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The Roman theatre of Benevento: reconstruction of sound propagation with a multichannel microphone

Antonella Bevilacqua
Department of Industrial Engineering,
University of Parma
Area delle Scienze, Parma, Italy
antonella.bevilacqua@unipr.it
orcid 0000-0002-5938-9749

Francesca Merli
Department of Architecture,
University of Bologna
Bologna, Italy
francesca.merli8@unibo.it

Lamberto Tronchin
Department of Architecture,
University of Bologna
Bologna, Italy
lamberto.tronchin@unibo.it

Gino Iannace
Department of Architectur and
Industrial Design
University of Campania “Vanvitelli”
Aversa, Italy
gino.iannace@unicampania.it

Abstract—The open-air theatre of Benevento is one of the few theatres built during the Imperial Age of the Roman Empire. Different acoustic studies have been undertaken on this cultural heritage throughout the centuries, but this paper deals with an alternative way of data representation: a visual video overlay showing the sound reflections hitting the steps of the *cavea* has been considered an added value to the acoustic parameters represented on graphs. Fortunately, during the 20th century, the archaeological excavations of the area brought to light the ancient monument that was buried under residential constructions built thereafter. Similarly, historical background and architectural features based on archaeological information have been briefly outlined. The acoustic reflections mentioned by Vitruvius are herein visible to be understood with the shots taken from the video of the impulse response (IR).

Keywords—Roman theatre, acoustic measurements, cultural heritage, acoustic parameters, spherical array microphone.

I. INTRODUCTION

The shape of the Roman theatre of Benevento has been covered by late constructions realized in the same area from its layoff, occurred with the advent of Christianity, to the 20th century. A survey undertaken in the archaeological site by employing a new generation of equipment allowed the authors to complete the understanding of the acoustic behavior of such unique place. As such, the characterization of the acoustic parameters acquired in line with the standard regulation ISO 3382-1 have been fulfilled with the visual analysis of the sound rays' reflections. This alternative and annexed methodology has been possible to be created by the utilization of a spherical arrays microphone. The multichannel receiver, equipped with 32 transducers, allowed the elaboration of 32 sound signals by generating a video overlay of the IR as output data. A few shots of the video have been herein introduced in order to show the reflections existing inside the Roman theatre that have been compared with the theory outlined by Vitruvius.

II. HISTORICAL BACKGROUND

The Roman theatre of Benevento has been built during the 2nd century AC [1]. It reflected all the architectural parameters outlined by M.P[2]. Vitruvius in order to accomplish the

visual and listening parameters of a show space [2]. The theatre was the center of the artistic performance, but with the barbaric invasions and the development of Christianity during the 4th century AC, the theatre fell in disuse [3]. Furthermore, natural events (e.g. earthquakes) contributed to damage the construction until when all the citizens forgot about the theatre because of residential properties built on top of the radial walls [4]. Still in 18th century extraneous constructions continued to be built in the same area; an example is the church of Madonna della Verità, which is the only building left after the archaeological excavations. Unfortunately, all the development throughout the time compromised the demolition of the scenic building and of the orchestra floor, that were partially restored later on [4].

The architect A. Meomartini was the first scholar having the intention of giving light to the original shape of the Roman theatre by demolishing all the private properties built upon it [1][5]. The initial intervention happened in 1920, followed by a second campaign of excavation occurred between 1934-38 and led by A. Zazo. In 1950 all the was acquired by the city council that promoted the rebuilding of the *ima cavea* and the *vomitioria* [1]. What is left from the scenic building and the *summa cavea* has been partially reconstructed [5].

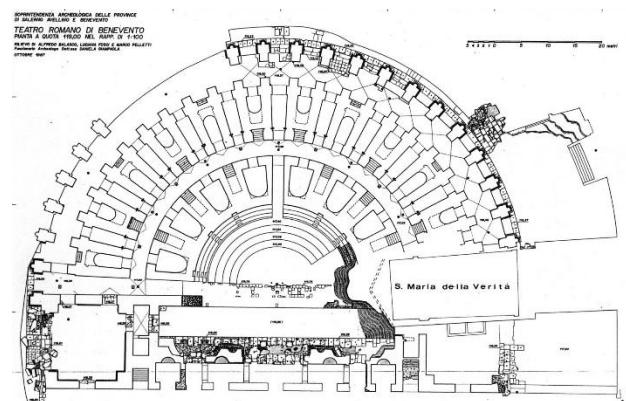


Fig. 1. Plan layout of the Roman theatre of Benevento.

III. ARCHITECTURAL CHARACTERISTICS

The theatre of Benevento is composed of 25 arcades built on three levels. The radius of the *cavea* is 40 m related to the maximum dimension and 10 m corresponding to the radius of the orchestra [4].

