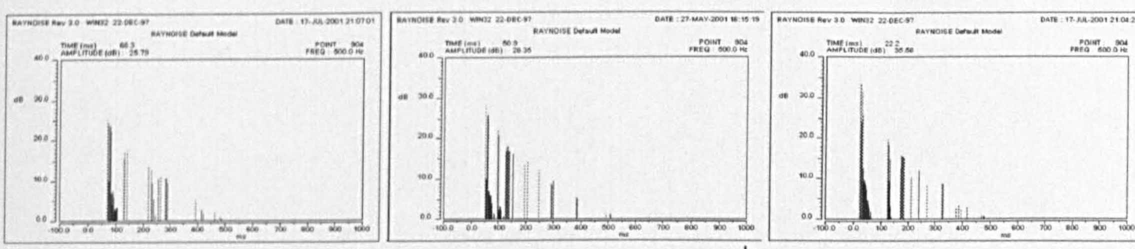


Figure 10.8.2. *Comparison between three actor's positions in the theatre of Dion. a) SPL (dB) for the receiver line at 500Hz, b)RT30 (s) and c) C80 (dB) for the typical receiver from 124 to 4kHz and d) D50 (%) for the receiver line at 500Hz.*

Figures 10.8.2a and b show the SPL and RT30 for the typical receiver at the frequency range respectively. It is indicated that as the source moves towards the audience SPL increases, from 34 to 39dB for example at 500Hz, due to its interdependence with the direct sound. Similarly, while the actor-receiver distance increases the SPL becomes lower, by approximately 1dB. It is noted that for reverberation the results depend mostly on reflection patterns created by the source's position. For this reason high variation can be observed between the RT30 results. For the source situated near the centre of the orchestra or close to the audience, namely y positions at -1 and 9 respectively, the RT30 is almost at the same levels, at 0.95-1.20s across the frequencies, as seen in Figure 10.8.2b. However, for the actor at (-1, -7) longer RT30 values are produced, at around 1.20-1.50s, most probably due to longer reflection paths. This is also illustrated in the energy responses of Figure 10.8.3. Less clarity is found for the actor being positioned near the centre of the orchestra, at around 7.2-10dB, compared to the other two situations, while definition is quite high for the former, at 86-91%, mostly for the receivers high in the auditorium.

The energy responses for a typical receiver and the three source positions are shown in Figure 10.8.3. The amplitude of the direct sound is obviously higher for the source closer to the receivers, while it reduces as the source moves towards the scenery. However, the opposite phenomenon appears at the reflections. When the receiver is situated close to the background scenery wall the reflection path is smaller, thus the low order reflection's amplitude is higher. The high order reflections cover longer reflection paths from the source to the koilon, the scenery and the receivers, sometimes repeatedly, creating smoother decay curves and, consequently, longer RT30 values.



a b c

Figure 10.8.3. Energy responses for three actor positions in the theatre of Dion. a) (-1, -7), b) (-1, -1) and c) (-1, 9).

10.9 Conclusions

In this chapter four generic categories of scenery design were examined to identify their effect on the acoustic environment of three ancient theatres. Several variables were investigated from the viewpoint of acoustics. Also, optimum shapes of sceneries were found and simplification of the scenery representation to facilitate the acoustic simulation was carried out. Regarding the different categories the results are presented in sections:

For Category 1, namely the scenery in the form of a background wall, it was shown that soft materials used in the construction of the theatres, in particular Dion, lead to low values in SPL curves, although smooth decays are mainly found in hard materials and higher inclinations. Wider theatre layouts, in terms of the fan shape, produce comparatively long reverberation, like in Dion, while with one koilon inclination instead of two smoother curves are created. The effect of the materials used for the scenery wall is generally trivial on the SPL and more significant on reverberation. Higher variations due to different background scenery wall characteristics are found in theatres built with hard materials. The height of the wall is particularly important for RT30, especially for the rear seats of the koilon, due to additional reflections provided with high walls. Nevertheless, compared to the condition of the theatre without any scenery the effect of the wall's presence is high, even in SPL. Linear walls are more effective, compared with other shapes, due to the distribution patterns. The scenery is also valuable even for the occupied condition since it increases reverberation. On the other hand the audience absorption is of less importance when there is no scenery.

In Category 2 four geometric objects, namely a cube, a sphere, a cylinder and a pyramid, have been applied to the theatre for these simulations. The sphere and the cylinder increase SPL due to the distribution of early reflections throughout the koilon. The cylinder provides the maximum number of reflections, using most of its surface area, and consequently long RT30 values, which is a contribution of the reflection patterns in addition to the high reflection order. The reverberation with the cube and the sphere is shorter, while with the pyramid it is not affected, due to the high number of lost reflections. In general, objects that provide diffusion distribute sound more evenly to the audience area increasing SPL and decreasing RT30, which corresponds to higher STI and C80.

In Category 3 small objects in the form of panels are installed in the orchestra, in different densities, sizes and distribution. It is indicated that dense objects contribute to relatively long reverberation, while the effect of edge diffraction is related to the number of the panels. Uneven SPL and RT30 distribution, when the objects are not dense, can be avoided by providing surface diffusion. Variations in acoustic indices are generally less obvious close to the source.

For Category 4 the parameters investigated are the orchestra material and the heights of the orchestra level. The SPL and the RT30 are not particularly influenced material characteristics, since the reflections from the orchestra's floor are less in number than the ones from the koilon. Corresponding to the absorption coefficients, the variations are more distinct at high frequencies. On the contrary, the height of the orchestra's floor presents much more flexibility to a designer, since it can influence the acoustic indices. Similar to the raised stage of the late Classic and the Hellenistic theatres, presented in Chapter 7, the increase in height can affect both SPL and RT substantially.

Especially regarding Category 1 a schematisation of the plain background wall was achieved, by the use of the acoustic simulation through colour maps of direct sound and SPL, in relation to reflections paths and energy responses during the design process. It was suggested that it is possible to maintain the area of the wall that 'functions' acoustically and create a scenery that will take any form required. In this way, acoustically effective scenery areas could be kept, with more complicated scenery shapes. Moreover, through this examination it was found that the cylindrical thymele, positioned at the middle of the orchestra may have contributed to more even distribution of sound, in addition to the original skene-building of antiquity.

Furthermore, because of the complexity the scenery design usually presents, a simplification was engaged, with the use of five methods of representation, most of which used combined absorption and diffusion coefficients. It was indicated that the most efficient way was to represent the scenery by a plain wall, divided into segments that stood for the solids and voids the original scenery created. By applying the absorption coefficients of the scenery panels and of air to the corresponding wall areas, accuracy of acoustic indices' results was achieved.

Regarding the variation in source positions it has been suggested that higher SPL values are created when the actor approaches the audience, as expected, while the opposite phenomenon is observed for reverberation. This is due to reflection patterns and reflection path distances. For clarity and definition the best results are found when the source is close to the audience or near the centre of the orchestra respectively.

From the above it is noted that it would be possible for a skenographer to use these results as a guideline and, with a use of the imagination, create shapes and adjust inclinations and heights in order to exploit the essential reflections and produce the desired acoustic environment during a performance of ancient drama.

CHAPTER 11

DESIGN IMPLEMENTATION

11.1 INTRODUCTION

The application of contemporary scenery to open-air theatres is necessary for drama performances. Drama, architecture and acoustics are closely related in this study. In antiquity scenery was used to lead the viewer into the imaginary world the play referred to. Conventional use was frequent, as discussed in Section 4.3. Today scenery is more related with the aesthetic aspect of the performance rather than the functional. Abstract representation, forms that reflect art movements, like symbolism, constructivism, post-modernity and deconstruction are significant to scenery designers. Through the audience's impressions the scenery becomes the symbol of each performance. However, the acoustic effect of scenery, as examined in Chapters 8-10 is also useful for the sensory experience of the performance as a whole. Moreover, open-air theatres created in the 20th century can also benefit from the application of scenery in the form of boundaries.

This chapter addresses mostly designers interested in open-air theatre use and particularly in scenery design. It initially examines the relationship between architecture and acoustics, regarding theatre design and function. It considers the acoustic aspect of theatre performance and certain principles followed during the design and construction periods. Then, based on the previous analysis in Chapters 9 and 10, the effectiveness of scenery design is emphasised and guidelines for architects, scenery designers, directors and acousticians are provided. Furthermore the application of scenery to contemporary open-air theatres is investigated through nine case studies.

11.2 RELATIONSHIP BETWEEN ARCHITECTURE AND ACOUSTICS

Basic principles of acoustic design of outdoor performance spaces have been used for the planning and construction of ancient theatres. In most of the cases the contemporary use is viable, given that their conservation is accompanied by appropriate architectural and acoustic measures. The ability of specific scenery applications to activate the acoustic capabilities of an outdoor performance space was one of the major subjects of investigation in this PhD research. In the meantime, the individuality of each theatre, either in terms of construction or background noise, can be encountered through architectural and acoustic design.

11.2.1 ANCIENT PERFORMANCE SPACES

As discussed in Chapter 3, the first performance spaces appeared long before drama was born. They belonged to what is called today the Minoan type, situated near the entrances of palaces in Crete and used for celebrations. They were rectangular spaces, where no acoustic considerations seem to have been involved in their construction. This study examined the Minoan type, and in particular the performance space of Knossos, revealing that the hard materials used for their construction, in relation to their size and layout, contributed to high amplitude early arriving sound, while reverberation is at the range of 0.5s with 50% occupancy. The intermediate stage between them and the circular layout of later theatre constructions was the Pre-Aeschylean type, which may have also been constructed almost at the same time as the Classic theatre type, in trapezium shape, like the theatre of Thorikos. Its materials are though softer, like earth and wood, which led to shorter reverberation, while the trapezium shape discouraged flutter echo effects.

