

Article

Acoustic Design of Ancient Buildings: The Odea of Pompeii and Posillipo

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Abstract: In this paper, a typology of a building erected in Ancient Greece and Ancient Rome is described: the Odeon. The Odeon is a covered building, but more modest in size than traditional open-air theatres without roofs. The Odeon could hold a few hundred spectators and therefore a smaller audience. The roof covering allowed the possibility of meetings even in adverse weather conditions. The etymology of the word of the Odeon (covered theatre) means the place of the ode, or of the songs. In this paper are discussed the architectonic and acoustic characteristics of the Odea of Pompeii and Posillipo. With commercial software (Odeon, Room Acoustics Software, Lyngby Denmark) we assess the acoustic characteristics of the Odea of Pompeii and Posillipo in the presence of an original roofing system and show that these buildings were well suited for music, songs and speech.

Keywords: ancient theatres; Odeon; cavea; orchestra; reverberation time; audience

1. Introduction

The ancients had no scientific knowledge of the physics of sound; they relied on the observation and interpretation of natural phenomena in a mythological key and through oracles. Priests interpreted the sounds emitted by nature, the rustle of leaves or the roar of thunder, as the voices of the gods and thus predicted the futures of travelers. The Ancient Greeks observed the phenomenology of nature and sensed the principles that underlie the science of sound; they were aware that empty amphorae could alter the acoustic characteristics of a closed environment. Theatrical buildings have been built since antiquity to contain the public and to better see and listen to performances [1,2]. The theatres built in Greece rested on the slope of a hill, with a concentric stepped structure, and this configuration, in addition to improving the view, allowed a more optimal distribution of sound, so the legend of good acoustics was born. M.P. Vitruvius' treaty, "De Architectura", written during the Augustan period in the first century BC (Before Christ), is the only book that has come down to the present day in which the principles of architectural acoustics are stated [3,4]. Book V shows the possible interventions to be taken to improve speech understanding inside an open-air theatre. Vitruvius describes the analogies between the wave motion of water and the propagation of sound in the air. To improve acoustics, Vitruvius suggests placing vases (echeia) under the steps to better tune the sound inside the theatres; this very fascinating hypothesis today finds application in acoustic resonators, which are widely used for the correction of modern theatres. However, the good acoustics of the ancient theatres were mainly due to the regular arrangement of the steps, which were aligned and, with regular geometries, behaved like diffusing surfaces. The sound perturbation advanced, impacting on the corners of the steps, and then spread throughout the theatre in all directions, as if the corners were secondary sound

sources. Therefore, a diffused sound field was created which improved the acoustics of the theatre; this complex phenomenon has only recently been understood [5,6].

During the Imperial period, further measures were used to improve the acoustics of the theatres, such as covering the orchestra with square marble slabs so that the discontinuities generated greater sound diffusion in all directions [7,8]. The scenic building was covered with a canopy to improve the reflection of sound towards the cavea. The size of the scenic building covered the maximum height of the cavea in order to enclose the scene and the cavea in a single body. The size of the stage was doubled compared to that of the Greek theatre [9]. The scene became a building with columns, stuccos and colored plasters; moreover, the rows of columns, arranged on several levels, created diffusing surfaces that improved the propagation of sound. Figure 1 shows a reconstruction of the scene building, orchestra and cavea of an Ancient Roman theatre.

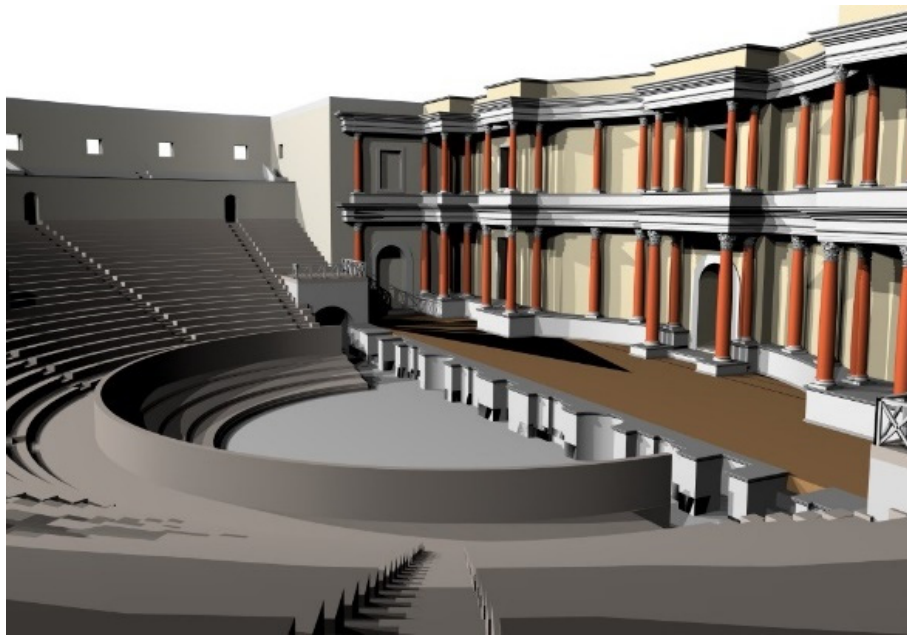


Figure 1. Reconstruction of the scene building, orchestra and cavea of an Ancient Roman theatre.

The presence of the stage building allowed a better distribution of sound in the cavea, where audiences were seated. In fact, the voice of the actor on the scene was reflected by the stage wall and then returned to the audience sitting in the cavea [10].

