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Evaluation of the acoustics of the Roman theatre in Benevento for discrete listening points

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ABSTRACT

This work reports the acoustics of the Roman Theatre in Benevento evaluated for discrete listening points positioned in the cavea along three radial directions. The theatre, built in the second century A.D, was abandoned due to historical reasons and natural events. The recovery works ended in 1950. The theatre is the centre of important social activities. The theatre acoustic measurements were taken by placing an omnidirectional spherical sound source on the stage and in the orchestra, with the microphones along three distinct radial directions on the steps of the cavea. The acoustic properties in the various seating areas were measured. The aim of the work is to evaluate in which sectors of the cavea the acoustic parameters are optimal for listening to different types of theatrical performances.

Keywords: theatre ; stage; orchestra ; acoustic measurements ; sound source ; ima cavea.

1 Introduction

Benevento was an important Roman city during the Imperial Age, placed along the Via Appia that connected Rome with Brindisi; so Benevento had a strategic role in the connections between Rome and its colonies overseas. The theatres built in the Imperial Age were set inside the cities and in brick that composed a series of arches. The representations were developed on the stage, the senators were entertained in the orchestra, the people occupied the cavea from the lower to the upper part, according to the importance of their social class; the plebians and women occupied the upper part of the cavea, further from the stage.

How the theatres had to be built is described by Vitruvius (first century B.C.), in the "De Architectura". In the 5th book, the fundamental principles for achieving a correct vision and listening of the theatrical performances are introduced (1, 2).

The theatre of Benevento was built in the second century A.D., made up of 25 arcades on three levels; the orchestra with 10 m radius, the cavea with 40 m radius, the cavea could contain over 10,000 spectators, (3, 4, 5). The cavea is the part of the theatre where spectators sit. The "*ima cavea*" is leaned onto two semi-circular ambulacra, each connected through corridors alternated with staircases that lead to the upper part. The theatre had also a summa cavea. When the theatre was built in the second century A.D., the tragedy was an exhausted theatrical genre by that time, so the theatre represented the symbol of the greatness of the city, public meetings took place inside it and the shows were comedies and satirical representations. The experience that a Roman citizen experienced while assisting a show was no different from what a fan going to an indoor stadium experiences nowadays (6). With the advent of Christianity, the theatre was abandoned, and the following earthquakes, floods and lootings led to its destruction. During the centuries, some houses were built inside on the cavea and in the 18th century, on the right side of the cavea, the church of the "*Madonna della Verità*" was built, using the structure of the theatre as substratum. The church is still used today for sacred services. Figure 1 shows a painting from the 18th century by Antonio Joli (7), with it being possible to see how only a few external arcades remained of the whole theatre, and the first level was completely covered with earth.

Figure 1- Painting from the 18th century, in which only a few external arcades remained of the whole theatre.

Figure 2 shows a photo of the early 1900 in which the houses placed inside the theatre are visible. The houses built in the cavea were demolished in 1930 so as to rebuild the cavea and a part of the stage building. Only the church (*Santa Maria della Verità*), over a part of the cavea, has survived.

2 The Roman Theatre nowadays.

During the Imperial Age, thousands of theatres were built throughout the whole empire (Jordan, Turkey, Libya, France, Italy, Spain, Germany, Greece). The best preserved are in Jordan and Turkey, but there are also examples in Italy, Spain and France. The theatres admired nowadays are often not a very faithful reconstruction of the original theatres. An axiom known among the archaeologists is that the more a monument is famous, the more the remaining structures are not original. The theatre of Benevento confirms this axiom.

Figure 2 - Picture of the beginning of the 1900s. The houses inside the cavea of the theatre.

Nowadays a visitor entering in the Roman theatre of Benevento is struck by the red colour of the bricks covering the cavea, but in the Imperial Age, it was covered with white marble and the stage building was adorned with columns and marbles. The "*ima cavea*" was rebuilt with terracotta bricks with fifteen steps, a height of 0.40 m and depth of 0.70 m, while the "*summa cavea*" was only partially rebuilt and cannot be accessed by spectators. The theatre began to be used for events in the 1950s. Today, the theatre is used for different types of shows: opera, drama, dance as well as symphonic, jazz and pop concerts. During the annual national cultural meeting "*Benevento città spettacolo*", the theatre becomes the centre of the most important performances including comedy, drama and musical shows, with the maximum capacity being about 1,800 spectators.