It has been indicated that the majority of drama texts corresponds to the evolution of the Classic theatre, in the form of the theatre of Dionysus in Athens [Mparkas, 2006]. Although the primary performance space was composed by the orchestra, the altar, the parodoi, the koilon, later with wooden seats facing the temple, in the first drama performances by Aeschylus it is indicated that a stage, a few steps higher than the orchestra, had been created to draw attention to the actor and distinguish him from the chorus. In this way the function of the theatre from the acoustic viewpoint was based upon the direct sound, due to the amphitheatric layout and the polyphony of the chorus, and the enhancement of the voices through the reflections of the orchestra.

11.2.2 Theatre Orientation

The exploitation of the hillside with the placement of the stepped seating area favours sound distribution in connection with temperature, atmospheric pressure and wind. The gradual overheating of the orchestra during the day in antiquity led to distribution of sound upwards. In the meantime, the drop of the temperature with the altitude led to the decrease of the energy losses in the koilon. The placement of the theatres is said to follow specific orientation. However, the majority of theatres reveal that each one is placed towards certain directions, probably according to local winds or external sound sources. When the theatre was constructed in urban environments the organisation of the city, the temple, the public buildings and the cultural needs formulated the orientation.

11.2.3 Skene-Building and Scenery Use

Several innovations have been observed in the ancient theatres, which were related with new performances and the introduction of scenery for the performances of the Orestean trilogy by Aeschylus, as mentioned in Chapter 4. The process of the scenery and consequently of the skene-building evolution enabled conventional use of the visible-invisible, outside-inside, close-far, approachable-unapproachable and led to the move of the focal point of the ancient theatre, from the orchestra to the stage, allowing for further enhancement of the actors' voices by the reflectors the scenery provided. The dramatic action slowly moved from the orchestra to three levels of the stage building, the logeion, the front of the second floor of the stage building and the roof of the stage building. Chapter 7 indicated that the raised stage and, consequently, the move of the actor to a higher level, were beneficial for acoustic purposes, due to relative source-receiver heights, further explained in Section 11.3.3. However, the positioning of the actor at the roof of the skene-building was disadvantageous because of the lack of a background reflective surface.

During the 4th century B.C. the stage building was built with stone that allowed low sound absorption compared to previous wooden and fabric constructions. In the Hellenistic and Greco-Roman theatre types the stage building was enlarged, risking the appearance of delayed reflections off the orchestra, with higher reverberation and lower intelligibility. This was encountered by the decorative facade with statues, niches and other objects to allow diffusion. The position of the stage building opposite the audience area in Roman theatres, created an enclosed autonomous shell that increased reverberation, and prevented urban noise from interfering in the performance. It is possible that for this reason fabric and wood had been used to provide absorption.

11.3 ACOUSTIC PRINCIPLES IN ANCIENT THEATRE DESIGN

The simultaneous function of two reflectors, the orchestra and the facade of the stage building in ancient theatres resulted in combining the reflections and adding them to the direct sound, so that a strong signal of the early sound would be created. Chapter 10 indicated that the space between the proskenion and the orchestra's centre is beneficial, particularly for the amplitude of low order reflections. To take advantage of this phenomenon the actors had and still need to limit their movement in the orchestra, and remain closer to the stage building rather than the audience. Despite this limitation in the performance of ancient drama, the functional, dramatic and acoustic importance of this intermediate space is still of major importance. Previous studies that referred to the 'Haas zone' suggest that it was a useful acoustic zone, a narrow space created by the tangent of the orchestra, the paraskenia and the stage building facade [Canac, 1967]. At the same time it is shown that the layout of ancient theatres is determined by what is called 'equation canonique' of ancient theatres, a complex trigonometric equation that involves the inclination, the axial development of the koilon, the orchestra radius, the width and height of the proscenium and the position of the stage building [Canac, 1967]. This is useful in designing contemporary stage buildings or scenery. The gradual expansion of the stage building in Roman times, in relation to the raised platform, led to acoustic deficiencies and the reduction in occupancy.

The aim of the actors and the audience during a performance is common: visibility, low background noise, liveliness, clarity and definition and speech intelligibility. The ancient performance spaces combine two contradictive functions: large occupancy and optimum visual and acoustic comfort. This study has indicated that the basic principles used in the design of ancient theatres succeeded in:

- reducing background noise
- developing the space around the performance through geometric principles regarding the orchestra's radius, the inclination of the koilon and the dimensions of the stage building, based on human speech and acoustic scale
- elevating the direct sound and enhancing it with early reflections and
- reducing late reflections and echoes and exploiting the advantages of the open plan layout, like the absence of the roof and the abolishment of the lateral walls.

11.3.1 THEATRE LAYOUT AND REFLECTION PATHS

The open-air form and the shape of the space has ensured the elimination of delayed reflections, due to the absence of the roof that could have created large reflection paths, so that the reverberation was restrained into the limits that secured clarity and definition and have been proved to be appropriate for theatre use. The reflections off the orchestra, being close to the actors and the chorus, enhance direct sound especially towards the lower part of the koilon.

The parodoi, the entrances and exits of the theatres, provided lateral reflections towards the koilon. Their function was diminished in the Greco-Roman and Roman theatres and they were finally replaced by the vomitoria. The paraskenia prevented the appearance of echoes and sent the reflections from the stage building facade to the koilon. The audience's visual and acoustic comfort is strongly related to the inclination of the koilon. The width-to-riser proportion in ancient theatres resulted in very inclined audience areas, of 21°-30° instead of 13°, which is the minimum required according to Mparkas [2004a], reducing audience absorption through exposure. It has also been suggested that due to atmospheric conditions the minimum inclination should be 8° [Goularas, 1995].

11.3.2 AUDIENCE AREAS

The 'so called' excellent acoustics of ancient Classic theatres was a result of the ideal conditions in reverberation and speech intelligibility, due to the layout that allows the distribution of direct sound, with early reflections off the orchestra, the stage building/scenery, the combination of both and the immediate decay of high order reflections. In this study this was clearly indicated in the impulse responses of the Greek theatre, compared to the Roman. In general, the overall sound level is better at central receiver positions than at the sides of the ancient theatres, in particular at the higher part of the koilon, because of the angles of the reflections off the orchestra floor and the skene-building's position. Hence, the disadvantages of the receiver positions high at the sides of the koilon are stressed out, when compared to the axis of the theatre, the advantageous seats. Usually, the former seats were the ones cancelled (destroyed) when the Hellenistic theatre type was constructed.

11.3.3 Actors' Positions

As far as the actor's position on and in front of the stage building is concerned, the direct sound was enhanced by the stage building and scenery when the actor was situated in front of the stage building or on the logeion, while the position on the roof, preferred mostly for the appearance of gods was less successful from the acoustic viewpoint. The orchestra provided the only reflections, less for the audience seated high at the koilon, due the small angles of incidence. However, the acoustic disadvantages of specific actor positions could have been balanced by other theatre means, like for example the plot, which at some points through the amazement of the audience reduces background noise.

11.3.4 Organisation of Absorption, Reflection and Diffusion

Overall, due to lack of electroacoustics, the ancient theatres needed the maximisation of reflective boundaries near the source, in relation to the minimisation of distant reflective boundaries. In other words, the maximisation of the absorption of distant boundaries was vital to avoid delayed reflections. They succeeded this by creating an outdoor space, so that the atmosphere would absorb sound, large smooth surfaces with low absorption (orchestra and scenery) and sound diffusion in small dimensions, in the lateral structural walls, the analemata, the perimetric corridors and the high parts of the stage building. Regarding the koilon, the risers, with heights varying from 17 to 40cm, constructed by large stones, correspond to frequencies that are closely related to hearing sensitivity and human speech (800-2500Hz). The provision to create these surfaces close to each receiver ensures sound distribution of a crucial frequency spectrum. Several years ago it was suggested that with the *"use of electroacoustic facilities of our time, the practical interest in the problem of the special acoustical qualities of the ancient theatres disappears"* [Cremer, 1974]. Indeed, a few performances today take advantage of the new technology and apply electroacoustics to ancient theatre productions, while others attempt to reproduce sound, although by cleverly hiding the electronic equipment. One of them was 'Eleni', performed in 2006, shown in Chapter 4, Table 4.1. In terms of sound intensity it is clear that the use of speakers is helpful. Fortunately though, most of the directors rely on the physical acoustic attributes of the ancient theatres; hence the performance sound is more 'original'.

It has also been indicated that through appropriately placed reflectors or stage enclosures, incorporated in the scenery application, the sound amplitude can be enhanced, the energy loss at the upper part and the sides of the audience can be avoided, the unwanted side reflections can be counteracted, while the useful early reflections can be embodied with the direct sound. In parallel, the emergence of the useful sound signal, when high background noise is observed, is optimised.

11.4 Design Guidelines

This study aimed to assist individuals, stage designers and directors, to comprehend how stage/scenery design can affect the perception of a performance in terms of sound. Since vision and sound are the two senses that the viewer/receiver mostly uses during this experience, the temporary architectural elements of each performance can help identify and adjust the intended feeling leading to the overall experience.

11.4.1 General Guidelines

Several measures can be taken during the design of an open-air theatre/performance space, while solutions can be also provided for ancient theatres that lack acoustic quality. A major concern of the architect/acoustician would be to try not to weaken the direct sound. This can be achieved by appropriately orientating the theatre to protect it against wind and background noise and at the same time to take advantage of the wind that is blowing from the actor towards the audience. The direct sound should be enhanced by early reflections, in less than 50ms after the emission of the former.

The orchestra should be covered by a highly reflective material and be as empty as possible. It needs to be noted here that contemporary trends in scenery design involve the use of fabrics that cover the orchestra's floor, which is detrimental from the acoustic viewpoint.

Apart from the purposely-designed scenery, in a variety of shapes, based on the categorisation discussed in Chapter 10 and the combination of different materials, categories, and surface effects, other parts of the theatre can be used. For example the parodoi, the entrance and exit of the theatre, which, according to Section 11.3.4, provided useful reflections for the sides of the audience area in antiquity, can be re-placed by using contemporary light boards. The acoustics of the last rows of the audience area can also be optimised by appropriately designing inclined reflective surfaces at the back, resembling the perimetric corridor of the Roman theatres. However, they should be carefully design to avoid delayed reflections reaching the front seats.