Regarding the acoustics of ancient theaters, the most famous book is that of Canac [11], which reported open-air theater research. However, there are few studies about Odeon acoustics because there are few restored buildings (e.g., Patras, Pompeii, Athens, Greece), and nowadays, they are without roofs. Thus, it is possible to perform building acoustic research only with the help of dedicated architectural acoustics [12–14]. Studies of the acoustics of the Odeon have shown that these buildings, smaller than open-air theaters, were used for a more demanding audience and were used for musical performances or poetry recitation. In this paper are reported the acoustic characteristics of two Odeon buildings located in Pompeii and in Naples on Posillipo’s hill. These Odeon buildings have different dimensions; in fact, that of Pompeii is much larger than that of Posillipo. Consequently, the first could be used for musical performances, the second for the recitation of poems.

2. The Odeon: The Origins

The etymology of the word Odeon, which refers to a covered theatre, means “the place of the ode”—that is, of song—even if today we do not know which and how they were performed. Closed small buildings with roof coverings were widespread in Ancient Greece and subsequently spread to the Roman Empire. In Greece, this type of theatre, like a closed building with a roof,

was widespread because it was a place where political meetings and city government assemblies were held. Only later, these buildings were modified for performances [15,16]. The Odeon is a covered building, but of a more modest size than traditional open-air theatres, and it is supposed to be used for musical performances, recitations, for literary and poetic declamations; it could contain a smaller audience. The presence of the roof allowed the possibility of meetings even with adverse weather conditions. The first Odeon of which we are aware were made in Greece starting from the fifth century BC. In the city-state of Athens, the Odeon of Pericles and Agrippa were built near the acropolis. The Odeon of Pericles was built around 442 BC. According to Pausanias, it was similar to the tent of Xerxes, with a square plant and a domed roof, with a double order of columns that turned around, and, according to Vitruvius, it had the roof made with wood from the masts of the Persian ships defeated in the battle of Salamis. Next to these two buildings, in the 2nd century AD (Anno Domini), the Odeon of Herodes Atticus was built in honor of his deceased wife; today it is still possible to admire the beauty of this building. Figure 2 shows the Odeon of Herodes Atticus in Athens in actual state [17–20].



Figure 2. Odeon of Herodes Atticus in Athens in actual state.

Another Odeon rebuilt in Greek is in Patras (Figure 3) [21].



Figure 3. Odeon of Patras in actual state.

The Romans copied the construction technique from the Greeks and improved it making the building more functional to the needs of the shows. The presence of a roof limited its dimensions, however, since an excessive length of the trusses could have brought the roof down; the same applies to the side walls which had to resist the weight of the roof. According to some authors, the roofs of the Odeon were in terracotta tiles, and this involved the construction of resistant trusses and reduced dimensions. Another problem, not secondary, was the lighting and the exchange of air, which was carried out with large windows open on the sidewalls. Odeia were built in many cities of the Roman Empire: In Italy, are famous the Odeia in Syracuse, Catania, Naples, Pompeii, Aosta and Taormina. In literature, there are few papers that described those buildings, and only few authors mention their existence. Vitruvius, Tertullian and Cassiodorus wrote a few descriptions in their treatises. Vitruvius in the treatise “De Architectura”, although he dedicates (Book V) a lot of space to the Greek and Roman open-air theatres, he mentions the building built by Pericles in the fifth century BC and mentions the existence of a small theatre, near Tralles, when describing the paintings (Book VII). Today, however, we do not know much about the type of roofing used, if the roofs were with trusses or with suspended canopies, and only a few scholars have ventured into the reconstruction of these environments, one of these being G.C. Izenour [22,23]. Two Odeia are famous in Campania: one located in Pompeii and the other one located in Naples on Posillipo’s hill, which was built in the first century BC.

3. The Odeon of Pompeii

The Odeon of the city of Pompeii was built in the Roman age, in the Sullan period, 80 BC, as can be seen from some inscriptions found in it, next to the large theatre. The cavea rests on the slope of a hill. Figure 4 shows the large Theatre and the Odeon of Pompeii in an aerial view.



Figure 4. The large Theatre and the Odeon of Pompeii in an aerial view.

It has a square plant and is surrounded by a perimeter wall on which the roof rested. In the first four steps of the cavea, near the orchestra, are larger than the other seventeen subsequent ones, in fact, these steps are low and wide for the seats reserved for the personalities of the city. All the steps of the cavea, in tuff, are made with a cavity in the back so that the spectators were not disturbed by the feet of those behind him. The orchestra, small in size, has a floor made of irregular and colored marble slabs. The scenic building is straight (with three doors) from which a second wall could be glimpsed with the creation of perspective effects. The general dimensions of the Odeon are the following: cavea width

35 m, orchestra width 15 m, scene length 18 m, volume 25,000 m³ and plant area 1200 m² [24–27]. Figure 5 shows the plant of the building with the main dimension. While Figure 6 shows a hypothetical reconstruction, and Figure 7 shows the sections by G.C. Izenour [22,23].

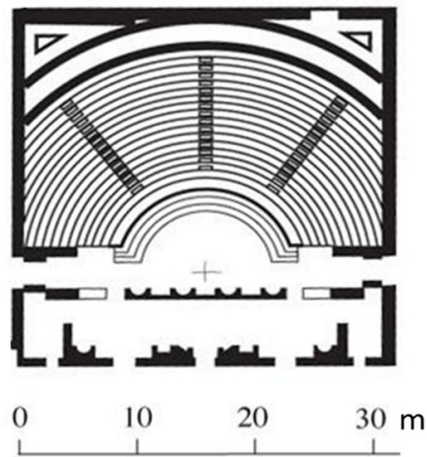


Figure 5. Plant of the building with the main dimension.

