

Article

# The Contribution of the Stage Design to the Acoustics of Ancient Greek Theatres

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**Abstract:** The famous acoustics of ancient Greek theatres rely on a successful combination of appropriate location and architectural design. The theatres of the ancient world effectively combine two contradictory requirements: large audience capacity and excellent aural and visual comfort. Despite serious alterations resulting from either Roman modifications or accumulated damage, most of these theatres are still theatrically and acoustically functional. Acoustic research has proven that ancient theatres are applications of a successful combination of the basic parameters governing the acoustic design of open-air venues: elimination of external noise, harmonious arrangement of the audience around the performing space, geometric functions among the various parts of the theatre, reinforcement of the direct sound through positive sound reflections, and suppression of the delayed sound reflections or reverberation. Specifically, regarding the acoustic contribution of the stage building, it is important to clarify the consecutive modifications of the *skene* in the various types of theatres, given the fact that stage buildings were almost destroyed in most ancient Greek theatres. This paper attempts to demonstrate the positive role of the scenery in contemporary performances of ancient drama to improve the acoustic comfort using data from a sample of twenty (20) ancient theatres in Greece.

**Keywords:** ancient Greek theatre; Classical Era; scenery; acoustic design

## 1. Introduction

In ancient drama the term used for scenery is *opsis*, as Aristotle mentions in the *Poetics*. *Opsis* has to do with a wide variety of elements relating to the *skene* (stage building), such as their decoration and infrastructure, the positions of the actors, or the props used in performances. Although Aristotle's text was written at a time when the Theatre of Dionysus in Athens was undergoing its final construction phase during the Hellenistic Era (334/330 BC, at the same time as its reconstruction in stone under Lycurgus), it gives us quasi direct insights into the theatrical world of the Classical Era. All the other references to the conditions of those performances (the accounts by Pausanias, Plutarch and Strabo, the descriptions by Julius Pollux, Vitruvius' analyses and Horace's comments, as well as the depictions on vases) are indirect information from later periods. In reality, the texts that have survived from the dramatic output of the 5th and 4th centuries BC constitute the only authentic records of the performance requirements of Classical drama [1]. As a result, the present study draws data on the form and evolution of the *skene* from the dramas of the classical period, combined with archaeological, architectural and acoustic findings.

Nevertheless, the precise position of the *opsis* behind the orchestra, the length, width and height of the scenery, and the possible installation of a raised *proskenion* are all complex, thorny issues which have turned Classical theatre into a highly controversial subject [2] (p. 376), [3] (p. 27), [4] (p. 259), [5] (p. 142).

During the last few years, there has been a bulk of research on ancient theatre acoustics. The most common method used for studying the acoustic behaviour of ancient theatres combines on-site measurements and computer simulations. The software most commonly used in such computer simulations is CATT and ODEON, although use is also made of EASE, RAYNOISE and OTL-Terrain. The data from the acoustic measurements are used to weigh up or evaluate the results of the simulations. Various hypothetical scenarios are studied (such as the influence of the audience, the ancillary use of loud speakers, skene installations and scenery) [6–19]. This is often followed by a detailed examination of the effects of natural frequencies and diffraction on individual architectural elements (particularly resonators) [6,20,21]. A rather restricted amount of research focused specifically on the acoustic contribution of the stage by comparing theatres with different type of stage ruins [22], by assessing the impact of noise barriers and background scenery wall for optimum performance conditions [23], or by proposing and evaluating the impact of different scenic elements aiming to establish guidelines for stage design [6,24,25].

However, with regard to the available software, concerns have been recorded about its suitability in terms of its capacity to take into account or assess the importance of the special characteristics of the ancient theatres, or the effects of outdoor noise in the modern environment [26,27].

To a lesser extent, use is made of scale simulations which are used to investigate and assess the acoustic properties of building materials, as well as additional acoustic phenomena in ancient theatres, such as diffraction [28,29]. In connection with this, correlations are drawn between various functional parts of ancient Roman theatres (e.g., the wall of the skene, the perimetric passageway around the amphitheatre, the slope of the cavea, the addition of scenery or an ancillary microphone installation) [30]. Some researchers also investigate to a limited extent the subjective criteria of the acoustic quality of theatres by using questionnaires distributed to the spectators of performances or listeners of recordings. Finally, listening tests are also carried out on sound data produced by software programs in varying sound absorption conditions [31–35].

A limited amount of research has been carried out on the effects of environmental noise during the contemporary use of ancient theatres, the nature and the characteristics of nuisance sources and the monitoring of noise levels in the surrounding environments of ancient theatrical monuments. The findings of this research highlighted the impact of environmental noise on contemporary performances and emphasised the acoustic contribution of the scenery for the re-use of ancient theatres [26,36,37]. By coincidence, all of these studies examined the theatre of Philippi and its soundscape. Chourmouziadou and Kang (2011) estimated that traffic noise could be avoided by the application of a scenery which could reduce SPL by 5dB and improve the performance conditions due to early reflection distribution. Additionally, they proposed that a barrier near the source could restrict noise by reducing direct sound [26]. Barkas (2004) and Barkas-Vardaxis (2011) have calculated that the positive contribution of the scenery reflector is min +3 to +5 dB, and the reduction of the environmental noise due to the barrier of the scene is min –2 to –4 dB, namely a total of min +6.5 dB in the acoustic comfort [36,37]. According to all authors, such applications, with adaptations to the specific local conditions, could be used for other archaeological sites with similar results.