The basic distinction between outdoor and indoor performance spaces is that the latter, being enclosed, have surfaces treated to control early and late reflections for accepted values of reverberation, clarity, lateral fraction and to avoid echoes and flutter echoes. Also, the fact that indoor spaces have padded seating means that the difference between occupied and unoccupied conditions is not as different as for outdoors.

To treat the uncontrolled acoustics of outdoor theatre could be to control the way absorption, reflection and diffusion is distributed. A first attempt to succeed this would be to control the way the audience is seating. By identifying in advance the parts of the koilon that contribute to useful reflections, one could arrange the audience, so that useful reflective surfaces will not be obstructed. Consequently, the theatre can accommodate concerts, since the combination, for example, of high background scenery walls and the reflective surfaces of the seating area could increase RT and enhance sound. In this way the audience will provide absorption only at specific seating areas. When there is a need to provide diffusion, panels can be placed in front of the reflective unoccupied seating areas.

This organisation of the theatre's layout with appropriate zones of absorption, reflection and diffusion should be carefully designed and applied, in relation to the scenery that will be installed, due to the individuality of each theatre, with unique reflection patterns. Moreover, this is a step forward, since it considers the uniqueness of each space rather than generic layouts and can be used once the percentage of occupancy is known.

Finally, for new theatre structures, the performance style intended for the specific theatre should be identified, to provide the initial construction of the performance space with the preferred acoustic quality, which can then be altered accordingly, by applying temporary scenery design. The audience area should have seats with relatively high backs, so that sound can be reflected. This is easily achieved without affecting the visual sightlines, since the inclination is or can be quite increased.

11.4.2 SCENERY GUIDELINES

This study suggested that scenery design, either in the form of the ancient stage building, or as contemporary scenery applications contributes to the improvement of the soundscape of ancient theatres. Some basic characteristics of ancient theatres can be applied to modern outdoor performance spaces, as will be seen in Section 11.5. Also, specific properties can be manipulated in order to produce the desired acoustic effect. One can argue that a method like this could constrain the imagination and creativity of the designer and director. In fact its aim is to provide useful information about the effect of scenery design on the total experience (*katharsis* was the term used by Aristotle).

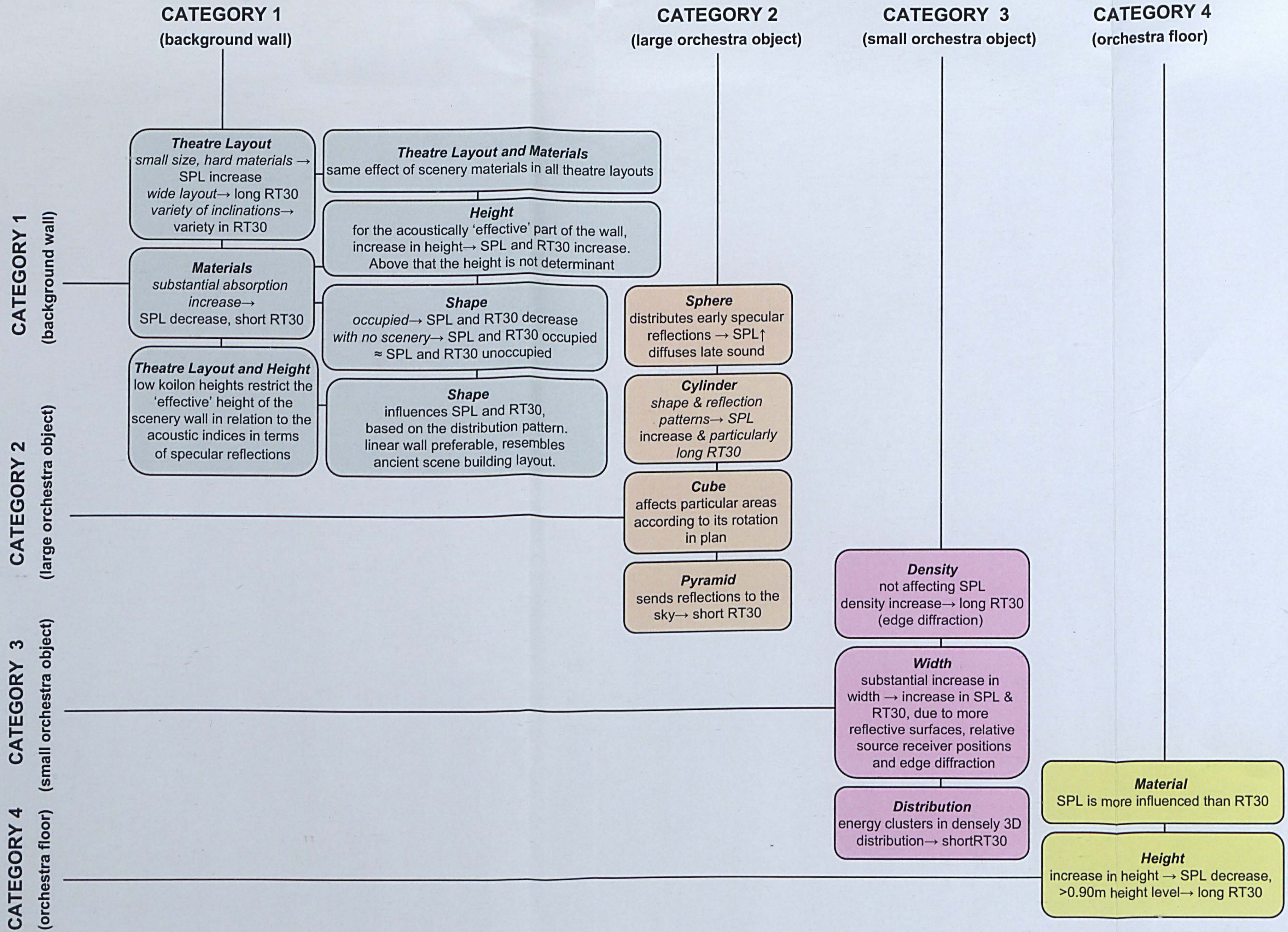
Initially, the director can choose the materials and scenery design that would enhance the actor's voice, or alternatively diminish its strength. For example, since the entrances/exits of the actors and the protagonists are usually pre-defined, the designer/director can choose the appropriate design so that the king's sound level would be higher than common people's. This can be achieved by placing a hard surface near the leading actor, to enhance the direct sound by providing early reflections towards the audience area.

Also, as shown in Chapter 10, a simple, low in height, not aesthetically obtrusive, lightweight background wall, placed appropriately and in a right size, is the gentlest intervention one could use to enable useful reflections and improve the soundscape. It is a structure that can be adjusted during the summer and removed every winter, since it does not restrict the artistic creativity and freedom for the selection of scenery, or the use of minimum skenography in the form of small objects. This boundary can nevertheless be created by glass. Being transparent it would no obstruct the view of the surrounding landscape and would at the same time provide the desirable acoustic effect. In the case of a platform, it has to be narrow and long, in order to reflect sound coming from the background wall, without affecting the reflections off the orchestra.

Moreover, to avoid delayed reflections and noise coming from the audience, the background wall should not exceed the height that is useful for the early reflection distribution, as seen in Section 10.4.1. A background wall with a height that is greater than necessary would reflect the audience voices and send them back to the audience area. Alternatively, absorption and diffusion should be applied to the higher parts of the wall. In general, decoration that would diffuse sound would be appropriate for some areas of the scenery/stage building. The irritating background noise, mainly in the form of traffic noise, in cases like the theatre of Philippi, seen in Section 9.3, can be counteracted by designing acoustic barriers in relation to appropriate lightweight structures, as mentioned before. While the former will be placed near the source, next to the motorway, parking etc., the background wall, which is the simplest generic scenery application, consisting from one or a combination of objects, will be strategically positioned at the tangent of the orchestra circle. Nevertheless, other scenery shapes and arrangements can be used, either in combination with the background wall, or not. The effect of generic scenery categories on the acoustic environment of ancient theatres, examined in Chapter 10, has been discussed in Sections 10.4-10.7 and is presented in Table 11.1, in the form of a summarised matrix.

It has been indicated in previous studies that in ancient Greek theatres the reflections from the orchestra and the koilon introduce a measurable source signal level amplification [Vassilantonopoulos and Mourjopoulos, 2003]. It was found that the combination of direct sound, early reflections, diffused sound and late reflections results in low RT, at around 0.2s, which was regarded useful for speech intelligibility, acoustic quality and the sense of intimacy and communication. However, Vassilantonopoulos and Mourjopoulos [2003] suggested that it was inappropriate for music performances. This study has identified rather increased levels of reverberation, around 1.0s in Hellenistic and 1.5-2.0s in Roman outdoor theatres, based on measurements that were carried out with the prerequisite that temporary scenery was installed. Hence, with appropriate scenery use, as discussed in Chapter 10, optimum values of reverberation and other indices can be produced, and consequently an ancient theatre can accommodate concerts and other kinds of music performances.

Table 11.1. *Final matrix with guidelines for scenery design applied to open air theatres.*



11.5 Application to Contemporary Open-Air Theatres – Case Analysis

The results of the research on ancient theatres can be applied to contemporary outdoor performance spaces, either constructed in the same form as an ancient theatre or in other forms, as will be seen later. This section presents nine contemporary open-air theatres, aiming to identify applications of the findings of this study.

The open-air theatres are briefly discussed in this section, in terms of their general layout, architecture and soundscape. The first three are based on the design of Hellenistic/Roman theatres. Three have been designed by M. Perrakis, and three by N. Tsinikas and F. Vavili, among a number of indoor and outdoor theatres in Greece, in more contemporary layouts.