Figure 3 – The theatre in actual state, cavea.

Figure 3 shows the cavea of the theatre in actual state. Figure 4 shows the theatre in actual state: stage, orchestra and the church "*Santa Maria della Verità*".

Figure 4 – The theatre in actual state, stage, orchestra, cavea and the church "*Santa Maria della Verità*".

3. Acoustic measurements

The acoustic measurements provided the acoustic features of the theatre, when either the actors are on stage or the musicians are in the orchestra. In order to obtain this information, a spherical sound source was first placed on the stage and then in the orchestra. The sound is detected through a microphone set in the cavea staircases at constant space in three radial directions. The sound emitted by the sound source interacts with the surfaces of the theatre and is then detected by the microphone set in the cavea. The sound detected by the microphone is the composition of the direct component, that means the one let out by the source and that directly reaches the microphone, and the one of the reflected components, that means the components of the sound that are reflected by the surfaces of the theatre before they reach the microphone. The sound source used to carry out the acoustic measurements consisted of an omnidirectional sound source, Peeker Sound JA12 (Peeker Sound Corporation, Reggio Emilia, Italy) a power amplifier KT 150. MLS signals of order 16 with a length of 5 seconds were generated by a 01 dB Symphonie system. The impulse responses were detected by a microphone type GRAS 40 AR ½". The sound source height from the floor was 1.60 m from the floor. Figure 5 shows the omnidirectional sound source in the orchestra during the acoustic measurements. The microphones were placed on the steps of the cavea, at a height of 0.8 m, with a fixed pitch along three radial directions, one central and two laterals, in order to obtain the average spatial values of the acoustic characteristics of the theatre.

Figure 5 – Omnidirectional sound source in the orchestra during the acoustic measurements.

The acoustic measurements were carried out with the method of the impulse response, the monaural acoustic parameters analysed in accordance with the ISO (ISO 3382, 2012) (8). Such as the reverberation time (T_{30}), the Early Delay Time (EDT), the sound pressure level (Lp), the clarity (C_{80}), the definition (D_{50}), and the sound transmission index for speech intelligibility (STI). To reduce the background noise, the acoustic measurements were taken without visitors, so the impulse response was recorded in empty conditions. Figure 6 shows the positions of sound source (stage and orchestra) and the positions of the twelve receivers in the cavea along three radial directions. The theatre is an open-air space so the calculation of the room criteria which assess the delay of sound reflections is partially valid, since the absence of the ceiling and lateral walls often make the acoustic field more similar to a free field rather than a typical room. In room acoustic evaluations, clarity represents the degree to which different reflections arrives and are perceived by the listener, and it is assessed as an early-to-late arriving sound energy ratio. This ratio can be calculated for 80 ms early time limit. The definition considers the early arriving sound energy over the overall sound energy and, similarly to the clarity, it can be calculated for 50 ms early time limit. The acoustic procedure and post processing methodology were similar to those used in other spaces, such as the large theatre and the Odeon of Pompeii (9, 10, 11). Table 1 reports the optimal values of the acoustic parameters in different musical listening conditions or speech intelligibility.

Parameters	EDT, s	T_{30}, s	C_{80}, dB	D_{50}
Values for musical performances	1.8 < EDT < 2.6	1.6 < T_{30} < 2.2	-2 < C_{80} < 2	< 0.5
Values for speech performances	1.0	0.8 < T_{30} < 1.2		> 0.5

Table 1. Optimal values of the acoustic parameters in different musical listening conditions or speech intelligibility.

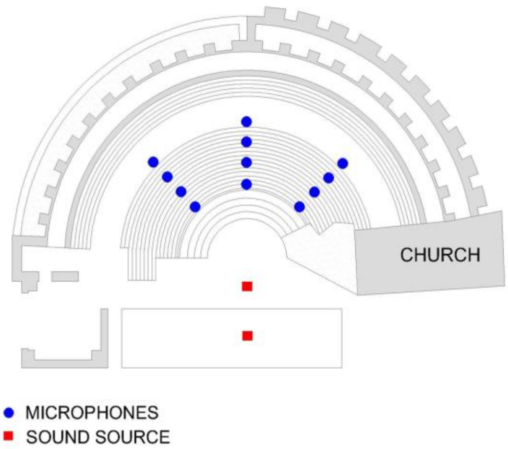


Figure 6 - Positions of sound source (stage and orchestra) and the twelve positions of the receivers in the cavea along three radial directions.