Given the above, the present paper attempts to demonstrate the acoustic contribution of the scenery in terms of improving the acoustic comfort in contemporary performances of ancient drama. Data from a wider, long-lasting research on a sample of twenty (20) ancient theatres in Greece were used, focused on the positive role of the scenery.

However, to study the acoustic contribution of the skene, it is necessary to define the form of the scenery in the original conditions, meaning during the classical Era.

## 2. The Evolution of Skene during the Classical Era

In the early 5th century, when the cult of Dionysus was formally established in Athens, a sanctuary to Dionysus was laid out at the foot of the Acropolis, and next to it was created a circular threshing-floor for devotional performances. Originally, the spectators gathered on temporary tiered wooden benches

(ikria) on the south slope. However, following the collapse of the ikria (in theatre games held between 499 and 496 BC) with large loss of life, the Athenian state created a safe and permanent theatre in the sanctuary of Dionysus, a development that marked the birth of the Athenian or Attic Theatre of the Classical Era. The theatre of Dionysus is considered as the basic model for all the other theatres of the Antiquity, in Greece, in Sicily and Italy, in Asia Minor, and in all the Mediterranean area. Furthermore, this was the place where all ancient dramas were performed and the model of the theatrical space for all Athenian poets [38].

The functional parts of this theatre building in the early Classical Era were as follows:

- the orchestra/threshing-floor (with a radius of approximately 12 m) on a fill in the lowest flat opening;
- the thymele, an altar to Dionysus on a stepped base in the orchestra;
- the pranes, a supporting wall approximately 2.5 m high behind the fill which separated the orchestra from the sanctuary and concealed a roughly constructed theatre storeroom (the actors' dressing-rooms);
- the parodoi, side-entrances affording access for the public, the chorus and/or the actors between the retaining walls of the cavea and the natural ground of the sanctuary;
- the koilon or cavea, with tiers of seats for the spectators, either made of wood or hewn out of the rock, arranged concentrically around the orchestra and laid out in an arc of 240° on the natural slope of a hill [39] (pp. 30–35), [40] (pp. 40–44).

If we place the dramas surviving from the Classical Era (44 tragedies and comedies) in chronological order, we find that the references to the drama space begin with allusions and gradually evolve into clear, detailed descriptions [38,41–44]. Aeschylus' early work, therefore, required an indeterminate setting, with an altar or mound, while the thymele ensured that actors could stand out clearly above the chorus or as a counterpoint to the appearance of a chariot (Persians, Seven Against Thebes, The Suppliants).

Figure 1 presents the relative connection among the orchestra/threshing-floor, the pranes and the old temple according to Doerpfeld [2]. The height of the old temple and the possible presence of a small storeyroom (a dressing room for the actors) in a lower level behind the pranes are given by estimation [39].

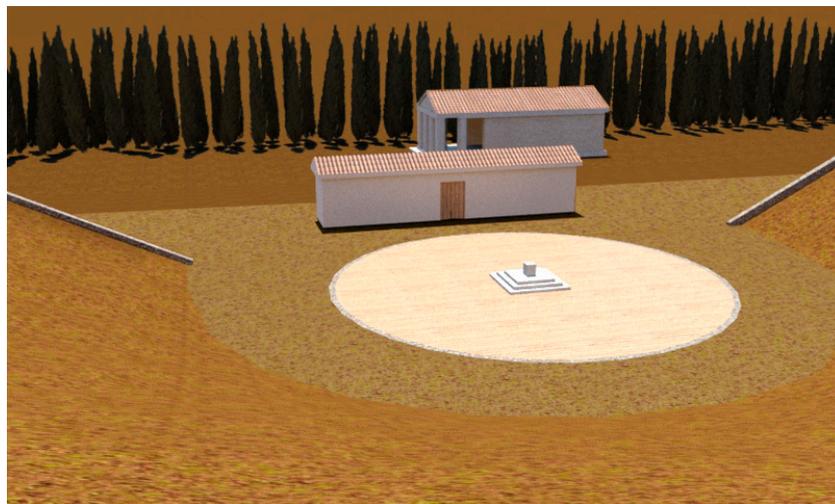


**Figure 1.** Representation of Dionysus theatre from the koilon before the burning of Athens (480 BC).

The first substantial breakthrough in the representation of theatre space appears in the prologue of Aeschylus' trilogy, when the watchman appears on the roof of the palace, sees the light signalling the fall of Troy and runs to announce the good news inside the building, while Clytemnestra silently emerges from it in order to offer sacrifices. These movements indicate a stage with a number of conventional possibilities, as the action acquires physical boundaries and the performance space material form, distinct areas and a clear setting. This composite representational function marks the beginning of an evolutionary process in stage design which broadened the representational possibilities of the conventional space, increased the functional requirements of stage infrastructures and created new acoustic conditions [1].

As excavations in the area of the cavea at the Theatre of Dionysus have revealed, successive layers on the south slope (laid between 460 and 440 BC) created a steeper incline in the cavea and increased the theatre's capacity. A new orchestra (with a radius of approximately 9.9 m) was formed within the orchestra/threshing-floor and was moved closer to the auditorium, leaving a free space behind it facing downhill, in which a wooden stage framework with scenery was installed (across the central axis of the cavea). This served to focus the dramatic interest behind the orchestra, separated the visible façade of the skene from its invisible rear and provided a tall support for the roofing [2] (p. 130), [3] (pp. 27–31), [45] (p. 15), [46] (p. 66), [47] (p. 10).