For the lightweight theatre, built of iron and wood, simulation has been carried out by the acousticians and is briefly presented here. The theatre accommodates 4,860 persons. Its radius is 33.5m with 8m orchestra radius. Although at first it was an open-air theatre of Roman type, in a strict semicircular shape, additional seating rows were added to create an open plan at 227° with 26° inclination [Tsinikas, 1990]. Figure 11.5.1 illustrates the plan of the theatre. However, despite the circular orchestra, the stage is located near the centre. Through the simulation it was found that the absence of seat risers in the audience area allows for background noise to enter the theatre, while sound energy is lost. It is noted that a road is very closely situated. The disadvantages of the theatre are the same as those in ancient theatres, like lack of multiple reflections, acoustic deficiency at the sides etc.

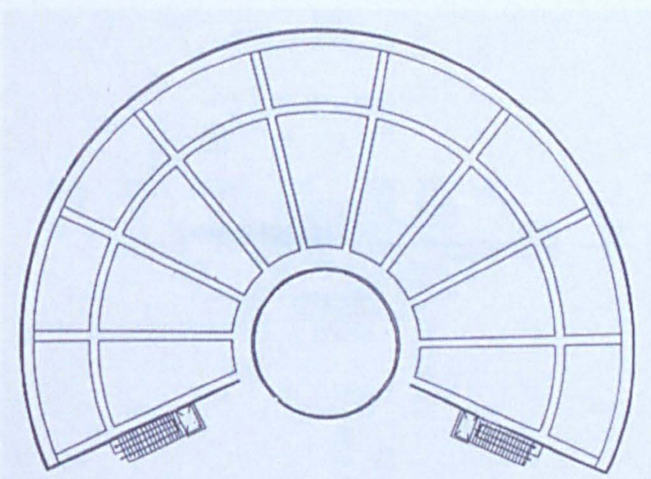


Figure 11.5.1. *Plan of the new open-air theatre of northern Greece [source: Tsinikas, 1990, pp. 92]*

The acoustic proposal was to cover the seat risers, so that no energy would be lost, to raise the stage, to add a background wall to the stage, so that additional reflections would be provided, to add an inclined surface, attached to the background wall, similar to those described in Chapter 9, so that a stage enclosure would be formed, to create diffusely reflective surfaces on the background wall with two kinds of diffusers to compensate for the low frequencies, and to construct a boundary at the perimeter of the audience so that the last row will be benefited.

The second theatre is of Greco-Roman type, built outside the city of Thessaloniki, used for several kinds of performances, including theatre and music concerts [Tzekakis and Schubert, 1999]. Although it is semicircular, there is no stage building to provide an enclosed layout. It has 22 rows, with 2 diazomata, accommodating 5,000 people. Its examination resulted in relatively good acoustic conditions, due to the hard materials used, especially when there is the addition of appropriate scenery design. Figure 11.5.2 illustrates the Theatro Dasous (Θέατρο Δάσους) during a performance of ancient tragedy, 'Iphigeneia en Taurois', in summer 2006. It was one of the performances with sound deficiencies, since the orchestra was covered with a heavy and folded fabric, and the scenery was also absorptive. The result was the absence of any kind of reflected sound, with weak early sound. As expected, when music concerts take place in the theatre, electroacoustic facilities are used.

Figure 11.5.2. *The Theatro Dasous before the performance of 'Iphigeneia en Taurois'.*

The third theatre, Theatro Kipou (Θέατρο Κήπου), is situated in the city centre of Thessaloniki, Greece. It was in use for several decades before the need for reconstruction that emerged from the increase in traffic and the general redesigning of traffic and planning of the city centre in 1997 [Mparkas, 2004b]. The initial drawings on the reconstruction of the theatre were never followed due to economic reasons. The theatre was redesigned architecturally based on Greco-Roman prototypes, accommodating 800 persons, with 10m orchestra radius, 225° in plan, 23° inclination and a low stage, as shown in Figure 11.5.3. The theatre was oriented with its back to the traffic junction, with further submersion of the orchestra floor and walls at the perimeter to protect the space from traffic noise. Also a kind of roof covers the corridor at the upper part of the audience area. In terms of acoustics, its design could be further improved, with additional submersion of the orchestra floor and if several measures were taken regarding the night club playing loud popular music, situated in the adjacent building.

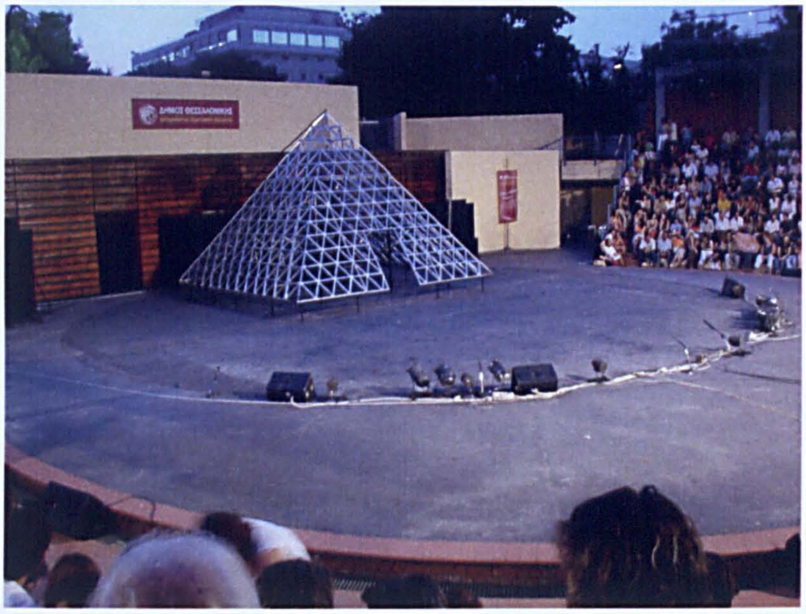


Figure 11.5.3. The Theatro Kipou before the performance of 'Eleni'.

The following three theatres were built by the same architect, Manos Perrakis, who is regarded an expert in theatre design in Greece. The first is situated in the centre of Athens, next to the Roman Agora, built in 1985 [Varopoulou, 1991] for 1,200 persons. It is illustrated in Figure 11.5.4. It is placed at the corner of a rectangular space, in 90° in plan, with the orchestra in an almost trapezium shape, three seating areas at the low and two at the upper part. It is an asymmetric construction, the right side exceeding the left, where Perrakis managed to provide a lot of reflections from adjacent buildings and nine additional reflective surfaces, positioned behind the stage and at the audience's sides. Circular columns also diffuse sound. In the 80's it was regarded one of the most important outdoor theatres.

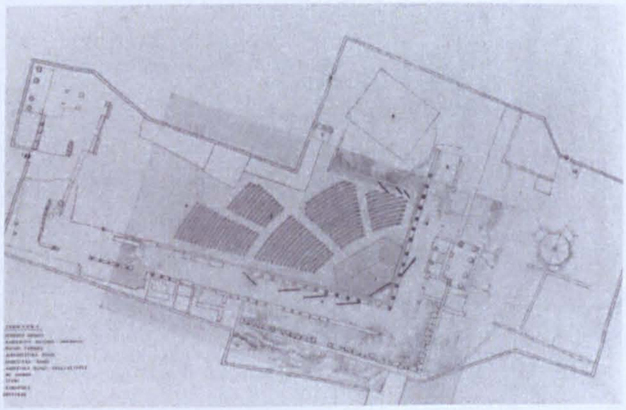
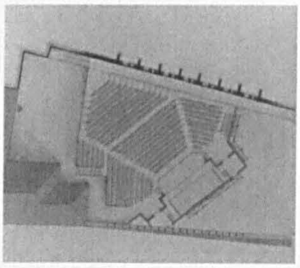


Figure 11.5.4. Plan and view of the theatre of the Roman Agora in Athens [source: Perrakis, 1991, pp.21-22].

The theatre of Firka in Chania, Crete was an earlier product of Perrakis' creativity, where a lightweight theatre structure is movable and can be adjusted according to the needs of each performance [Varopoulou, 1991]. In 1974, when it was created, it was used by the director

Minotis, with the scenery design by Kleovoulos Klonis, introduced in Chapter 4. Its shape is similar to the Athenian one, with three audience areas at the low and two at the upper part. Its shape is almost symmetrical, in fan shape, as seen in Figure 11.5.5. The theatre is surrounded by tall walls that allow multiple reflections to reach the audience. However, the reflections can be multiplied and create a noisy background, since the hard surfaces cannot be treated acoustically.



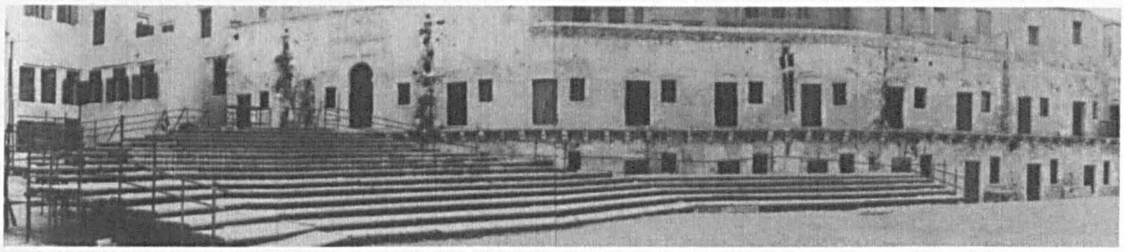


Figure 11.5.5. *Plan and view of the theatre of the Roman Agora in Athens [source: Perrakis, 1991, pp.25].*

The theatre in Fortezza in Rethymno, Crete, was designed by Perrakis and built in 1975 [Varopoulou, 1991]. This is a structure made of stone, in a rather small angle in plan, resembling the enclosed theatres. Because it is situated in the fortress of the old city of Rethymno, the surrounding walls diffuse sound effectively. Figure 11.5.6 illustrates the plan and a drawing of the theatre.