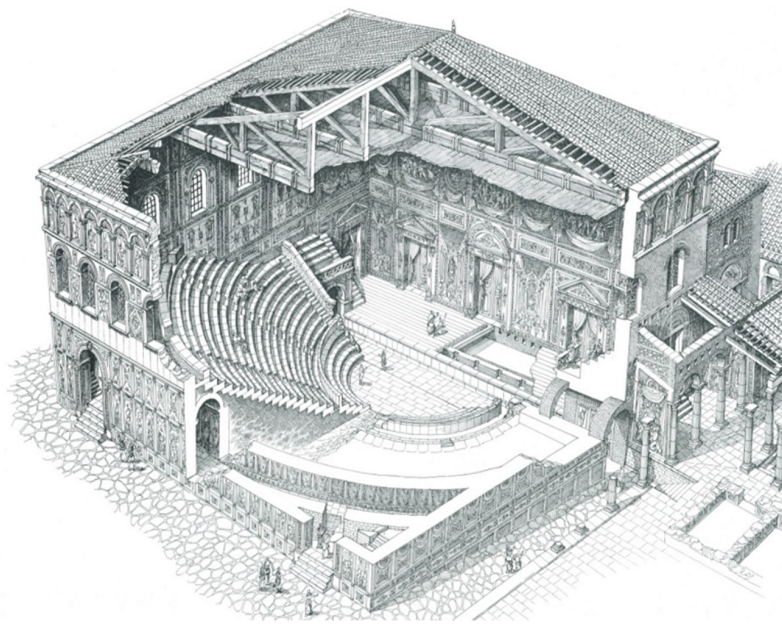


Figure 6. Odeon of Pompeii: hypothetical reconstruction by G.C. Izenour [22,23].

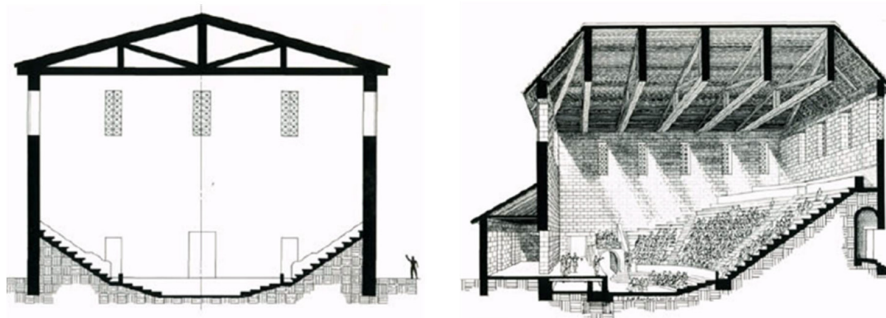


Figure 7. Odeon of Pompeii: hypothetical reconstruction of the sections by G.C. Izenour [22,23].

The peculiarity of the Odeon of Pompeii is that the cavea is not perfectly semicircular, but it is cut at the ends (Figure 5), and it is enclosed within the perimeter of the walls that supported the roof. Probably the reduction of the auditorium was forced by structural requirements, as an excessive length of the spans could not have supported the weight of the roof. Figure 8 shows the cavea and scene building in actual state.



Figure 8. Odeon of Pompeii: (right) cavea and (left) orchestra of the in actual state.

4. Odeon of the Posillipo Hill

On the hill of Posillipo was built in the 1st century BC the Odeon aimed at poetry auditions [28]. Nowadays only a few remains are left such as the scene, the steps and some perimeter walls. The plant was characterized by a central area with scene, seats and imperial stage. The cavea consisted of four semicircular seating orders, plus two quarter—circle—seating orders. Behind the scenes, there was a portico with plastered brick columns that formed the scenic backdrop. The Odeon was built mainly in terracotta bricks; the most important parts had been covered with ornamental marble, including red and yellow. The main body of the structure: (25 m long and 12 m wide and 4.6 m the diameter of the orchestra), it was covered, and the spectators entered it by two lateral corridors, which led to the steps in front of the scene. The cavea, consisting of nine steps, is not continuous but interrupted in the central part, to give access to an apsidal room, whose floor level was raised by 1.70 m compared to that of the orchestra. Various academics have identified this room as an imperial stage. It was also accessible not only by a staircase placed in the center of the first four rows of the auditorium but also by two lateral ramps placed behind the main body of the building, also connected to the two lateral corridors. The scene (19 m long and 3 m wide) features an apse with niches. Figure 9 shows the details of the remains of the Odeon located on the Posillipo hill.



Figure 9. Detail of the remains of the Odeon located on the Posillipo hill.

While Figure 10 shows a hypothetical reconstruction of the plant by G.C. Izenour [22,23], and Figure 11 shows the main dimensions. The volume 3500 m³ and the plant area 300 m².