Figure 2 presents a roughly crafted stage (theatrical storeyroom) behind the new orchestra (in the free space of the old orchestra/threshing-floor according to Allen [3]). The dimensions of the stage façade, and the height of the new temple are given by estimation [44]. The walls of the stage are wooden, the roof is covered with tiles. The position of the koilon and the walls of the side-entrances (analemata) according to Doerpfeld [2]. The exact configuration of the wooden benches, on the given tilting of the koilon, remains unclear.



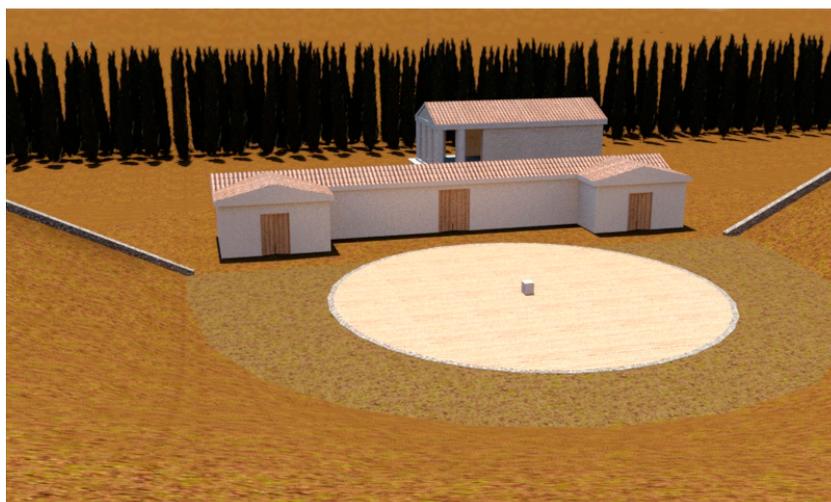
**Figure 2.** Representation of Dionysus theatre from the koilon at the time of “Oresteia” (460 BC).

During Athens' great construction boom (between 449 and 429 BC, under the rule of Pericles) great changes took place in the precincts of the Theatre of Dionysus (such as the construction of the Odeion in the upper eastern section of the hollow in which it lay, and the construction of the stone retaining walls of the outer terraces and the staircases leading from the horizontal diazoma). In the area of the skene, the paraskenia were created—new theatre storerooms which projected from either side of the stage set—and formed (in the shape of a Π) a proskenion at ground-floor level [38] (p. 50), [41] (p. 68), [48] (p. 55).

The extension of the skene (across the main axis of the theatre), and the formation of numerous openings in it, constituted a second development concerning the functional possibilities of the skene infrastructure during the Classical Era. The use of one and (necessarily) only one doorway for

movement of the actors and the ekkyklema (a kind of removable raft) between the front and rear sections of the skene also appears for the first time in the *Oresteia* and more specifically in *The Libation Bearers*, during the episode in which a series of murders takes place inside the palace. In later years, the existence of a single opening in the scenery is pointed out deliberately in moments of drama where the doorway is supposedly closed or blocked for some reason (until about 427/425 BC) in *Alceste*, *Hippolytus*, *Andromache* and *Oedipus the Tyrant*. Evidently, during quite a long period (about thirty years) after the introduction of scenery, the lengthening of the skene led to the establishment of a new convention through the incorporation of the *paraskenia* into the stage buildings and the use of their openings as auxiliary doorways for the movements (not mentioned in the texts) of the prop masters. Finally, the *paraskenia*, as parts of the skene infrastructure, were incorporated into the stage design (after 430 BC), permitting the representation of lateral buildings with independent doorways next to the central stage building (*Andromache*, *The Acharnians*, *Oedipus the Tyrant*, *Herakles*, *Clouds*, *Peace*, *The Trojan Women*, *Lysistrata*, *Philoctetes*, *The Bacchae*, *Frogs*, *Ekklesiazousai*) [1].

Figure 3 presents the stage set with the lateral buildings (*paraskenia*) and the *proscenium* between the orchestra and the stage according to Allen [3]. The floor plan dimensions of Π according to Allen's theory of the two orchestras [3]. The height and the roofing of the lateral buildings are given by estimation [1]. The walls of the stage are wooden, the roof is covered with tiles. The position of the *koilon* and the walls of the side-entrances (*analemata*) according to Doerpfeld [2]. The exact configuration of the wooden benches, on the given tilting of the *koilon*, remains unclear.



**Figure 3.** Representation of Dionysus theatre from the *koilon* (period 430–415 BC).

One of the most notable architectural developments in the skene infrastructure (during the period of the Peace of Nicias, 421–415 BC) was the construction of the *skenotheke* (behind the skene), a building buttressed by the so-called “Foundation T”, the stone base at the level of the orchestra that facilitated the rolling-out of the ekkyklema and supported the weight of a small wooden propylon in the centre of the stage. On either side of this base two symmetrical, matching rows of conical stone apertures were constructed (similar to those found in the Classical ruins of the theatres at Pergamon, Oropos and Corinth), which housed the supporting beams of an extensive, two-storeyed wooden skene [2] (p. 150), [3] (p. 15), [47], (p. 15). In the dramatic output of the following period, this secure stage installation made it possible to stage certain artistic performances of a symbolic and abstract nature, as can be seen in the prologues of Sophocles and Euripides (*Ion*, *Herakles*, *Iphigenia in Tauris*, *Helen*, *The Phoenician Women*, *Orestes*), where there are numerous verbal descriptions of the structure representing a propylon before the central doorway of the stage set, on a distinctly higher level in the area of the *proscenium* that was 2–3 steps above the orchestra (*Ion*, *Philoctetes*, *Wasps*, *Lysistrata*, *Ekklesiazousai*) [1]. In other words, it appears that in a slow and conservative process that lasted for

about fifty years and involved a series of changes and gradual modifications, the temporary skene structures eventually evolved into a wooden installation with a relatively high propylon before the central doorway and another two lateral doorways in the facades of the paraskenia, the episkenion in the superstructure and the theologeion on the roof [49].