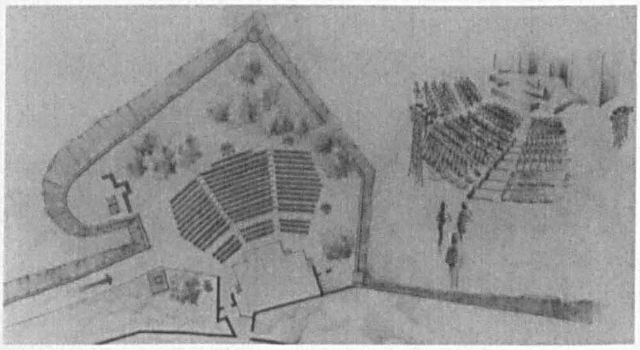


Figure 11.5.6. *Plan and view of the theatre of the Roman Agora in Athens [source: Perrakis, 1991, pp.27].*

The following three theatres were designed by N. Tsinikas and F. Vavili, Professors at the Aristotle University of Thessaloniki. They were based on basic principles of open-air theatre design, like the good distribution of direct sound, by applying a maximum of 16 rows of seats (or 20m maximum distance from the source at the axis of the theatre), the steep inclination, translated through the relationship between the height and width of the audience's seating, the short source-receiver distance, and consequently the sound emission angle, the raised stage, the provision of early sound distribution through reflection and diffusion and the prevention of background noise [Tsinikas, 2005]. All theatres were designed in cardioid (heart) shape.

The first theatre is the open-air theatre of Kalampaka, illustrated in Figure 11.5.7. It was built in 1993-4 with 6 and 9 rows of seats at the low and upper part, with 22^{o} and 29^{o} respectively. The design was enhanced by a semi-circular orchestra enclosure and low reflective parapets at the perimeter of the theatre. It is noted that the parapets at the perimeter of the audience area are compulsory, according to planning restrictions in Greece.

Although there are no data or measurements on the acoustic performance of the theatres, the concave shape of the orchestra's enclosure could lead to 'focus effects', unless it is covered by ephemeral diffusive surfaces, as also indicated in Chapters 9 and 20. The hard concrete used for the theatre's construction is useful for providing high amplitude early reflections, while the cardiod shape of the orchestra area, resembling contemporary indoor performance spaces is successful regarding the directivity of human speech. Nevertheless, through this study it was shown that, from the acoustic viewpoint, the sides of the ancient theatres are the 'weak' areas.

Figure 11.5.7. *Photo and plan of the theatre of Kalampaka [source: Tsinikas' personal archive].*

The most recent theatre of Cholargos in Athens, designed in 2002, is shown in Figure 11.5.8. It consists of 17 rows of seats, a folded suspended stage enclosure, to be built with a metal structure and fabric, low side parapets and high reflectors at the back.

This theatre seems successful both from the architectural and the acoustic viewpoint, with impressive layout and stage enclosure design and consideration of reflection distribution for the audience area and in particular for the last rows respectively. Acoustic simulation carried out by the architects has also indicated this, although it hasn't been published yet. Additionally, the inclinations and the complexity of the enclosure seem to reflect and diffuse sound effectively, according to the results and discussion in Chapters 9 and 10.

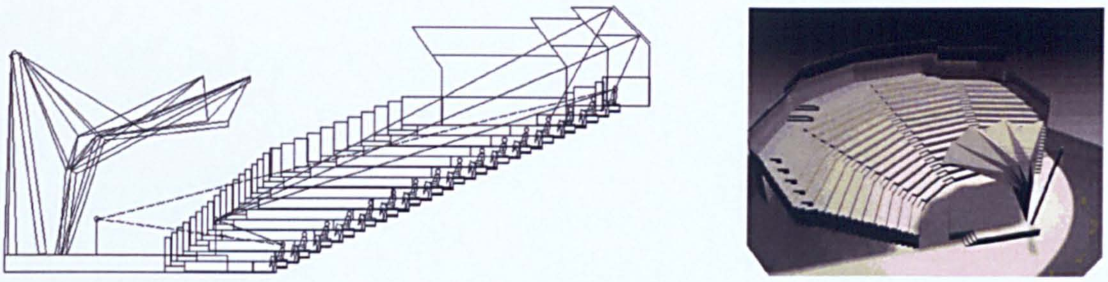


Figure 11.5.8. Section and axonometric view of the theatre of Cholargos [source: Tsinikas' personal archive].

The theatre in Zarkadia, Chrysoupoli, designed in 2002, is based on an ellipse, with 13 rows of seats with inclination of 25.2°, with stage reflectors and a stage enclosure, low reflective parapets at the sides and high reflective panels at the back. The theatre is presented in Figure 11.5.9.

Its design is based on principles of open-air theatre design that have also been discussed in this study. The cardioid shape, the reflections from the lateral and the rear panels, the hard materials and the purposely-built stage enclosure seem to contribute to a successful acoustic environment. However, the only restriction that will be applied to the performers through the design of this theatre is the metallic gate at the front of the oval orchestra. This was probably designed for functional reasons; to accommodate the lighting for the performances and the loudspeakers for concerts. However, for performing drama it would obstruct the view for some parts of the audience and, maybe, force the actors to perform in front of it. The implication of the latter would be decreased angles of incidence of the direct sound and the orchestra's reflection.

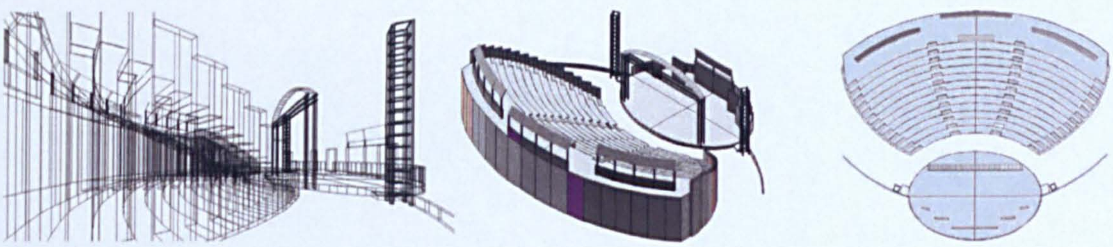


Figure 11.5.9. Perspective, axonometric view and plan of the theatre of Zarkadia [source: Tsinikas' personal archive].

From the above it can be seen that in contemporary theatre structures there is a number of reflective and diffusive surfaces in the theatric space, to allow for early reflections to reach the audience. Apart form the orchestra's floor, the added reflectors, the diffusers, the surrounding walls, the partial roofs and the stage enclosures contribute to an optimum soundscape. Many design decisions have been made most probably because of planning restrictions. Through this study it is indicated that acoustic design can be incorporated in the architectural design, while it can also complement possible architectural defects. In ancient theatres, or contemporary open-air theatres, application of temporary scenery or movable reflective and diffusive panels is appropriate for the improvement of the acoustic environment.

11.6 Conclusions

This chapter presented the ways theatre and scenery design is implemented according to basic principles used in antiquity and today and the results presented in Chapters 2-10 of this study. The relationship between architecture and acoustics was first presented, according to this study's findings.

Ancient theatres functioned acoustically based on the direct sound, the amphitheatric layout and the enhancement of the voices through the reflections of the orchestra and the stage building. This can be also applied to contemporary open-air theatres, by creating steep inclinations, hard orchestra surfaces and background scenery walls, to distribute and reflect sound efficiently. The 'Haas zone', the zone between the orchestra and the stage building, is also important for the placement of the actors or the chorus in terms of acoustics. Moreover, other parts of the theatre can be used, like the parodoi, to reflect sound towards the sides of the audience area and the perimetric corridor, to provide early reflections to the last rows. Furthermore, with appropriate orientation, temperature, atmospheric pressure and wind directions can also be integrated in the design.

The findings of this study regarding reflectors and stage enclosures, incorporated in the scenery application revealed that the acoustics can be optimised. Without constraining the creativity of the designer, scenery can, in simple forms or by being transparent, enhance the actor's voice, increase or decrease reverberation and provide better conditions in speech intelligibility, definition and clarity. Consequently, open-air theatres can, with appropriate scenery, accommodate concerts and other performance types. Combination of different materials, categories, as seen in Chapter 10, and surface effects can be used. By organising the way absorption, reflection and diffusion is distributed through audience absorption, reflective and diffusive panels respectively, in relation to scenery application, the acoustics can be manipulated accordingly.

Finally, the case studies presented in Section 11.5 showed that the results of this study can be applied to contemporary theatre structures, through reflective and diffusive surfaces, to allow for early reflections to reach the audience. Apart form the orchestra's floor, the added reflectors, the diffusers, the surrounding walls, the partial roofs and the stage enclosures contribute to an optimum soundscape. Hence application of temporary scenery or movable reflective and diffusive panels is useful both in ancient and contemporary open-air theatres.

CHAPTER 12

CONCLUSIONS

12.1 INTRODUCTION

The study of the acoustic function of ancient performance spaces is related to the investigation of the development of theatre architecture and the clarification of the theatre layout in every historic period. Generally, due to the dissimilarity of the scientific and artistic theories theatre, as a term, belongs to, according to the several viewpoints of the topic of this PhD study, the fragmentary study of theatre, either as space where archaeological excavations are carried out, as a field of acoustic research, or as a self-existent artistic creation, faces several difficulties. Sometimes, the interpretation of the remains of the past combines the archaeological findings of several construction stages and periods. At the same time, to approach a performance of drama, mainly from the Classic period, the theatre's infrastructure and the conventions of drama are needed. The interdisciplinary nature of this study and the interaction of all these parameters, although proper from the viewpoint of methodology, constitute a difficulty in interpreting the functions of ancient theatre, the architectural interventions and the interpretation of the original texts.

This study was mainly focused on the evolution of performance spaces in antiquity, the appropriate research methods used for their examination and their contemporary use with the application of appropriate scenery design. Performance characteristics, architectural innovations, simulation parameters, effects of absorption, diffusion, diffraction, on-site measurements and subjective evaluation were some of the basic means used. For the acoustic simulation comparison has been carried out between common software, to select the appropriate to be used for accurate results. The focus of this study was the identification of generic scenery layouts, based on trends that scenery designers followed in the past century for the revival of ancient drama. Acoustic evaluation of the contemporary use of ancient theatres was carried out with the use of generic scenery categories, the examination of their effect on the acoustic environment of ancient theatres and their application to contemporary open-air theatres.