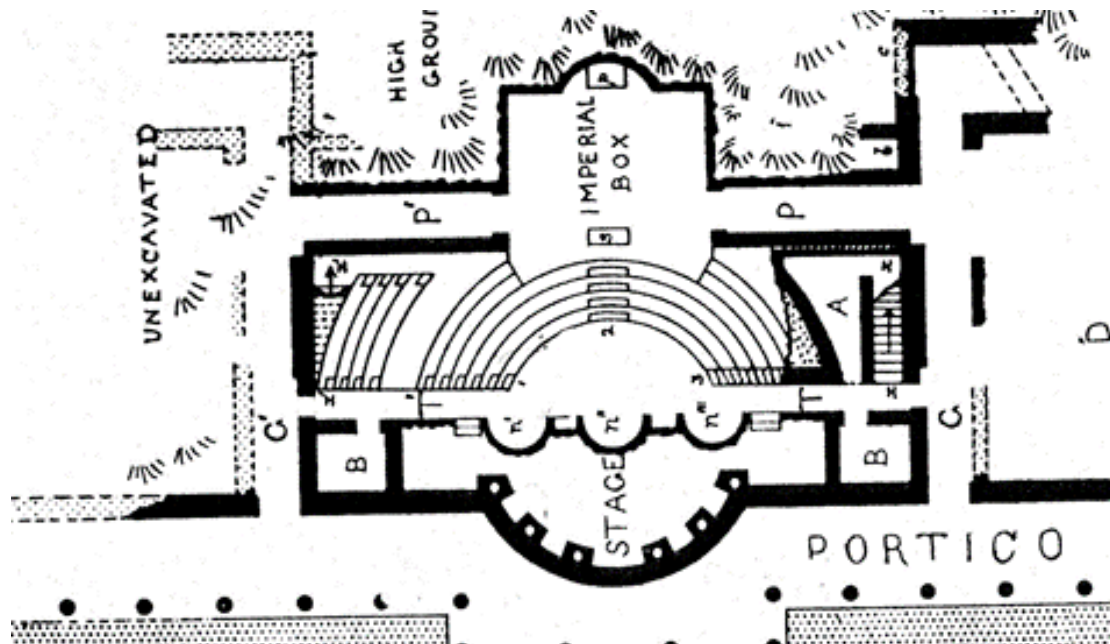


Figure 10. Odeon of Possilipo: hypothetical reconstruction of the plant by G.C. Izenour [22,23].

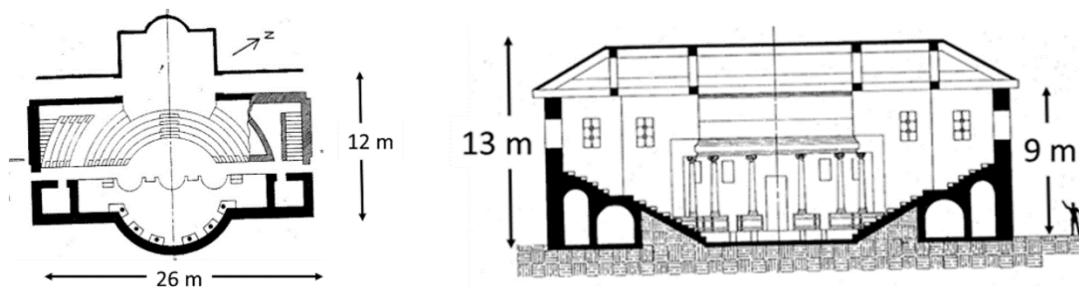


Figure 11. Odeon of Possilipo: main dimensions by G.C. Izenour [22,23].

5. Acoustics Reconstruction

The virtual model was simulated using a commercial architectural acoustics software (Odeon ver. 11). The virtual model was realized with a 3D design software, starting from the geometric measurements of the building in its current state. Subsequently, the virtual model was integrated with the roof in analogy to the drawings available in current literature and by Izenour books [29–31]. The architectural acoustics software is based on geometric acoustics principles with the tracking of sound rays technique [32–34]. This software uses the principles of the geometrical acoustics and adopts a hybrid calculation method that combines two classical methods, the image source method and the ray-tracing method. The approach used by the software merges the best features of both models, since the image source method is used for the early-scattered rays of the first reflections, while later a ray-tracing technique which also considers the surface scattering according to a Lambert's cosine law, is used for the more statistically computed late part of the impulse response. The transition order (TO) at which the software changes from the early image source method to the late ray-radiosity method was set equal to 2 in order to consider some efficient early reflections coming from the theatre surfaces; the impulse response length equal to 3000 ms, with a resolution of 3.0 ms. The number of rays equals to 100,000. In the virtual model, the receiving points were positioned in the cavea towards the radial direction, in the same position where the audience would have been seated. The point

source was placed on the stage to simulate the presence of actors. The scattering coefficient (s) is introduced to take into account the diffusion of sound on the steps. The seating rows were modelled with a scattering coefficient of $s = 0.7$, while the stage wall and floor were assigned a scattering of $s = 0.5$. In the numerical model the seating rows, the orchestra and the scene building as acoustic rigid materials [35–38]. Physically, this condition corresponds to small values of the sound absorption coefficient, while the wooden ceiling corresponds to a condition of sides values of sound absorption at low frequencies. Those theatres, as was typical for Roman buildings, were made of hard materials such as stones or marble [39,40]. The open windows, which were included for daylight and ventilation, and the audience seated in the cavea provided the main acoustical absorption in this kind of buildings. While the air conditions are taken into account by the software: temperature, 20 °C, and humidity, 50%. Table 1 reports the main values of the absorption coefficients used in the simulations.

Table 1. Absorption coefficients of the surfaces used in the virtual model.