This third major development concerns the upward extension of the skene. The plays that have survived from the decades following the *Oresteia* contain a multitude of divinities or supernatural creatures (Ajax, Medea, Andromache, Hippolytus, Herakles, Euripides' *The Suppliants*) that appear (with or without the aid of a stage machine) on the span roof of the stage building. This high position—which later came to be called the theologeion—served for the (almost exclusive) appearances of divinities that formed a typical ending to dramas (Iphigenia in Tauris, Helen, Euripides' *Electra*, Philoctetes, Iphigenia in Aulis).

Later, however, literary references of this kind reveal the use of yet another distinct level—which later came to be known as the logeion—on the first storey of the stage building. In other words, it appears that the gradual separation of the actors from the chorus and their confinement to the proskenion led to the dramatic action taking place, either sequentially or simultaneously, on the three successive levels of the stage building (*Wasps*, *Peace*, *Lysistrata*, *The Phoenician Women*, *Orestes*, *Ekklesiazousai*, *Rhesus*) [1,49]. This form of stage design ultimately crystallised into the stone stage building that was incorporated into the definitive reconstruction of theatres that took place in the Hellenistic Area (338–326 BC) [2] (p. 28), [46] (p. 70).

Figure 4 presents the two-storeyed wooden skene with the slightly elevated propylon in the central doorway of the ground floor and the episkenion in the superstructure according to Flickinger [46]. The front part of the paraskenia was designed by combining the theories of Fiechter [45] and Doerpfeld [2]. The floor plan dimensions of stage were set according to Doerpfeld's theory for the two rows of foundation holes in front of the skenotheke building [2]. The height of the paraskenia, the storeys, and the roof are given by estimation. The walls of the stage are wooden, the roof is covered with tiles. The basement of the propylon is made with pieces of marble. The position of the koilon and the walls of the side-entrances (analemata) according to Doerpfeld [2]. The exact configuration of the wooden benches, on the given tilting of the koilon, remains unclear [45].



**Figure 4.** Representation of the theatre of Dionysus from the koilon (after 415 BC).

### 3. The Acoustic Design of Ancient Greek Theatres

Ancient Greek theatres, unlike Roman ones, made empirical use of the slope of a hill in order to create tiers of seating for the spectators around the performance area. Ancient theatres were not all aligned in a specific direction (e.g., towards the south, as Vitruvius claims), nor were they governed

by certain rules dictating their precise location in the urban plan (e.g., in the agora, on a sacred site, within a complex of public buildings or in an organised sanctuary) [50]. The central axis of an ancient theatre can be aligned in any direction, depending on the prevailing winds and the sources of external noise (across the axis of a valley, along the axis of a ravine, in the hollow of a bay or on an artificial embankment), so that, with the aid of flexible adjustments and creative on-the-spot solutions, the structure can fulfil the theatrical, architectural and acoustic requirements of any historical era [4,40].

The stage building was not a primary element in theatre and acoustic design. The use, initially, of a temporary wooden framework gradually led to the establishment of a variety of theatrical conventions that served as a backdrop for the action on stage and facilitate the focus of the dramatic interest behind the orchestra. The later stone structures of the Hellenistic skene (4th and 3rd BC), apart from serving other expedencies, also provided an even more effective reflective surface compared with the original wooden structures of the permanent scenography of the Classical Era. However, when the skene evolved into a two-storey or three-storey building, like those in Late Hellenistic and Graeco-Roman theatres (3rd and 2nd BC), there was a danger that delayed sound reflections might be created by the extensive façade of the skene and the orchestra. In order to deal with this problem and control reverberation, the facades of stone stage buildings acquired a typical form of decoration (with hollows, relief elements and groups of sculptures) which were designed to diffuse the sound. Later, in order to further minimise the acoustic side-effects created by the construction of a raised proskenion, like those found in Graeco-Roman and Roman theatres, once again temporary forms of scenery (the sound-absorbing surfaces of wooden screens or cloth decorations) were adopted in the numerous openings of the skene and the hyposkenion [39,40,51].