12.2 CONCLUSIONS OF PHD RESEARCH

The conclusions of the ten main chapters of the PhD study are presented in this section, organised by part and chapter, following a brief discussion of their contents.

12.2.1 PART 1: LITERATURE REVIEW

Part 1 was composed by Chapters 2-4. Chapter 2 briefly reviewed the literature on the theory of sound, sound propagation, basic acoustic indices and the first evidence of architectural and applied acoustics. It described the nature of sound in ancient theatres and the effects of temperature, relative humidity, wind, ground, trees and planting. Beranek's subjective attributes were also briefly discussed. Then it consisted of a description of and comparison between CATT, ODEON and Raynoise, commonly used acoustic software, to select the appropriate for the simulation of ancient theatres. Basic algorithms, simulation process and appropriate calculation parameters were also described.

It was found that auditory judgement, mathematics and logic had been criteria for interpreting acoustic phenomena. Ancient philosophers, mathematicians and naturalists tackled with sound generation, sound transmission between rooms, concord, the optical principle of equal angles of incidence and reflection, and voice propagation. They compared the speed of sound with the speed of light and indicated that sound energy is decreased with the increase of distance. In the field of architectural acoustics they observed the decrease of the chorus' voices in the ancient theatre when the orchestra was spread with straw, as well as wall reflections in a house. Vitruvius examined the acoustics of ancient Greek and Roman theatres in a general study that involved their design and geometrical principles considered for their layouts.

Regarding sound propagation outdoors it was demonstrated by modern acoustics that, in an outdoor performance space, reflective boundaries can improve the listening conditions for both performers and audience, and steeply raked seating, like in Greek and Roman theatres, is better for acoustic conditions, since the angle of reflection is not parallel to the seating plane as with a horizontal layout. The addition of a stage building for the performers evolved their design acoustically, and also provided a protection against background noise. Hard reflective surfaces improve the acoustic conditions through early reflections that enhance direct sound, and diffusion from destroyed edges or people's heads. Also, audience is usually very dense; hence the difference between the unoccupied reflective seats and the closely seated audience is large.

Ancient theatre layouts create focus areas and multiple reflections between parallel sides. However, one of their components, the stage building, is usually missing from their present condition, which alters their sonic environment. Moreover, the climatic and environmental conditions are very important. Temperature and wind gradients affect the acoustic conditions, like fog and snow affect background noise, with maximum effect in the summer period, corresponding to the use of open-air theatres. Furthermore, through the investigation and comparison of commonly used acoustic software, namely CATT, ODEON and Raynoise, based on similar algorithms, Raynoise was preferred for the simulations, due to its compatibility with CAAD software and the ability to produce reverberation time for outdoor spaces, despite the long calculation times.

Chapter 3 focused on the theatric space in antiquity, the forms of drama performed in it and the acoustic environment according to previous research. It particularly reflected upon the types of theatre from the Bronze Age and until the Roman times, with emphasis on the Classic times, when Greek drama flourished. Components of the theatric space were examined and the 'evolution' this study later investigated from the acoustic viewpoint was discussed. The audience's part and the chorus's role in the sensory experience of a performance were also presented.

The initial form of performance spaces had angular layouts and small sizes. The acoustics depended mostly on direct sound and adjacent buildings provided useful reflections. The construction of theatre buildings was related to material use, while the transformations in their layout were related to the performance type and innovations in drama. The evolution from the Classic theatre type, which was created after the birth of drama in the 6^{th} century B.C., to the Hellenistic type, at around the 2^{nd} century B.C., was a consequence of changes in the performance style. The Roman theatres had probably evolved from the Greek open space into a building because of an aesthetic reason and to acquire unity of mass. The architects' attempt to cover the theatre with the velarium, together with the use of a stage curtain during the performances, brought the Roman theatre another step closer to the indoor playhouses of later periods.

The evolution of theatre layout in antiquity is a systematically examined subject, mainly for acoustic purposes, although rectangular and circular layouts could have been constructed simultaneously. A fundamental difference between the Greek and the Roman theatre is the fact that the Greek theatre emerged from the orchestra, whereas the Roman theatre stemmed from a rectangular stage. The Greek theatre had three components, the auditorium, the circular orchestra, and the stage building or skene, which were separated. On the other hand the cavea of the Roman theatre was semicircular, united as a single structure with the stage building.

The ancient theatres were quite successful for their purposes. The Greek theatres provided reflections off the orchestra, the back stage wall and the heads of the seated audience. The acoustics depended on direct sound, due to the koilon's satisfactory layout. The role of the low background noise level was also important for the acoustic conditions, despite the large numbers of audience. The best position for the actor on the orchestra was at the centre, for visual, focal and acoustic purposes, or when he approached the stage building. His appearance on a higher platform also seems to have improved the acoustic conditions. From the visual and acoustic viewpoint, the ancients were aware by experiment, of the specific seats that provided good acoustics and sightlines to the audience. The disadvantageous seating areas at the sides of the orchestra were usually the last to be occupied.

The steep seating area provided good conditions, because of larger angles of incidence to the seating area, while the unoccupied seats, with backs or risers sloped backward by about 10^{o}, and the heads of the audience also scattered sound to adjacent areas. Although it is believed that the acoustic environment created in the Roman theatre was better than the Greek, because of the enclosed space it provided, multiple reflections between the stage building and the audience area contributed to the increase of reverberation. Furthermore, the presence of the chorus that described the myth and played an important part in ancient drama was significant, both in terms of the performance and the acoustics, since they formed a unified voice, clearly heard throughout the audience area. Also, it was found that the acoustic quality of many ancient Greek and Roman theatres cannot be ascribed to the vases placed under their seats.

Chapter 4 was the last component of the literature review. The layout, creation and development of the stage building in antiquity, as well as the productions of ancient performances in the 20th century with temporary scenery design were presented. After a discussion on famous scenery designs of the last century, adaptable to many theatres, a categorisation of generic sceneries was carried out, while the need to investigate their effect on the acoustic environment emerged.

The wooden platform, the first stage of antiquity, was replaced by the stage building of the Classic period, gradually altered in heights and components, and evolved into a permanent stone construction in late Classic and Hellenistic times. Roman theatres used a higher stage building, attached to the main audience area to create an enclosed in the perimeter space. Conventional scenery was used in antiquity and today, while entrances and exits of actors from specific stage areas are also of major importance for Greek drama and can be used for the acoustic design.

In recent performances the scenery followed several trends in art and architecture, like constructivism, symbolism, abstract art and modernity. The new trends involved three-dimensional scenery characteristics, between which the actors could move. Based on this, the sceneries were classified according to architectural characteristics in four groups: (a) background, (b) large object, (c) combination of small objects and (d) orchestra floor, to allow easier acoustic investigation.

12.2.2 PART 2: RESEARCH METHODS

The second part of the PhD study, the research methods, was comprised by Chapters 5 and 6. Chapter 5 consisted of the methodology used in this PhD study. The simulation methods included number of rays, reflection order, background noise, diffusion distribution, absorption, area and directional source, energy responses and reverberation of open-air layouts. Methods of simplified representation of ancient Greek theatres were also investigated. Finally, it presented the methodology for absorption coefficient testing, on-site measurements and subjective evaluation, to be followed in later chapters.

Regarding the appropriate parameter tests it was shown that the highest possible number of rays was preferred, at the range of 10,000-20,000 rays, depending on the complexity of the model, while the reflection order should be 10. For background noise it was indicated that it is possible to separately simulate the two sources, the main source and the noise, or integrate the background noise in the simulation only by providing its power level. The latter produces very long RT values, which consequently leads to very low STI. Hence, since the presence of background noise will affect the acoustic indices, it was not included in the simulation in this manner.

The comparison between an omni-directional source and a source with human directivity, positioned both on the stage building and the orchestra of an ancient theatre, indicated that there are insignificant differences between the two sources. The omni-directional source presents higher direct sound and SPL, less reflections and lower definition and clarity at the sides than at the middle, compared with the directional source. Also, there are small variations in reverberation between the two sources. In general, it was decided that the simulations of this study should be carried out with the omni-directional source for the sake of convenience.

For the relationship between the layout of the theatre, the impulse response and reverberation, exact representation of the model is needed to ensure accurate reflection paths. Moreover, regarding the simplified representation of circular shapes of ancient theatres, shape hardly affects SPL, large enclosures (rows of koilon far from the source) eliminate representation differences, fewer segments representing the circle provide more reflections, while diffusion reduces the differences. Therefore, it was decided that the minimum number of segments used in this study would be 24.

Chapter 6 focused on the effects of diffraction on sound distribution in ancient theatres, discussing (a) diffraction to the shadow zone behind a panel, (b) diffusion/diffraction due to limited surface size, (c) diffraction from a panel edge, and (d) diffusion effects due to the acoustic roughness of panel surface. Although the effects of diffraction are not always considered in computer simulations, open-air performance spaces present few strong reflections, so even the weak scattered energy would influence results and form decay curves in impulse responses. In cases of actors situated behind a scenery panel or object, additional diffraction at edge points should be considered.

Edge diffraction is significant, especially at high frequencies and for geometries with small surfaces and/or several wedges, like scenery designs that involve several smaller objects/panels. For ancient theatres the frequencies mostly affected are lower than 500Hz.

Based on previous work on the effects of diffraction and research on diffraction in computer simulations, two methods were developed and tested in Raynoise. By comparing diffusion application (Method 1) and theoretical approach on a combined diffraction/diffusion coefficient for reflecting panels (Method 2), RT30 was the index mostly affected, compared to other acoustic indices. Both methods underestimate reverberation, with a difference of almost 1s compared to the flat panel diffusion (no diffraction considered). Especially for Method 2, it was indicated that by increasing the distance between the reflection point and the edge of the riser the combined coefficient reduces. Increasing the length of the panel (which is around 2m) has no effect on the coefficient, but decreasing it ensues increased diffusion. By changing the panel's width the coefficients are mostly determined by the surface roughness. In general, the combined coefficients are stable after a specific distance. The formulae of Method 2 were further developed to incorporate the 3D characteristics of the reflection paths, both by analysing the reflection paths and by using the normalised vectors, namely the scalar product. It was shown that scattering increases as the distance of the reflection surface increases and that there is a 'pattern' regarding the coefficient value and the theatre's layout.