Referred to the sound source on the stage and the sound source in the orchestra, Figure 7 shows the average measured values of T_{30}; Figure 8 shows the average measured values of EDT; Figure 9 shows the average measured values of C_{80}; Figure 10 shows the average measured values of D_{50}.
The average values are reported in the octave band frequencies from 125 Hz to 4.0 kHz. The standard deviation are reported up for the sound source on the stage (quadrate) and down for sound source in the orchestra (triangle). The measured values confirm that the present lack of a roof, lateral walls, and scene wall, led to reduced sound reflections with small reverberation, as highlighted by the values always below 1.0 s of the T_{30}.

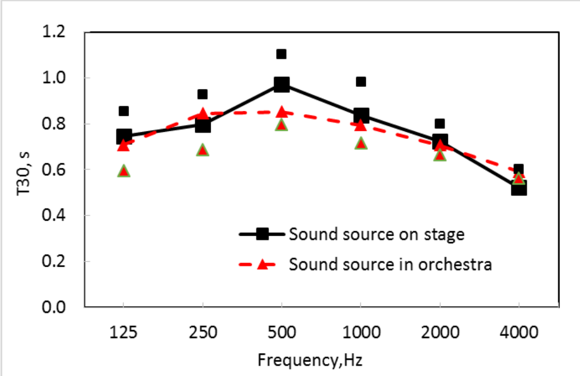


Figure 7 – Average measured values of T_{30} .

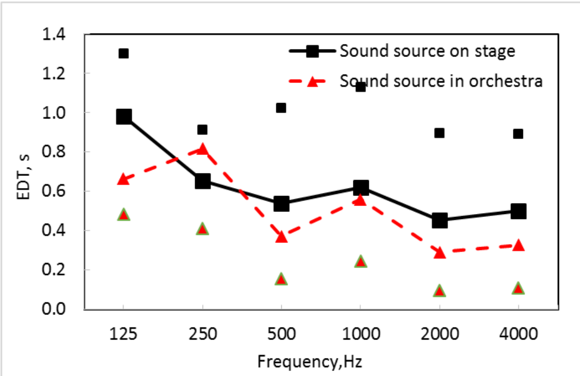


Figure 8 - Average measured values of EDT.

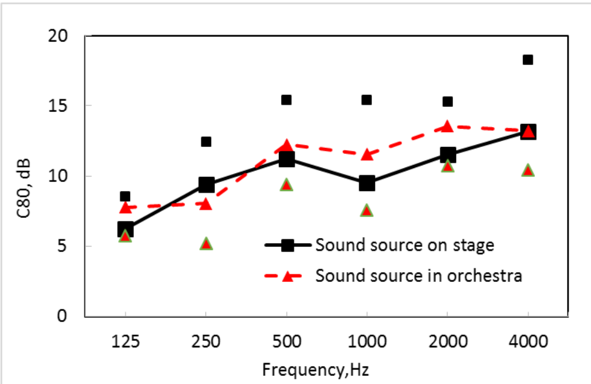


Figure 9 - Average measured values of C_{80} .