The simultaneous functioning of two strong reflectors (the orchestra and the stage set) that was typical in Classical theatres inevitably posed the problem of homogenising the discrete sound reflections and incorporating them into the direct sound. The combined use of these reflectors obliged the actors to limit their movements on the proskenion area, in front of the stage set. The interpretations of archaeological finds and the geometric relationship between the orchestra, the skene and the parodoi lead to the conclusion that the proskenion was a narrow, ground-level space confined between the tangent of the orchestra, the projections of the paraskenia and the skene [2,48]. This space formed a “Haas zone”, a useful acoustic zone in front of the scenery, outside where the combined sound reflections from the orchestra and the façade of the stage building began to be noticeable as discrete entities, meaning reverberation increased and the speech of the performers became less intelligible [52]. Acoustic experiments have demonstrated the superiority of ground-level or low proskenion platforms over higher platforms and have confirmed the archaeological and theatrical theories regarding the ground-level proskenion of the Theatre of Dionysus (up to the late 5th cent.), where a formal propylon gradually developed—a miniature version of those in public buildings of the Classical Era—resting on a low base of limited length (abutting the so-called “foundation T”) in front of the central doorway of the temporary wooden stage set [4,40]. On the other hand, the gradual raising of the proskenion platform and its extension (initially by one third of the radius at the theatre on Delos, then by one half of the radius at various Graeco-Roman theatres and finally around the whole of the orchestra semicircle in Roman theatres), in conjunction with the placing of mobile seats in the free semicircle of the orchestra (in Graeco-Roman and Roman theatres), cancelled out the positive effects of the orchestra’s reflector and increased the amount of sound absorbed by the bodies of the spectators. This development led to a decrease in the amount of sound energy that was produced and degraded the intelligibility of the theatrical message, a situation which (in tandem with other social and cultural changes) resulted in a necessary reduction in the capacity of Roman theatres [39,40,50,51].

The paraskenia, as lateral projections at the aisles of the stage set, directed the useful, central beams of reflected sound from the stage set to the auditorium. At the same time, they helped to protect the sides of the skene from combined reflections between the retaining walls (analemmata) and the skene, channelling the delayed, lateral beams of reflected sound towards the parodoi, which served to defuse the reflected sound (either directly by absorbing it or indirectly by diffusing it in the stone

structures of the retaining walls). The *parodoi* gradually declined in use in Graeco-Roman theatres and gave way to the *vomitoria* (vaulted arcades faced with rubble masonry to help deal with the delayed lateral sound reflections), while movement towards the tiers of seating was assisted by staircases on the outer edges of the *cavea* [4,53].

Finally, when Roman theatres were relocated in noisy urban centres, it became necessary to drastically increase the size of the *scaenae frons* (the stage façade) directly opposite the amphitheatre, so that a solid, uniform barrier on the perimeter of the theatre building could increase the sound protection of the theatre space [4] (p. 260), [39] (p. 41), [52] (p. 75).

Beginning with the on-site acoustic research of Fr. Canac in the theatres at Orange and Vaison (and later in ancient theatres in Italy and Greece) during the 1950's, successive acoustic studies have shown that ancient theatres display the basic principles that apply in the design of open-air venues, and also that, despite the damage and modifications that these theatres have suffered throughout the centuries, they continue to possess their own peculiar acoustic properties [7,52–54]:

- quiet acoustic environment (elimination of external noise and parasitic disturbances);
- harmonious arrangement of the spectators around the performance space within the limits of the human vocal and acoustic range;
- smooth transmission of direct sound, which is reinforced through early, positive sound reflections (from solid sound-reflective surfaces near the actors and small sound-diffusing surfaces near the spectators);
- low reverberation and increased intelligibility of speech due to the reduction of harmful delayed sound reflections and elimination of echo (small diffusive surfaces near the actors and elimination of solid sound-reflective surfaces near the spectators) [37];

As was mentioned earlier, the independent or combined acoustic contribution of the individual building parts of ancient Greek theatres includes;

- the siting of theatres on the lee slopes of hills and the steep, stepped arrangement of the *cavea* (at angles of between 21° and 30°, with steeper inclines in the upper *diazoma*) favour open-air sound propagation conditions;
- the reflector of the orchestra reinforces the direct sound—mainly in the lower *diazoma*—with almost no time delay (<5 ms);
- a stage set placed in a suitable position behind the orchestra (a reflective zone extending approximately 3.2 m above the level of the orchestra) amplifies the voices of the actors with small time delays (40~85 ms), particularly in the higher tiers;
- the combined effect of the orchestra and the scenery (with time delays of 45~110 ms) keeps the length of the reverberation time down to one that is suitable for speech thanks to the sound absorption of the unwanted sound reflections by the bodies of the spectators and the atmosphere [40].

The incorporation of the positive sound reflections into the direct sound makes up for the energy losses of the sound propagation over a great distance (between +2.5 and +5.5 dB, depending on the actor's position) and ensures an even level of acoustic comfort for the spectators (+/-3 dB over the height of each *diazoma* and +/-1.5 dB between the central and outermost tiers of seats in the auditorium). However, the most suitable and necessary condition for ensuring that the beneficial effects of the available sound reflectors are obtained is for the actors to gather in the intermediate *proskenenion* area (in a "Haas zone" 3–3.5 m deep). We are dealing here with a complex geometric function (which Fr. Canac called "l'équation canonique" of the ancient theatre) which tends to produce the optimum result, provided that the difference in height between the *proskenenion* and the orchestra is reduced to a minimum. The gathering of the actors in the *proskenenion* area enabled the monologue and dialogue parts of dramas (spoken by individual voices of limited acoustic power) to be heard in

the highest, outermost and most distant parts of the auditorium [4] (p. 34), [36] (pp. 382–386), [52] (pp. 103–127).

In addition, the suitable projection of the paraskenia at the ends of the stage (the ratio of the depth of the paraskenia to the length of the façade as quantities derived from the radius of the orchestra) reinforced the direct sound in the low outer tiers of seats. Later, this development led to the abolition of the outer tiers of seats in the upper section of the auditorium, as in Hellenistic theatres, and at the same time facilitated the concentration of delayed lateral sound reflections (with time delays of >200 ms) in certain sections of the low, lateral areas of the auditorium. In other words, these small (though crucial) projections of the paraskenia gave ancient open-air theatres all the advantages of closed spaces for speaking conditions, without the disadvantages at the sides [52], (pp. 78–80).