Elements	Frequency (Hz)					
	125	250	500	1k	2k	4k
scene	0.41	0.41	0.41	0.41	0.50	0.70
orchestra	0.05	0.06	0.10	0.11	0.12	0.14
cavea	0.30	0.28	0.28	0.28	0.28	0.28
roof	0.19	0.14	0.09	0.06	0.06	0.02

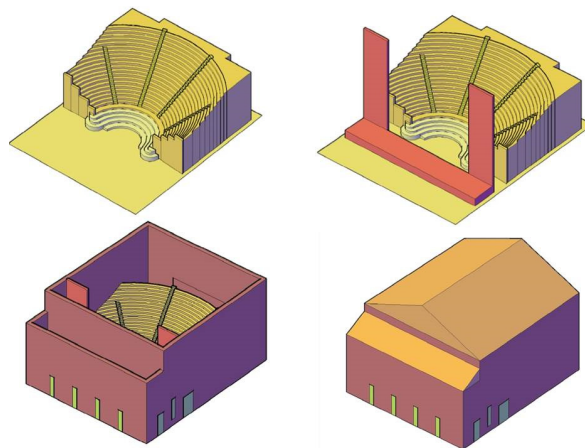
The monaural acoustic parameter considered in this study is T30 (reverberation time), which represents the reverberation time measured in seconds. It is the most used descriptor for evaluating the acoustic characteristics of an environment. It was defined by W. Clement Sabine in late nineteenth as the time required for, after sound emission interruption from a source, sound pressure level in the room decreases by 60 dB. The value of this parameter is a function of room volume and of total absorption of surfaces, and since the absorption of materials varies with frequency, reverberation time also varies according to the different frequencies considered. Other parameters are listed below:

- EDT, Early Decay Time, measured in seconds, is the time corresponding to a decrease of 10 dB of the decay curve of the sound pressure level, measured from when the sound is interrupted; this parameter is particularly sensitive to microphone position related to the source and is a particularly significant parameter in comparing different points of the same environment.
- C80, clarity (dB), is a characteristic parameter of goodness of a hall for listening to music; it is a descriptor obtained from the correlation of energy that reaches the listener within the first 80 milliseconds of sound emission (including directed energy and early reflections energy) and the energy that reaches in the following instants.
- D50 is a characteristic parameter of goodness of a room for purposes of speech understanding; it is a descriptor that is obtained through the correlation of energy that reaches the point of reception in the first 50 milliseconds of sound emission and entire signal energy, that is until the end of its decay. Experimental results confirm that early reflection energy, adding to that of direct sound, gives a positive contribution to speech understanding.
- STI, Speech Transmission Index, represents the degree of amplitude modulation in a speech signal and refers to the distortion in speech signals caused by reverberation, echoes and background noise. The indices STI can take values between 0 and 1, being greater than 0.5 for favorable speech conditions. Table 2 shows a synthesis of the optimal acoustic parameters' values for different listening conditions [41–45].

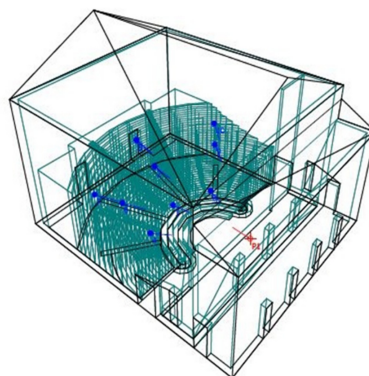
Table 2. Optimal acoustic parameters values for different listening conditions.

Parameters	EDT, s	T ₃₀ , s	C ₈₀ , dB	D ₅₀
Optimal values for musical performances	1.8 < EDT < 2.6	1.6 < T ₃₀ < 2.2	−2 < C ₈₀ < 2	<0.5
Optimal values for speech performances	1.0	0.8 < T ₃₀ < 1.2		>0.5

Figure 12 shows the scheme of the phases of realization of the virtual model for the Odeon of Pompeii, from the current state through successive phases; at the end, the building is closed with the roof; it was made of wood.

**Figure 12.** Odeon of Pompeii: scheme of the phases of realization of the virtual model, from the current state to the realization of the roof.

The cavea for spectators surrounds the orchestra for more than half a perimeter. While the scene represents the place where the theatrical action took place, which from a simple curtain has evolved over time to an architectural facade marked by three doors. The scene has a rectangular shape with an average depth from 5 to 7 m, width up to 30–35 m, and is closed by a wall towards the back with doors that allow access to the under scene intended for the storage of theatrical machines and the dressing room for the actors. The scene is turned in such a way as to have the sun rise on the right and the sunset on the left, thus having the possibility of exploiting the sunlight to illuminate the show that lasts for the whole day. In Figure 13 is shown the 3D virtual model for the acoustic simulation. The transparency of the perimeter walls and the roof allow to analyze the structure of the model.

**Figure 13.** Odeon of Pompeii: virtual model for the acoustic simulation.

It is possible to analyze the structure of the cavea which represents the element with a complex architecture due to the presence of the numerous steps on which the spectators sat. Figure 14 shows inside view of the virtual model of the Pompeii Odeon.

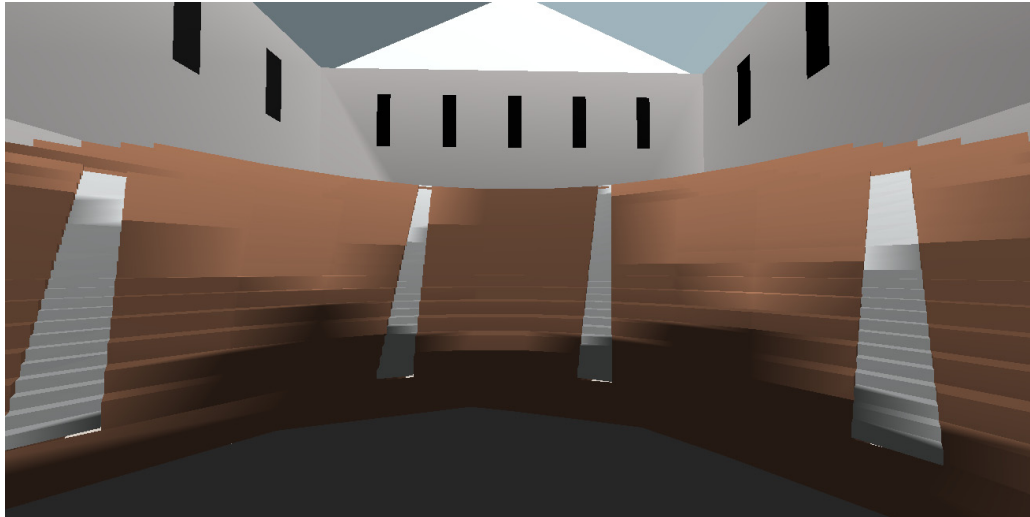


Figure 14. Odeon of Pompeii: inside view of the virtual model.