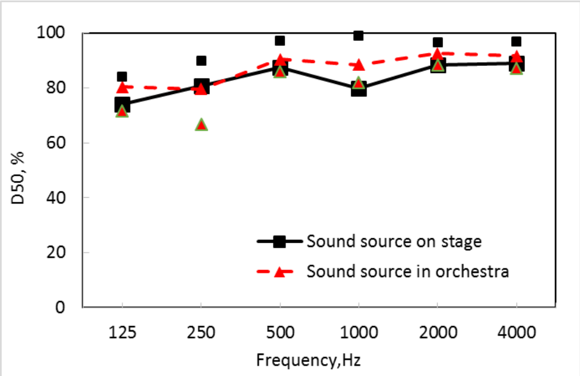
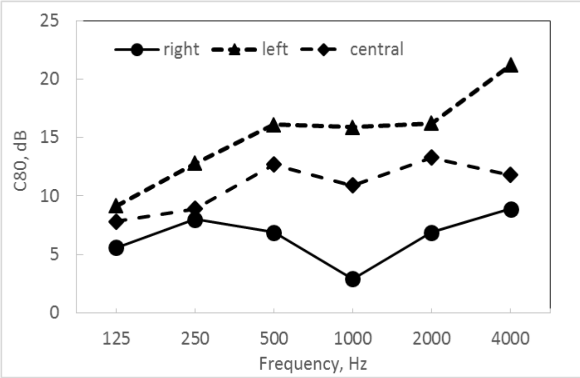
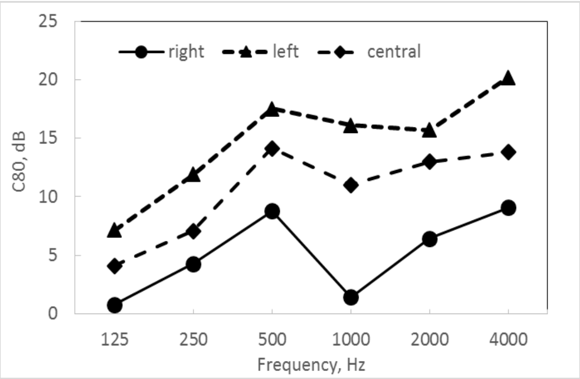


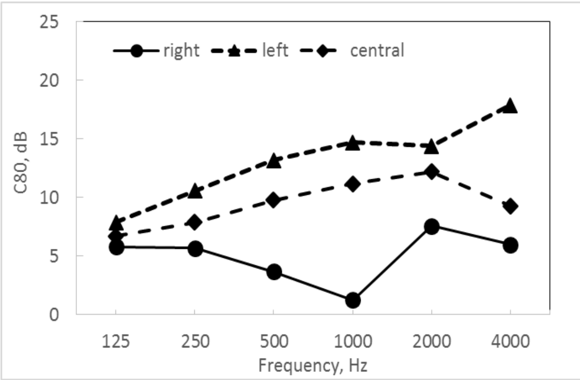
Figure 10 - Average measured values of D_{50} .



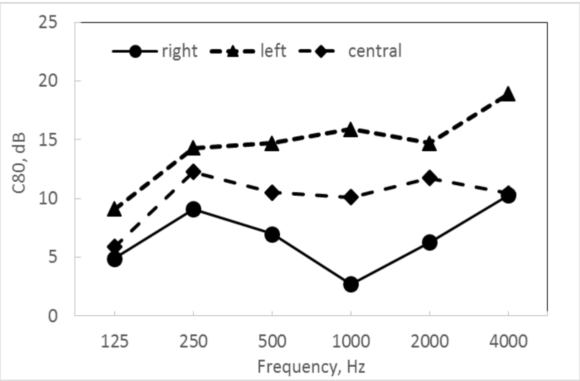
Figures 13 - C_{80} values for the eighth row.



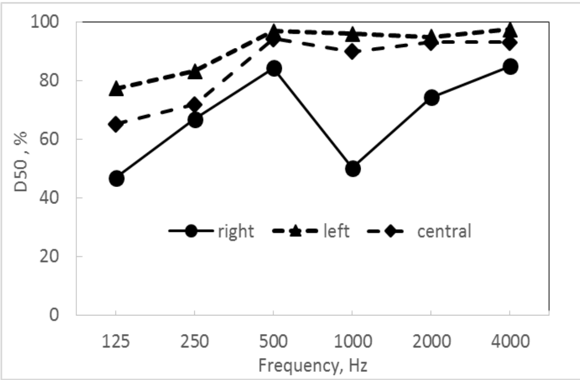
Figures 11 - C_{80} values for the first row.



Figures 14 - C_{80} values for the twelfth row.



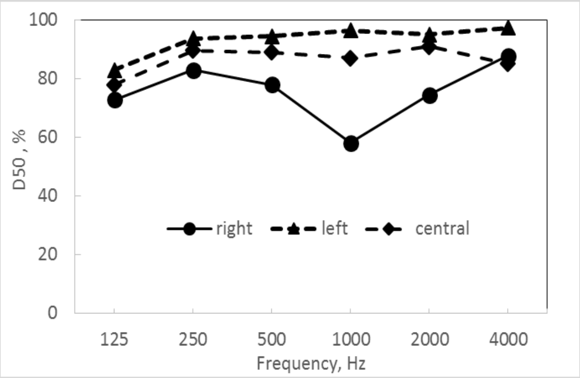
Figures 12 - C_{80} values for the fourth row.