The appearances of actors in the theologeion caused a considerable reduction in the loudness of the actors' voices (−3 to −3.5 dB in the central seats and approximately −4.5 to −5.5 dB in the upper and outer tiers), compared with the voices of actors standing on the ground-floor level of the skene. This acoustic disadvantage (i.e., the weak voice of a divine or supernatural presence in the theologeion), which required the assistance of the other co-functioning signs of the theatrical code [55] to compensate for it, was remedied by the formation of the logeion in the episkenion. Thanks to a reflective zone approximately 2 m high behind the actors, the sound losses were limited to around −2 dB in the auditorium as a whole (approximately −1.5 to −3.5 dB in the lower or central tiers), compared with the sound levels produced by actors on the ground-floor level of the skene [4] (p. 34), [49].

It is clear, then, that the acoustic comfort in ancient Greek theatres was due to a good proportion of overall useful sound energy compared with the initial intensity of the words spoken by the actors. There was a natural (passive) amplification of the actors' voices that compensated for the energy losses due to the sound propagation in the open air, a phenomenon that was particularly evident in the upper tiers of the auditorium. To implement such a design in large-capacity open-air theatres without electro-acoustic systems, architects and engineers used a variety of solutions, depending on the positions of surfaces in relation to the actors and the chorus, such as open-air auditoriums (sound absorption by the atmosphere), large smooth surfaces in the orchestra and the scenery (low sound-absorptive capacity), and the use of small irregular elements in the retaining walls, the passages running around the top of the cavea and the high walls of the stage facades of Graeco-Roman and Roman theatres (sound diffusion) [4,51,53].

#### 4. Acoustic Problems in the Case of 20 Greek Ancient Theatres

The famous acoustics of the ancient Greek theatre rely on the amplified acoustic response of the space, which is related to the replacement of the energy losses, thanks to early, strong-though of a limited number-sound reflections, in the specific performing occasion when the theatrical message is delivered by vocal trained and experienced actors providing clear distinction of the successive parts of the linguistic chain [36,49,52]. In the diagram "time-sound intensity", the emergence of the message is the visible part of the sound energy that is not distorted by background noise. The acoustic emergence depends on objective criteria such as: spectral density, ratios direct/total intensity, early decay of sound, and reverberation time, which are all connected to the basic subjective criteria of a space acoustic quality, such as colorization and intimacy, clarity, and finally, speech intelligibility [40,56].

In open air performances, the acoustic environment is dominated by urban noises and unexpected reactions caused by the audience (whispers, coughs and movements). The background noise covers a portion of the useful signal producing a kind of sound mask either permanently or occasionally. During the theatrical communication, the masking of the message is a complex psycho-acoustic process related to the visual comfort or the hearing angle of each spectator. It has been established that the parasitic signals of the continuous spectrum may eliminate the intelligibility of speech, even in low levels intensity circumstances (20 dB lower than the intensity of the useful signal). The values of the sound emergence (namely the acoustic comfort AC) in theatre spaces are evaluated according to

the following behaviour: excellent (>25 dB), good (20–25 dB), acceptable (15–20 dB), non-acceptable (<15 dB) [56,57].

Long-lasting research, aiming at monitoring the current status of the ancient theatres in Greece (modifications, destructions, protection works, and environmental noise levels) and evaluating their acoustic quality for contemporary operation conditions includes a sample of twenty (20) ancient Greek theatres: Amphiaraiion at Oropos, Argos, Delphi, Dilos, Dion, Athenian theatre of Dionysus Elefthereus, Dodoni, Epidauros, Eretria, Larisa, Mantinea, Maroneia, Megalopolis, Messini, Orchomenos at Veotia, Philippi, Thasos, Thira, Thorikos, Zea at Peiraeus. [27,37]. Figure 5 presents the distribution of the theatres of the sample.

**Table 1.** The sample of twenty (20) ancient Greek theatres.

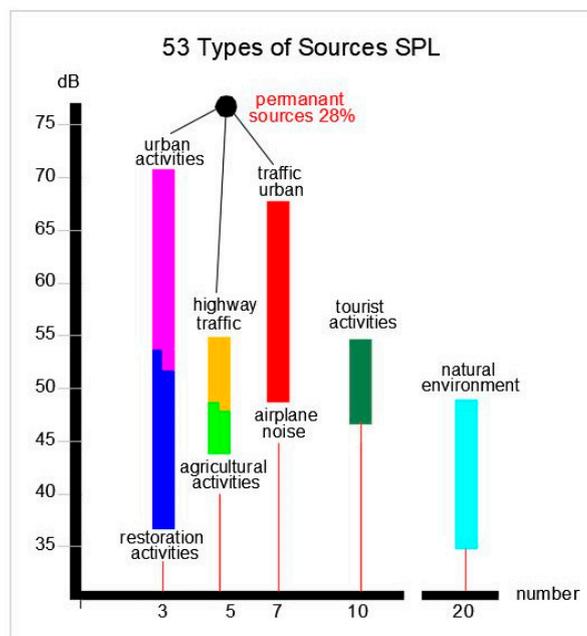
Index	Theatre	Contemporary Location/Type of Noise	Noise Sources	Min SPL
1	Amph. Oropos	natural/occasional	traffic 37/birds 41	32
2	Argos	urban/permanent	urban activities 43/traffic 46	37
3	Delphi	semi urban/occasional	traffic 46/tourist activities 50	34
4	Dilos	natural/occasional	wind 40	27
5	Dion	natural/occasional	birds 36/agricultural activities 39	31
6	Ath. Dionysus	urban/permanent	traffic 45/tourist activities 54	38
7	Dodoni	natural/occasional	wind 34/restoration activities 36	27
8	Epidauros	natural/occasional	wind 36/tourist activities 46	27
9	Eretria	semi urban/permanent	urban activities 41/traffic 47	39
10	Larisa	urban/permanent	urban activities 45, traffic 62	43
11	Mantineia	natural/occasional	restoration act. 41/airplane noise 48	32
12	Maroneia	natural/occasional	wind 45/agricultural activities 68	37
13	Megalopolis	natural/occasional	restoration activities 35/wind 41	32
14	Messini	natural/occasional	wind 40/agricultural activities 46	35
15	Orchomenos V	semi urban/permanent	religious activities 46/traffic 57	38
16	Philippi	semi urban/permanent	wind 44/traffic 52	40
17	Thasos	natural/occasional	wind 38/coastal activity 44	36
18	Thira	natural/occasional	wind 38/airplane noise 58	29
19	Thorikos	natural/occasional	birds 37/wind 48	34
20	Zea Piraeus	urban/permanent	traffic 52/airplane noise 67	44