While Figure 15 shows in the frequency function (octave bands from 125 Hz to 4.0 kHz) the average values of the acoustic parameters obtained by the numerical simulation, in two configurations, with roof and without roof.

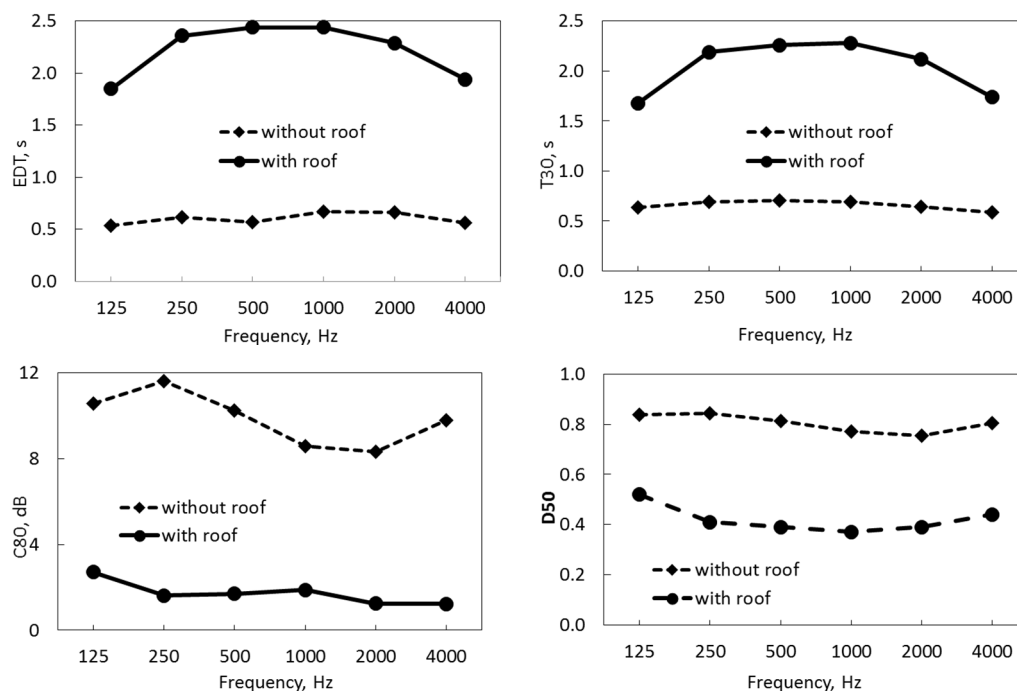


Figure 15. Odeon of Pompeii: average values of acoustic parameters from the virtual acoustic simulation in two configurations, with roof and without roof.

With roof the values of reverberation time (T30) and EDT simulated are over 2.2 s; these values for the volume of the room give the information that in this Odeon the conditions for listen to the music and songs were good (see Table 1). At the frequency of 125 Hz, those parameters are lower, because the roof was built with wood elements; in the acoustic simulation this effect is simulated with

higher sound absorption coefficient values at the frequency of 125 Hz and consequently lower T30 and EDT values [46]. Acoustic characteristics are very poor without the roof. The absence of the roof does not allow the formation of a reverberated sound field and consequently the building loses the characteristics for good music listening.

Figures 16–18 show the spatial distribution of T30, C80 and STI. Inside the room, there is not a T30 concentration in any area, but a uniform distribution.

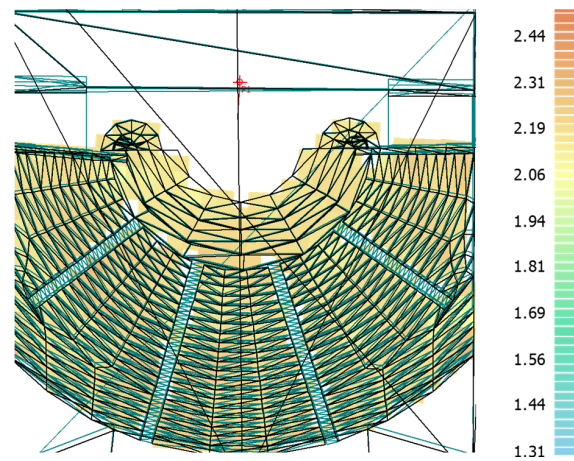


Figure 16. Odeon of Pompeii: T30 (s) parameter, spatial distribution.