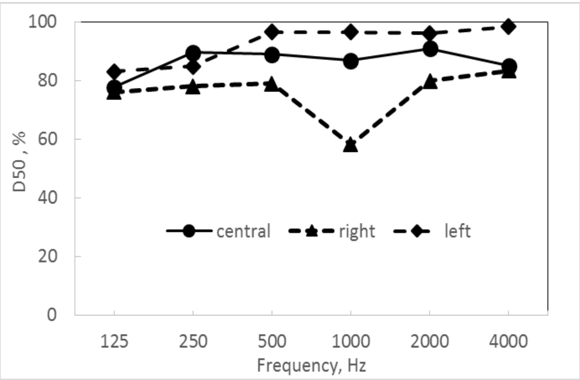
Figures 15 – D_{50} values for the first row.

With the source in the orchestra, the results of the reverberation time were slightly lower, but overall the acoustic parameters did not change significantly. Since the theatre is open, the change in the sound pressure level (Lp) with the distance from the source position is of particular importance.

For the position of the sound source on the stage, Figures 11, 12, 13 and 14 show respectively the C_{80} values measured for the first, fourth, eighth and twelfth rows. The C_{80} values are reported for each row and for three different directions. The measured values are based on 125 to 4 kHz octave bands, and are reported for the left, central and right rows.



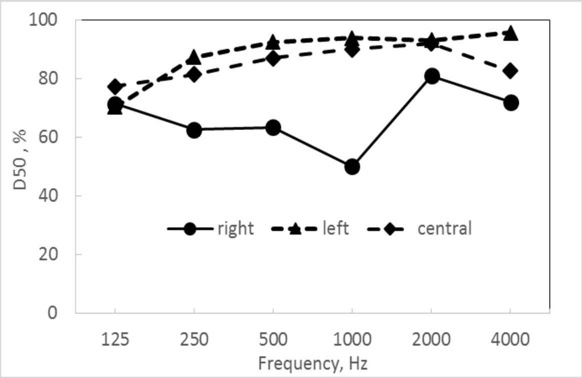
Figures 16 – D_{50} values for the fourth row.



Figures 17 – D_{50} values for the eighth row.

For the position of the sound source on the stage, Figures 15, 16, 17 and 18 show respectively the D_{50} values for the first, fourth, eighth and twelfth row respectively. The measured values are based on 125 to 4 kHz octave bands, and are reported for the left, central and right rows. D_{50} values measured for each row are different.

The D_{50} values are reported for each row and for three different directions. The C_{80} and In fact, the theatre, in its current configuration, does not have any symmetrical geometric structures, the walls of the stage are only partly reconstructed, and in the central area, there is no stage wall.



Figures 18 – D_{50} values for the twelfth row.

The cavea in the right area, compared to the stage, has not been rebuilt, and on the right upper part of the cavea is occupied by the church built in the Middle Ages, "*Santa Maria della Verità*". All these non-symmetrical surfaces help to obtain different values for each radial measurement direction. The D_{50} values are near to the unit value (good value for speech performances), while the C_{80} varies from 0 dB to 25 dB. Only the first row of the cavea area presents optimal listening conditions for music. The average values of STI =0.81 when sound source was on the pit and STI=0.84 when sound source was in the orchestra, This values confirm an high value for the direct sound components. The theatre nowadays is good for speech understanding, in fact the speech reception is very good throughout the huge audience area. Figure 19 shows the change of the sound pressure level (Lp) with the distance when the sound source is placed on the stage. The change in the sound pressure level along the right direction is lower than the other directions. While the change in the sound pressure level is greater along the left direction.

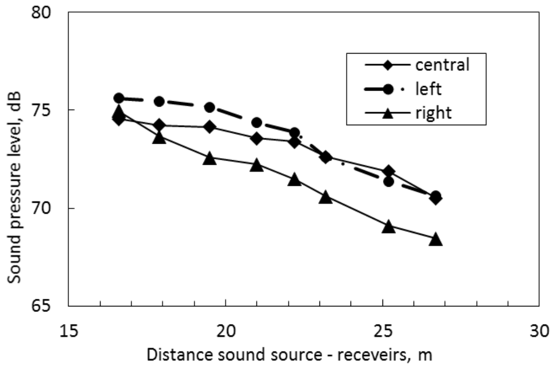


Figure 19 – Trend of sound pressure level with the distance when the sound source is placed on the stage.