The three methods of considering diffraction/diffusion have been tested and compared with the measurements in the ancient Greek theatre of Epidaurus, presented in Chapter 8. It was shown that the calculation by using the flat panel diffusion coefficients generally agrees well with measurements. Method 2 is useful in the case of scenery parts and small objects, in relation to their dimensions and surface roughness. It was noted that for other theatre layouts, such as the more enclosed Roman theatres, different diffusion/diffraction coefficients, namely Method 2, might be more appropriate. Additionally, it was indicated, through a comparison between the Lambert and the typical distribution, that the effect of reflection pattern/directivity is not significant.

12.2.3 Part 3: Analysis

The third part of the PhD, the analysis, involved Chapters 7-11. Chapter 7 discussed the acoustic evolution of Greek and Roman theatre types, in relation to architectural and material changes, and details in design. Also, a systematic study of the effect of selected absorption and diffusion coefficients was carried out, since exact material properties of ancient theatres are usually unknown. The aim was to examine how the changes in material properties could influence the acoustic evolution of ancient performance spaces.

The theatre evolution in antiquity showed that innovations in construction and layout generally resulted in acoustic improvements - the reverberation time had been increased and the sound level had been enhanced. The steeper seating areas, the harder materials and the higher stage in the evolution process were beneficial. However, although the Roman architects succeeded in uniting the theatre, the acoustics could lead to poor intelligibility, depending on the occupancy of the space. In particular, the materials used through the theatre transformation from the Classic to the Hellenistic period influenced the acoustic environment, also considering details in design. This part showed the insignificant effect of surface characteristics on the SPL, the usefulness of the circular shape for providing multiple reflections, the reduction in SPL in the occupied space, the relatively increased RT for the upper part of the koilon, due to the diffusion from the audience, the useful first reflections from the vertical surfaces of the koilon and the effectiveness of the raised stage, as developed during the Hellenistic renovations.

A comparison was also carried out between the unoccupied Greek theatre of Epidaurus and the Roman theatre of Aspendus. The simulation under the unoccupied condition showed that the uniform structure of Aspendus resulted in higher SPL and longer RT. The Roman theatre had long RT at the upper part of the auditorium because its layout provided reflections off the peripheral corridor. However, by comparing the acoustic indices of Aspendus to contemporary acoustic criteria, it is shown that speech intelligibility was very low under the unoccupied condition. The conditions were much better in Epidaurus. For the occupied theatre of Aspendus the conditions were much improved. RT and SPL were reduced by the audience's presence. Still, the values of D50 in Epidaurus were higher than that in Aspendus. Also, the reflections in Epidaurus were relatively more important for the distribution of sound, due to their small number. Regarding Aspendus the velarium increased SPL significantly and reduced RT differences between the upper and the lower part of the cavea, although it may have led to poor acoustic conditions under the occupied condition.

The results of the absorption coefficient range for stone, wood, earth and audience showed that changes in material properties have not affected the evolution, although extremely low or high absorption values could have presented rather unrealistic results. By changing surface absorption coefficients of materials used for large surfaces the results are quite affected.

Chapter 8 concentrated on the examination of the theatre of Epidaurus, through reverberation time measurements, acoustic simulation, subjective evaluation tests and their comparison. The measurements and final values of the absorption coefficients used in the simulation were also presented. Additionally, the theatres of Knossos and Philippi were measured, to validate the simulation results of Chapters 7, 9 and 10.

The absorption coefficients for local (Greek) porous stone, according to the measurements are: 0.01 for 63, 125, and 250Hz, 0.052 for 500Hz, 0.071 for 1kHz, 0.87 for 2kHz, 0.085 for 4kHz, and 0.063 for 8kHz. The on-site measurements showed that the effect of temporary scenery is significant, causing RT30 increase at the range of 0.5-1s compared to previous measurements that have been carried out with no scenery. Hence, although many studies have focused on the inappropriateness of Epidaurus for concert music, with appropriate scenery design reverberation can be significantly longer, and the theatre can accommodate concerts with improved acoustic results. For the theatres of Knossos and Philippi, the RT30 was around 0.43-0.58s and 0.31-0.8s respectively.

For the theatre of Epidaurus, the measurements and the simulation showed in detail that early reflections provided by the koilon risers, the orchestra floor and the skene-building and multiple reflections between the opposite sides of the koilon result in long reverberation times at the sides. Additionally, the subjective evaluation indicated that reverberation is definitely perceived in ancient theatres, as well as background noise. 'Medium' sound level, 'short but clear' reverberation, no delayed reflections, background noise, especially for the beginnings of the play, and 'normal' speech intelligibility were identified. The sound level depended on the actor's ability and position, and was reduced when the actor turned his back to the audience. Regarding background noise it was indicated that a constant noise is usually acceptable, except for the occasions it covers the sound level of the actor, while sudden and intense noises are more irritating. A very interesting comment was that the spectator in the theatre of Epidaurus has a general feeling of being in an indoor space from the acoustic viewpoint due to the intimacy the theatre provides.

Chapter 9 presented the analysis and results of the simulation of three theatres, namely the theatres of Mieza, Philippi and Dion. The importance of the stage building, purposely built scenery design and temporary scenery design for the acoustic quality, as well as the usefulness of acoustic simulation for the revival of ancient performances, were demonstrated.

The theatre of Mieza was the subject of the first case study, simulated in its original and present condition, as well as the restoration proposal submitted by the archaeologists. The original stage building contributed to a relatively long RT30, of about 1s. The restoration proposal, which is of particular interest, has proved to be generally successful, especially in terms of definition. Corresponding to the restoration proposal, the effectiveness of six scenery designs demonstrated the importance of scenery for the acoustic conditions. The purposely designed sceneries increase the SPL and, by careful acoustic consideration, distribute sound energy evenly to the audience area. A simple linear wall has similar effects with the original stage building. With the other scenery shapes including convex, concave and dome, the SPL distribution is not even in the audience area, since some create focus areas, and the reflection/energy-response patterns are uneven, although the RT30 may appear to be long. It is suggested that when the scenery consists of several small objects instead of one it is easier to improve/adjust the acoustic environment. The simulation also showed that surface diffusion causes a slight decrease in SPL as expected.

The second case study involved the theatre at Philippi in the original condition, present condition and with purposely built scenery. Its condition in antiquity was better than today's, with the stage building providing useful early reflections, increasing RT30 and SPL. For today's use the temporary scenery, in the form of a stage enclosure carefully designed for the specific theatre, increases the SPL and RT30 for the actor source, and reduces traffic noise. It also contributes to providing a more even reverberation distribution throughout the audience area, and a more uniform reflection/energy-response pattern. Overall, with strategically designed sceneries in terms of shape as well as surface absorption and diffusion, the soundscape of the contemporary use of ancient theatres can be much improved, with reduced background noise.

Regarding the theatre of Dion, the third case study, the simulation of the original condition and with purposely built scenery, especially designed in several stages in order to provide acoustic quality to the audience, showed that the former is characterised by higher levels of SPL, RT30, with the expense of clarity and definition. Moreover, when no scenery or stage building is involved, the variation in orchestra materials has no impact on the acoustics of the theatre. The application of careful and appropriate design of purposely built scenery improves the acoustic conditions. Similarly, delay gaps, which are a common characteristic of the impulse responses in ancient theatres due to large reflection paths, can be 'filled' by placing overhead reflectors that will reduce the reflection paths and provide additional reflections where needed.

Chapter 10 further investigated four generic categories of scenery design an architect/scenery designer should consider when creating temporary scenery, to identify their effect on the acoustic environment of the theatres of Mieza, Philippi and Dion. Several variables were examined, like material, height, shape distribution etc. Also, optimum shapes of sceneries were found and simplification of the scenery representation, to facilitate the acoustic simulation, was carried out. In general, the index that was mostly affected by the scenery layouts was reverberation.

Category 1 concerned the scenery in the form of a background wall. By applying the wall to the theatres of Dion, Mieza and Philippi it was shown that with soft construction materials SPL was low, while smooth decays were mainly found in hard materials and steep inclinations. Long RT30 was found in wider theatre plans, in terms of angles, like in Dion. SPL was less affected by material absorption than RT30, with maximum variations at high frequencies. Also, STI varied more for the theatre built with hard materials. Regarding the effect of the wall height it was revealed that, contrary to SPL, RT30 was increased with the wall height, by up to 1s, especially at the rear seats of the koilon because it provided more reflections. It was noted that maximum wall heights can be calculated for each theatre, corresponding to the influence on RT30. Nevertheless, the effect of the wall's presence is high, even on SPL. The most effective wall shape is the linear, due to the better distribution patterns, also seen in Chapter 9. Moreover, the effect of the background wall on SPL and RT30 of the occupied conditions of the theatres is still measurable, at 1-2.3dB higher and 0.15-0.30s longer compared with the theatre with no scenery respectively. Therefore the scenery is quite important even for the occupied condition, since it increases reverberation. The influence of audience absorption on the acoustic indices is less important when there is no scenery, because smaller reflection orders and fewer reflections between opposite sites are observed. Furthermore, schematisation of the plain background wall was achieved, by applying receiver points on the wall to calculate the useful areas in relation to the reflections paths and the impulse responses for a selection of receivers.