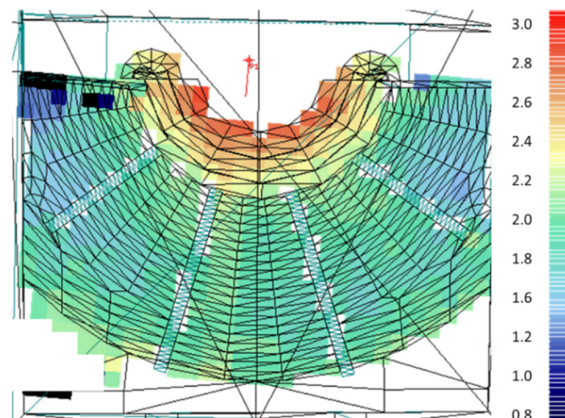


Figure 17. Odeon of Pompeii: C80 (dB) parameter, spatial distribution.

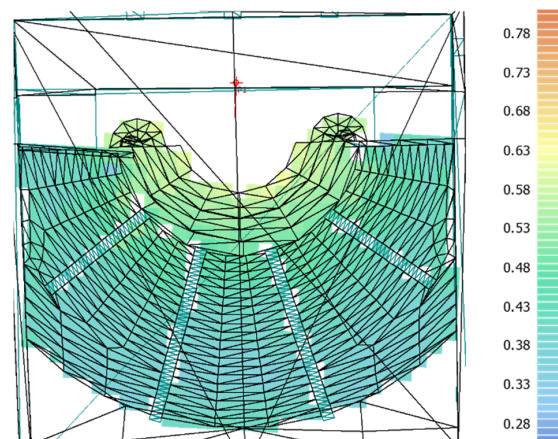


Figure 18. Odeon of Pompeii: STI parameter, spatial distribution.

The average calculated values of C80 parameter is equal to 1.5 dB, this value confirms that the room could be used in an appropriate way for listening to music, but C80 spatial distribution (Figure 17) shows that this parameter is higher near the actor position and then it decreases with the distance. While the STI parameter assumes a value of about 0.6 in proximity to the position of the actor position and then decreases with distance.

The Odeon of Pompeii with a reverberant sound were excellent for song and music from weaker instruments like the lyre. In this room, the reverberation time depends strongly on the ceiling height and the size of the windows. For the Odeon of Posillipo, Figure 19 shows the scheme of the phases of realization of the virtual model.

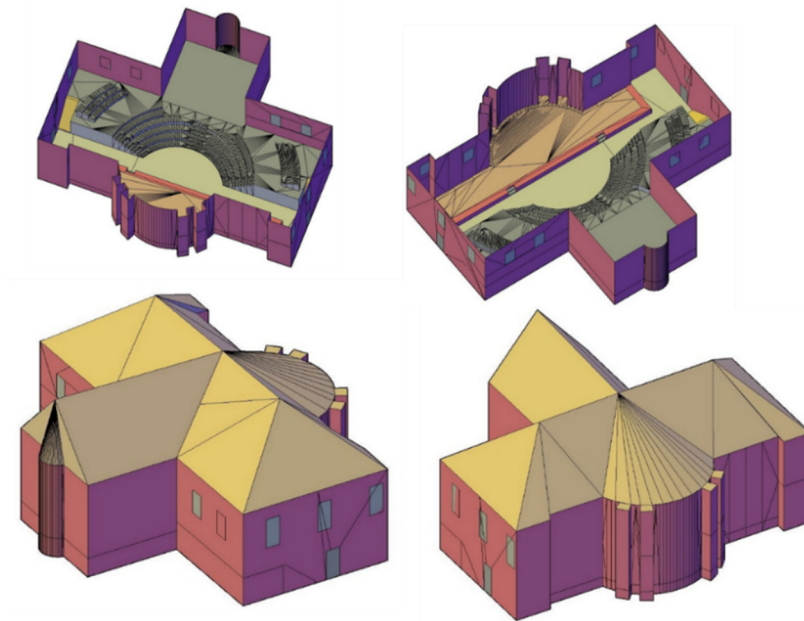


Figure 19. Odeon of Posillipo: scheme of the phases of realization of the virtual model, from the current state to the realization of the roof.

Figure 20 shows the external view of the building from the actual state to the virtual reconstruction.

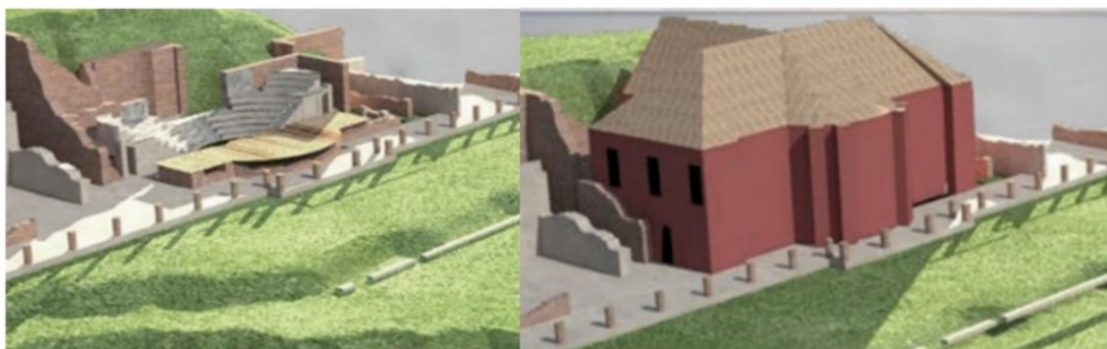


Figure 20. Odeon of Possilipo: external view of the building from the actual state to the virtual reconstruction.

Figure 21 shows the 3D virtual model for the acoustic simulation, and Figure 22 shows the inside view of the virtual model.