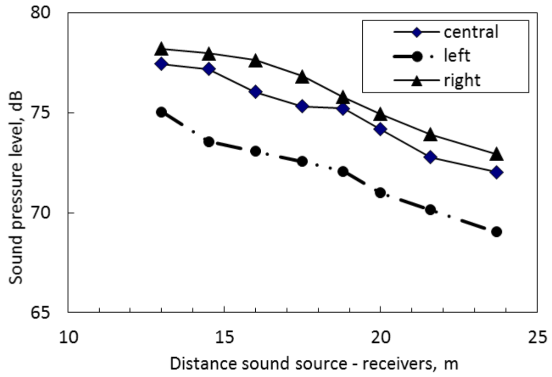


Figure 20 – Trend of sound pressure level with the distance when the sound source is placed in the orchestra.

When the sound source is placed in the orchestra, Figure 20, there is an inversion of the values of the sound pressure level (Lp). The change of the sound pressure level as the distance increases along the right direction is greater than the left direction. Moreover, in Figures 19 and 20, it can be noted how the change in the sound pressure level as the distance increases does not decrease in the average area of the cavea as expected but increases. This behaviour is due to sound reflections on the steps. In fact, in Figure 21, the impulse response trend is shown, with the sound source being on the stage and receiving microphone point on the octave step of the cavea (position at about halfway of the cavea). The impulse response is composed of a succession of reflections: the first due to the contribution of direct sound, the second due to reflection on the ground, while the latter are multiple reflections due to the presence of the steps that contribute to the reinforcement of the direct sound.

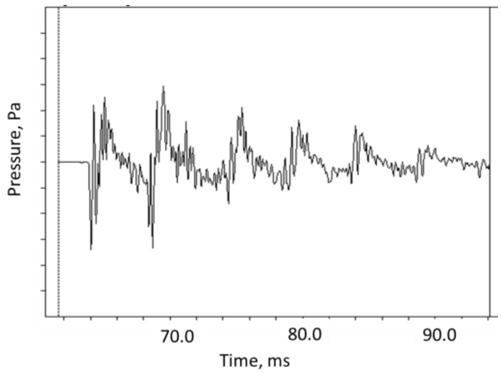


Figure 21 - Impulse response trend, with the sound source being on the stage and receiving microphone point in the cavea.

With the sound source on the orchestra, Figure 22 shows the value of sound pressure level (Lp) in dBA for six different microphone points in the cavea at the seventh step. The value of the sound pressure level (Lp) is higher on the right part of the cavea, while on the left part the sound pressure level (Lp) value is inferior.

The acoustic measurements confirm that the theatre is not symmetric, the levels on the right side of the cavea are greater than for the left. This is due to the contribution of the sound reflections of the exterior walls of the church built in the Middle Ages on the right side of the cavea.

4. Discussion

Regarding the extremely low measured average values of the reverberation time (Figure 7), it is possible to notice how due to the absence of the scene wall and therefore an important reflecting surface (the average measured time is 0.80 s, unlike the average times of the baroque theatres that are of 1.5 s).

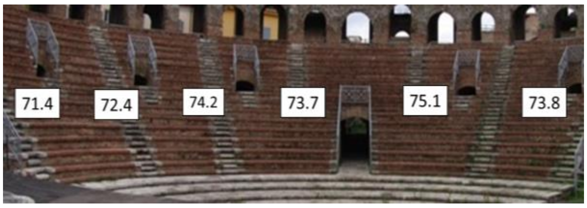


Figure 22. Sound pressure level (dBA) in the cavea, when sound source in the orchestra.