Research data are briefly presented in Table 1. Column “Theatre” shows the exact location of each theatre, and the column “Index” has the serial number for every theatre in the Figure 5. “Contemporary Location” refers to the type of environment (urban, semi-urban or natural). “Type of Noise” refers to whether the noise sources are occasional (e.g., an airplane crossing in the theatre of Thira, or seasonal agricultural works in the theatre of Dion) or permanent (e.g., distant traffic noise in the theatre of Dionysus or recreational activities in the case of the theatre in Larisa). The column “Noise sources” has the different type of noises with the recorded sound levels (maxL in dB for civil/agricultural/tourist/recreational activities and natural environment, Leq,h in dB[A] for ring road/highway traffic and airplane noise). Finally, in the last column the background noise in minimum SPL appears. The aforementioned noise levels are in global values. The frequency values for every noise source case will be discussed in a future paper.



**Figure 5.** The distribution of the theatres of the sample (the index number for each theatre in the Table 1).

Figure 6 presents a concise recording of the sound intensities measured in the environment of every theatre. For every research period and in each theatre, 12 measurements were conducted in the following positions: 2 at the remains of the stage, 1 at each parodos, 2 at the orchestra and 3 at the middle gradient of each part of the amphitheatre (1 at the central axis and 2 at the sides).



**Figure 6.** Measured intensities of various noise sources.

In order to evaluate the sample for contemporary performances or for potential future re-use, we have laid out a numerical model to calculate the acoustic comfort (AC), as the effective signal rising, based on the following assumptions [27,37]:

- the actor is at the back of the orchestra (not in the centre, but at the intersection of the potential scenery with the main axis of the koilon) 1.7 m above the level of the orchestra, while the audience is 1,1m above the gradients
- $L_0$ , the initial intensity (the human voice of an experienced actor) is 82 dB [A]/1 m (normal intensity) or 87 dB [A]/1 m (strong intensity), in spherical wave conditions (with no electrical reinforcement). The above-mentioned sound intensities do not correspond to the relative levels of an ISO, but have been already measured in ancient drama performances with trained and experienced Greek actors,
- $L_d$ , the corresponding decrease of the direct sound due to distance in a ray starting from the actor and corresponding to the 75% of the existing seats, either in lateral or central positions,
- $R_o/sc$ , the natural (passive) loudspeaker amplification of the theatre space (+3 dB) thanks to reflections coming exclusively from the orchestra (for minimum predicted values), or (+6.5 dB) thanks to the reflector of the orchestra, plus the reflector of the scenery, plus the combination of all the positive reflections near the actor (for maximum predicted values)
- $N_{bn}$  is the background noise in every theatre, plus the noise amplification (+5 dB) due to the presence of the spectators during the performance
- the predicted values accounted in accordance to the formula:  $AC = L_0 - L_d + \{R\} - (N_{bn} + 5)$

As shown in Figure 7 the ancient Greek theatres of the sample are classified as follows:

- for normal human voice intensity and in cases that active reflections come only from the orchestra (black index and bullets)
- for strong human voice intensity and in cases that active reflections come from the orchestra, plus the scenography background, plus the combination of all the active positive reflector near the actor (blue index and bullets).

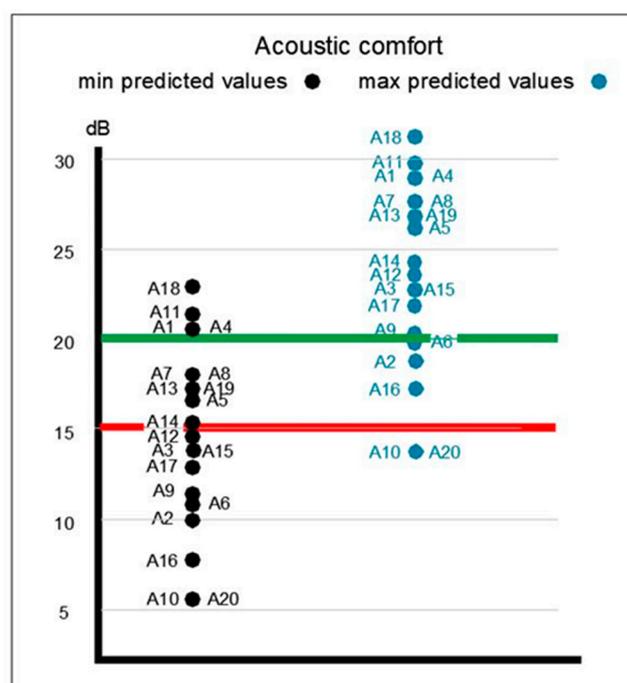


Figure 7. The acoustic comfort for min/max predicted values.