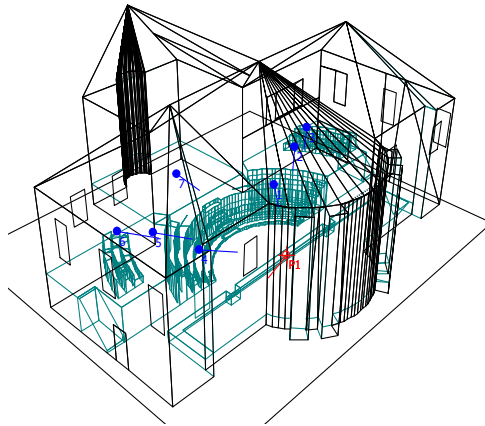


Figure 21. Odeon of Posillipo: virtual model for the acoustic simulation.

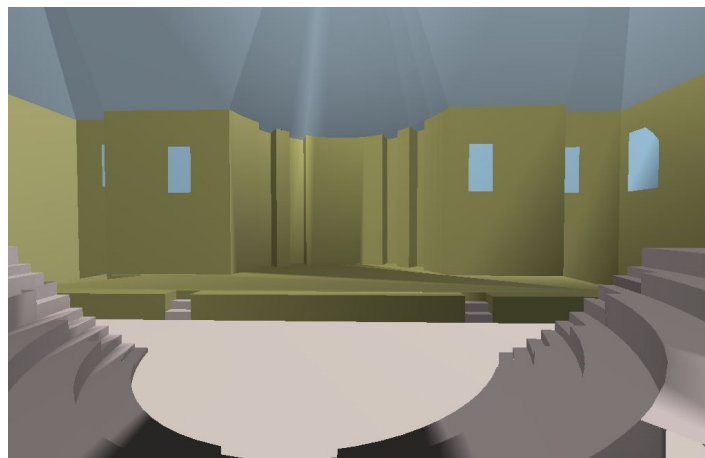


Figure 22. Odeon of Posillipo: inside view of the virtual model.

Figure 23 shows in the frequency function (octave bands from 125 Hz to 4.0 kHz) the average values of the acoustic parameters obtained by the numerical simulation.

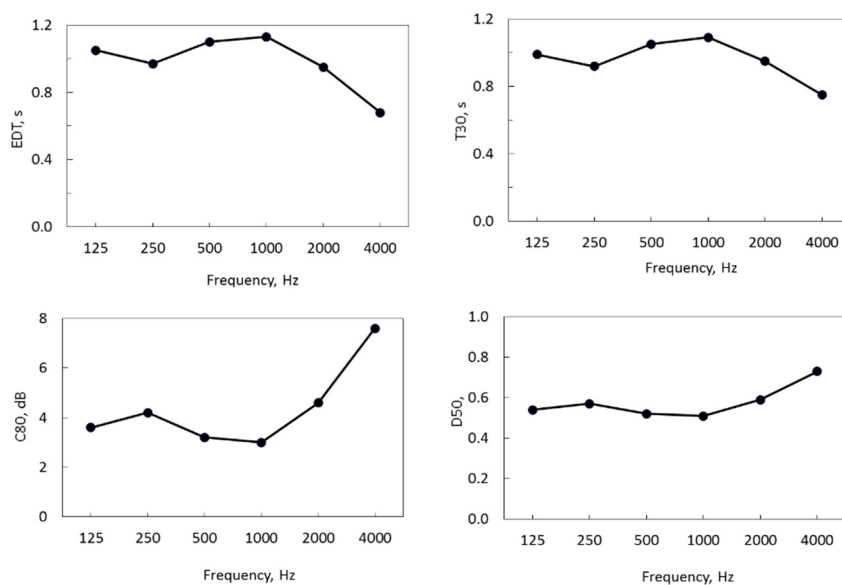


Figure 23. Odeon of Posillipo: Average values of acoustic parameters from the virtual acoustic simulation.

Analyzing Figure 23, the values of reverberation time (T30) and EDT simulated are over 1.0 s; these values for the volume of the room give the information that in the Odeon of Posillipo the conditions for the listening of speech were good. Furthermore, C80 calculated parameter is equal to 4 dB, while the D50 calculated parameter is over 0.5, and it confirms that the room could be used in an appropriate way for listening to speech performances [47,48].

Table 3 shows the calculated values of the simulated acoustic parameters for some roof Odea (Aosta, Aphrodisias, Pompeii and Posillipo).

Table 3. Acoustic parameters averaged at mid-frequency bands of 500 Hz and 1 kHz calculated through software simulations for ancient Odeon.

Odeon	T30, s	C80, dB	STI	Cavea Diameter, m
Aosta	6.0	−5.3	0.36	60.0
Aphrodisias	4.0	−4.2	0.38	45.6
Pompeii	2.2	2.0	0.50	35.0
Posillipo	1.0	3.0	0.60	18.0

These Odea are larger than those of Pompeii and Posillipo. The higher volume generates a longer reverberation time and negative clarity. The comparison of the values shows that in the Odea of Pompeii and Posillipo the conditions for listening to music and speech were better.

6. Conclusions

The acoustic of closed environments is studied theoretically with software based on the ray-tracing method or with the image method. Odeon were buildings used in ancient Greece and ancient Rome, and due to the presence of the roof they could also be used when the weather conditions were adverse. This paper described the virtual reconstruction and acoustic simulation of the Odea of Pompeii and Posillipo, in presence of a roofing system. The virtual reconstructions were performed, starting from the current geometrical configuration. The dimensions of the Odeon of Pompeii were larger than those of the Odeon of Posillipo. The numerical simulations were performed with the aid of commercial architectural acoustics software. The results obtained from the processing have shown how the Odeon of Pompeii was well suited for music and songs, while the Odeon of Posillipo was well suited for speech.

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