Category 2 used four geometrical objects, namely a cube, a sphere, a cylinder and a pyramid. It was shown that especially the sphere and the cylinder increase SPL, due to the distribution of early reflections throughout the koilon. The cylinder provides comparatively long RT30 values as well, which is a contribution of the reflection patterns in addition to the increased reflection order, considering the other shapes. The cube and the sphere produce short RT30, and the pyramid has no effect on reverberation due to the high number of lost reflections. Hence, it is clear that through diffusion sound is better distributed to the audience area increasing SPL and decreasing RT30, which corresponds to the STI and C80.

In Category 3 small objects in the form of panels were installed in the orchestra, with variables like density, size and distribution. It was shown that the dense objects do not alter SPL, although they contribute to relatively long reverberation, while the increase in the number of the panels allow for the effect of edge diffraction. However, with sparsely applied panels the distribution was not even. It is suggested that diffusion can be applied to the panel surfaces for even distribution. Also, SPL is analogous to the panels' width, with less variation near the source. With 2-row distribution SPL is increased, with scattered sound and short RT30.

Finally, Category 4 investigated the orchestra's materials and heights. Both SPL and RT30 were not particularly influenced by the change of materials with maximum difference of 2.8dB and 0.20s for 500Hz respectively, since the number of reflections from the orchestra's floor were limited compared to the ones from the koilon. The variations between different materials were more distinct at high frequencies. On the contrary, the height of the orchestra's floor presented much more flexibility to a designer, since it influenced the acoustic indices. Like with the raised stage of late Classic and Hellenistic theatres, presented in Chapter 7, the increase in height brought a decrease in the SPL values, due to the larger source-receiver distances, but increased RT substantially by up to 0.50s.

For simplifying complex scenery forms it was suggested that the most efficient and accurate way for quick simulations was replacing the scenery by a plain wall, divided into segments to represent the solid and empty parts of the original scenery created, with appropriate absorption coefficients. Also, for the variation in source positions, based on reflection patterns and reflection path distances, the best results for most of the acoustic indices were found near the orchestra's centre or between the orchestra's centre and the scenery/stage building corresponding to the previously mentioned 'Haas zone' [Canac, 1967].

Chapter 11 presented the ways theatre and scenery design is implemented according to basic acoustic principles used in antiquity and today and the results presented in Chapters 2-10, seen in more detail in this section. The discussion on the relationship between theatre architecture and acoustics was organised based on ancient theatre layouts and orientation, skene-building and scenery use, principles that apply to ancient theatres regarding optimum source positions, where the raised stage and the area between the stage building and the orchestra's centre are advantageous, and effects like reflection, absorption and diffusion. The guidelines, aiming to address architects, designers and directors, referred to theatre orientation, orchestra treatments, reflection provision and theatre use. In particular, the climatic conditions and local winds influence sound distribution and should be considered. Also, hard materials should be chosen for the orchestra and destroyed theatre parts, like the parodoi, which provided the sides of the theatre with useful early reflections, can be re-placed. Moreover, reflectors and diffusers may be added to reflect/redirect sound, while the audience can be strategically positioned to control absorption.

For the guidelines that referred to scenery, the performance style and the director's decision can be applied to the acoustic design and, consequently the scenery design, by placing reflective panels according to actor's positions and roles. A background scenery wall was suggested as the minimum intervention from the aesthetic viewpoint that would optimise the acoustic environment, while reflective panels can be adjusted behind the last audience rows to protect against background noise and reflect sound to the furthest seats. Nevertheless, through a presentation of contemporary theatre structures, it was indicated that in some cases the architects provide a number of reflective and diffusive surfaces because of planning restrictions and safety reasons, rather than to allow for early reflections to reach the audience. Furthermore, the architectural design of recent theatres suggested that apart from the orchestra's floor, the added reflectors, the diffusers, the surrounding walls, the partial roofs and the stage enclosures contribute to an optimum soundscape. Even when all these measures cannot be taken, the application of temporary scenery or movable reflective and diffusive panels is useful both in ancient and contemporary open-air theatres.

12.3 Contribution to Knowledge

This PhD study has contributed to the knowledge in the fields of architecture, scenery design, acoustics and theatre. Several subjects have been investigated for the first time, as will be indicated below. The hypotheses of the study are summarised in this section, and the uniqueness of the study is indicated.

The hypotheses of the PhD were related to ancient knowledge of acoustics, theatre evolution and effect of the stage building on acoustics and, in particular, the application of contemporary scenery design. In detail this study hypothesised that:

- Ancients studied sound and acoustics

- Ancient theatres have been improved through the centuries in terms of architecture and acoustics
- New construction methods with harder materials, used in antiquity for ancient theatres, improved the acoustic conditions
- Ancient theatre layouts functioned similarly to enclosed spaces from the viewpoint of the audience's perception
- Evolved designs with stage buildings worked better for performances
- Contemporary theatre conditions with missing stage buildings provide insufficient distribution of sound. Therefore:
  - Scenery can improve the acoustic conditions in a theatre with missing stage building
  - Scenery can be implemented so as to treat traffic noise and unwanted background noises
  - Treatments in the present layout of ancient theatre can improve the acoustic environment.
- Scenery can be adjusted according to the needs of a performance in order to amplify sound coming from specific actor's positions and characters' status in the play (kings, gods or important characters and leading roles)
- Overall, the ancient stage building was a vital component of the theatre in terms of acoustics

Through the investigation of the above hypotheses this PhD study presented several innovations and, in most cases, verified the initial hypotheses. The evolution of theatre design in antiquity for a span of 20 centuries was for the first time examined, both in terms of architecture and acoustics. Six basic theatre types were identified, while several changes within the same theatre type were observed and investigated in detail.

Early theatre forms, like the Minoan and the Pre-Aeschylean have been examined for the first time from the acoustic viewpoint. Especially for the former, on-site measurements were carried out that revealed that reverberation at the range of 0.5-1s can be found in the Minoan theatre of Knossos. This is in conflict with general assumptions that no reverberation can be measured in outdoor spaces. Regarding the later types of ancient theatres, reverberation of 1 and 1.7s was found both through simulation and measurements. The former value corresponds to the theatre of Epidaurus, which has been investigated before from the acoustic viewpoint, although with no particular attention to RT.

Because the influence of scenery design on the acoustics of ancient theatres was of major concern in this study, measurements were also carried out with temporary scenery installed, which presented long RT values when compared with the theatres with no scenery. Hence, this was the first study that identified the importance of scenery form the viewpoint of acoustics.

Moreover, the detailed examination of generic scenery forms, through a variety of forms, materials and trends in art and design, had not been systematically presented before. In this study, guidelines for those interested in theatre performances, for architects, designers, acousticians, directors are provided, as seen in Section 11.4 and Table 11.1.

Another contribution to knowledge was the acoustic examination of three important theatres in northern Greece, namely the theatres of Mieza, Philippi and Dion, in their original and present condition, due to their uniqueness in terms of restoration proposals, background noise, and construction material respectively. Their investigation included architectural solutions to enhance their soundscape, in the form of purposely-designed stage enclosures.

Subjective evaluation tests that show the audience's perception in relation to the scenery, the audience's senses and acoustics have also been carried out for the ancient theatre of Epidaurus, providing important insights for the revival of ancient drama and the use of ancient theatres for its production.

Finally, the contribution of this study in terms of methodology is of great importance. Appropriate simulation software for outdoor spaces, parameters to be selected, effects of source directivity and background noise are some of the subjects investigated. The simplified representation of the theatre model in the acoustic simulation is another input of this PhD study. However, the most important contribution in terms of research methods is the consideration, by theoretically developed formulas adjusted to computer simulation, of the effects of diffraction in the simulation of ancient theatres, a subject much discussed recently. Additionally, the measurement of the absorption coefficient of a Greek local porous stone that could not be found in previous absorption coefficient databases is another input to the development of the acoustic simulation techniques.

12.4 Further Work

The author is a part-time tutor, teaching theory and applications of acoustics to the students of the Department of Architecture, School of Engineering, Aristotle University of Thessaloniki. The particular subject of the course is the architectural and acoustic design of a theatre, a concert hall and a music school combining rooms for teaching and practising musical instruments. Lately, a local council came in contact with the author to design a contemporary open-air theatre. The findings of this study will be creatively used for the architectural and acoustic planning of the public theatre.

Ancient drama, ancient theatres and the application of acoustics to the design of temporary scenery as well as permanent stage enclosures are of special interest. Further work should include measurements in existing theatres in Greece, both ancient and contemporary, combined with simulations. In this way the reverberation of specific theatres will be measured, both with and without scenery. By selecting one theatre for the whole summer period, many scenery designs created for performances of ancient drama can be investigated.

Recently, two ancient theatres were found in Greece and are under excavation. Although this is a long term project, since the theatres will be fully revealed in several years, their investigation should be of great interest for the research and the design communities. This can be achieved by collecting drawings and other data provided by the archaeologists, creating the 3D representations using CAD design and simulating the acoustic environment in relation to on-site measurements.

Considering the increasing background noise, and its effect on the whole sensory experience during a performance, attempts of appropriate placement of panels – integrated into the scenery design – to reduce noise, need to be made. Systematic examination of the application of source directivity to several source positions and area sources representing the chorus in the simulation of ancient theatres would be a great contribution to the specific research area. Moreover, the use of open-air theatres for other kinds of performance, like popular music, needs to be investigated, especially with the use of electroacoustic facilities. In relation to this, the relationship between noise and cultural heritage for appropriate design application should be of great importance.

Since drama performances are closely related to the audience's perception, additional subjective evaluation tests are needed to identify more parameters to be accounted for in the design of new theatres. The questionnaires can refer to a variety of indices, as well as simple terms, comprehensible by the majority of viewers/listeners. Speech intelligibility test can also be prepared.

Finally, the effect of scenery design, through the generic categories identified in this study should be communicated to related fields, like architecture, scenery design and direction, through journal publications. Another interesting and amusing way to achieve this and combine acoustic courses for schools of architecture and scenery design courses for theatre studies would be to organise workshops, create several scenery designs and apply them to a relatively small sized open-air theatre. The application of different panel sizes and the comparison between them and a plain wall will also allow validation of the methods of simplification of scenery design for acoustic simulation.

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