Observing the course of the average time, it is possible to note an increase of the frequency of 500 Hz. This increase is due to the reflections of the sound waves on the staircases that, for their dimensions (0.40 m of height and 0.70 m of depth), allow for a greater reflection of the sound just at the frequency of 500 Hz. The acoustic measurements have highlighted how the legendary "good acoustics" of the theatres of the Greek and Roman age were not due only to the absence of any background noises and the features of the building materials (strongly reflecting surfaces), but also to the layout of the staircases (12, 13, 14). These being of regular shape and set at a constant pace, react as spreading surfaces, and therefore contribute to a uniform propagation of the sound in the theatre, improving its acoustics. The EDT values are lower than those obtained from T_{30}, since the absence of reflective surfaces does not provide adequate values for this parameter, whereas the standard deviation values are higher than T_{30}, with this being due to the EDT measured values varying significantly from point to point. The average D_{50} values are near the unit value, with the theatre therefore having good acoustic characteristics for listening to speech.

5. Conclusions

Even if the Roman theatre of Benevento can be considered one of the largest and best preserved theatres of the imperial era existing in Italy, an analysis of the acoustic data found that, given the absence of significant reflective surfaces (part of the front wall of the stage has not been rebuilt), the reverberation times do not exceed 1s. The theatre does not have the wealth of reflections to give it good acoustics for musical representations. In the current configuration, it can be used optimally for prose and acting performances, but not for performing lyric or symphonic music. The optimum listening conditions for this configuration are the first rows of the cavea near the orchestra pit. For a better sound perception by listeners with singers and actors without amplification, such as lyricism, prose, and comedies, it would be desirable for the actors to stand in the orchestra pit and not on the stage, as is the case today. The proximity of the actors to the stairs upon which the audience sits, would allow for a better vision and understanding of what is being said. For better acoustic performance, it might be hypothesized to install PVC rigid panels at a height equal to that of the columns on the stage and cover part of the stage with a roof of the same size as the stage so as to recover the sound that would otherwise go scattered through the open space of the stage wall. The benefits of this solution can be assessed using a virtual model and the use of an architectural acoustics software.

References

[1] G.C. Izenour, *Theatre Design*, McGraw-Hill, New York (1977).

[2] M.P. Vitruvius, *De Architectura*.

[3] P. Ciancio Rossetto, G. P. Sartorio, *Teatri Greci e Romani: alle origini del linguaggio rappresentato censimento analitico*, Torino, Seat (1994).

[4] G. Iannace, A. Trematerra, "The rediscovery of Benevento Roman Theatre Acoustics", *Journal of Cultural Heritage* 15(6), pp. 698-703 (2014). DOI: 10.1016/j.culher.2013.11.012

[5] F. B. Sear, "The Scaenae Frons of the Theater of Pompey", *American J. of Archaeology* 97(4), pp. 687- 670 (1993).

[6] N. Savarese, *In scaena. Il teatro di Roma antica*, Electa 2007.

[7] V. de Martini, *Antonio Joli. Tra Napoli, Roma e Madrid. Le vedute, le rovine, i capricci, le scenografie teatrali*, Napoli, Edizioni Scientifiche Italiane, 2012.

[8] ISO 3382 (2012). *Acoustics - Measurement of room acoustic parameters*.

[9] G. Iannace, A. Trematerra, M. Masullo, "The large theatre of Pompeii: Acoustic evolution", *Building Acoustics* 30(3), pp. 215-227 (2013). DOI: 10.1260/1351-010X.20.3.215

[10] U. Berardi, G. Iannace, L. Maffei, "Virtual reconstruction of the historical acoustics of the Odeon of Pompeii". *Journal of Cultural Heritage,* 19, pp. 555 - 566 (2016). DOI: 10.1016/j.culher.2015.12.004

[11] T. Lokki, A. Southern, S. Siltanen, L. Savioja, "Acoustics of Epidaurus – Studies With Room Acoustics Modelling Methods" *Acta Acustica united with Acustica* 99, pp. 40 – 47 (2013). DOI 10.3813/AAA.918586

[12] N. F. Declercq, C. S. A. Dekeyser, "Acoustic diffraction effects at the Hellenistic amphitheater of Epidaurus: Seat rows responsible for the marvelous acoustics" *J. Acoust. Soc. Am.* 121 (4), pp. 2011 - 2022 (2007)

[13] T. Lokki, A. Southern, S. Siltanen, L. Savioja, STUDIES OF EPIDAURUS WITH A HYBRID ROOM ACOUSTICS MODELLING METHOD. *Proc. of The Acoustics of Ancient Theatres Conference Patras,* September 18-21, 2011

[14] R. S. Shankland, "Acoustics of Greek theatres", *Physics Today* 26, pp. 30–35 (1973)