The major issue in all Greek ancient theatres is the condition of the stage. As Figure 8 shows regarding the theatres of our sample:

- in 2 cases there was never a stage building or an infrastructure for mobile stage (scenae ductilis) was used
- in 7 cases, only the remains of a low stage building (hypo-scenium) from the Roman period exists
- in 11 cases, only the ruins of a foundation from the Hellenistic period still remain.

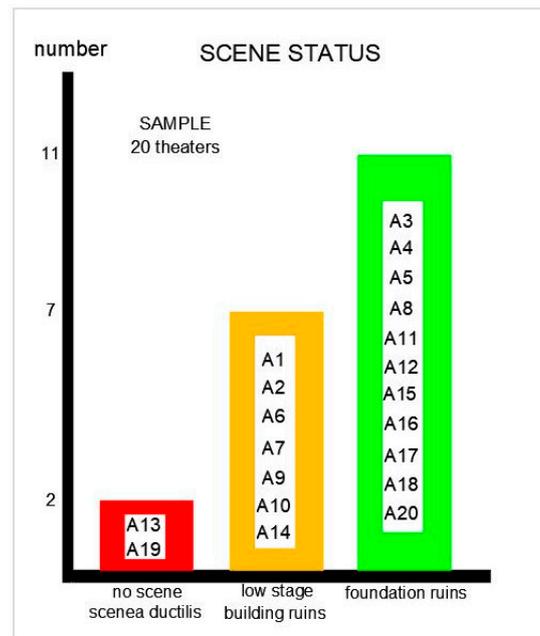


Figure 8. The current status of the scenes in the theatres of the sample.

Generalised destruction of the stage buildings is the most important problem in all cases. This fact, as discussed in previous paper, makes unavoidable the presence of a movable, low and lean scenery (a mobile stage background in the correct position and of a suitable size to be used during a performance), which could contribute mainly as an active sound reflector and secondly as a small noise barrier, as it has been proposed by other researchers, too [9,11–13,22–25].

Adding a scenery at the place of the ruins of the stage could ensure good or even satisfactory conditions in 90% of the cases, but most important, it could improve the acoustic comfort (acceptable conditions) in 45% of the cases. Specifically,

- only two (2) theatres seem to remain in non-acceptable conditions ( $AC < 15$  dB): Larisa, Zea at Piraeus (urban environment, traffic and activities),
- only three (3) theatres would have acceptable acoustic conditions ( $15 < AC < 20$  dB): Argos, Athenian of Dionysus Elefthereus, Philippi (urban environment with rural activities or traffic),
- the other theatres (15) would have good ( $AC > 20$  dB) or excellent conditions ( $AC > 25$  dB) [27].

The above estimation is rather conservative, because the usual absence of a scenery in contemporary performances obliges the actors to move towards the cavea in an attempt to compensate sound loss. As a result, the main sound reflector of the orchestra is also cancelled. The exact position, the size and the materials to be used for such a scenery depend on the specific conditions (theatre type, cavea size, environmental noise conditions).

## 5. Conclusions

It is difficult to compile an exact record of the types of scenery and skene installations used in the Classical Era either because they have been completely destroyed or because they have been

incorporated into later reconstructions. Various studies using modern software programs have attempted to make an acoustic evaluation of ancient theatres, based on the model of an “ideal” fully-formed architectural structure [6]. The whole question would be merely of academic interest were it not for the fact that, since the beginning of the 20th century, there has been a popular tendency for ancient drama to “return” to its natural home. However, there are main contradictions for the current re-use of ancient Greek theatres:

- the performance of Classical dramas takes place in the ruins of later construction phases or Roman modifications;
- the existing remains of the stage buildings constitute palimpsests of different construction phases, and restorations of ruins often include elements of Roman conversions of the theatres into arenas;
- the restoration works do not always take into account the “immaterial” acoustics in ancient Greek theatres.

The contemporary and proper use of ancient Greek theatres requires organisers of theatrical performances to understand and fulfil the architectural and scenographic requirements relating to the acoustic design and the demands of performing ancient drama. The present paper has attempted to highlight the interdisciplinary aspect of the contemporary use of ancient Greek theatres. The extent of the problems concerning open-air productions are connected with the anthropometric (phonetic and acoustic) factors involved in a theatrical performance and directly depend on the contribution of the scenery to the natural (passive) amplification of sound in the theatre.

First of all, the re-use of ancient theatres in Greece should begin with the necessary establishment of a quietness criterion similar to those used internationally to achieve the quietness required in open-air cultural venues. Furthermore, in theatres where contemporary use is both feasible and desirable, it is essential to provide a removable, plain and aesthetically neutral background in the right position and of a suitable size [27,36,58], to counterbalance the absence of the stage reflector during the classical Era.

The present paper demonstrated that a scenery could improve the acoustic comfort in most of the theatres. The addition of a temporary, removable scenery during performances can provide a crucial, auxiliary reflector (plus a sound barrier), of specific characteristics for each theatre, without restricting the artistic freedom and without jeopardising the protection of ancient theatrical monuments.

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