The scenic building survived in few parts, but these indications are considered not enough to be assuming that the *scenae* was composed of two orders of columns. What is known is the number of openings, organized in one to be central and the other two laterals. The scenic building should be 3.5 m wide and 44.2 m long [4][6].

The *cavea* should be divided into two sectors: the *ima cavea* should have originally 15 steps, with the addition of 4 steps around the orchestra, dedicated to the aristocracy, and the *summa cavea* composed of 8 steps. The separation between the two sectors was given by a corridor (*praecinctio*) interconnected with the staircase systems that gave access to the public. At the coronation of the *cavea* an ambulatory (*ambulacrum*) composed of niches placed in correspondence of each arch, should be representing the external construction element at the perimeter of the theatre [4]. Fig. 2 shows the existing conditions of the theatre.



Fig. 2. View of the Roman theatre of Benevento.

The presence of the *velarium* is not confirmed by any archaeological ruins [6]. One hypothesis might be referring to the mounting only during the summer seasons [7].

Table 1 summarizes the architectural features of the Roman theatre of Benevento.

TABLE I. ARCHITECTURAL CHARACTERISTICS OF THE ROMAN THEATRE OF VERONA AT THE ORIGINS

Description	Features
Total capacity (No. of seats)	1500
Number of steps in <i>ima cavea</i>	15
Number of steps in <i>summa cavea</i>	8
Number of horizontal corridors (<i>praecinctio</i>)	1
Stage dimension (m) [L × W]	44.2 × 3.5
Presence of <i>velarium</i>	Only during summer season
<i>Cavea</i> volume (m ³)	13190
Scenic building volume (m ³)	1900
Total volume (m ³)	15090

IV. MEASUREMENTS

An acoustic survey has been undertaken to understand the behavior of the existing conditions of the uncomplete volume

of the Roman theatre of Benevento. The analysis of the objective acoustic parameters has been done in accordance with the standard requirements given by ISO 3382-1 [8]. The acoustic survey was carried out with the following equipment:

- Equalised omnidirectional loudspeaker (Look Line);
- Microphones:
 - a) Binaural dummy head (Neumann KU-100);
 - b) B-Format (Sennheiser Ambeo);
 - c) Omnidirectional microphone (Bruel&Kjaer);
- Personal Computer connected to the loudspeaker and all the receivers.

The sound source was placed at the center of the *scaene frons* at a height of 1.4 m from the relative finished floor. The receivers were installed at the height of 1.2 m, in 8 positions across the *cavea*. The excitation signal emitted by the sound source was the Exponential Sine Sweep (ESS) having a duration of 15 s in a uniform sound pressure level for the range between 40 Hz and 20 kHz [9][9].

The measurements were undertaken in unoccupied conditions. Fig. 3 shows the measurement positions of the sound source and the receivers across the *cavea*.

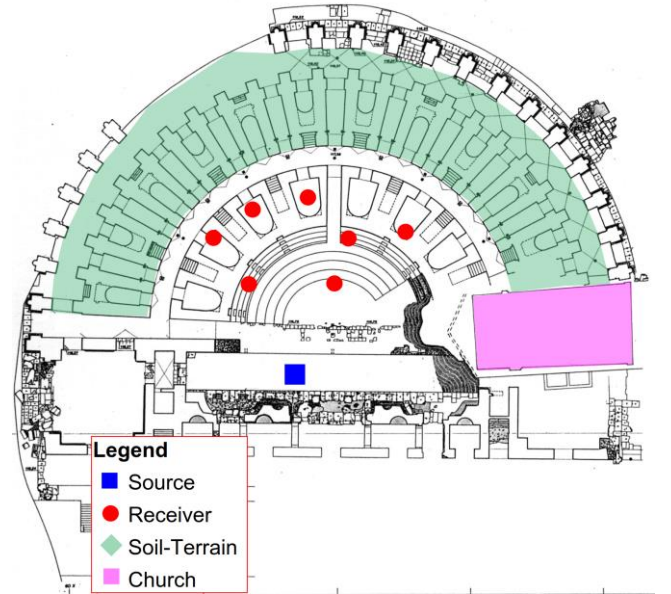


Fig. 3. Scheme of the equipment positions during the acoustic measurements in Benevento.

V. RESULTS

A. Acoustic parameters

By processing the ESS signal with the plugin Aurora for Audition 3.0 [10], different acoustic parameters have been analyzed, including the reverberation time (T_{20}), early decay time (EDT), clarity indexes (C_{80} and C_{50}), and definition (D_{50}). The graphs of the main acoustic parameters are reported in function of the frequency bands between 125 Hz and 4 kHz, considered as the average results of all the measurement positions [11]. The graphs shown in Fig. 4 to Fig. 6 represent the averaged values of all the receivers' positions.

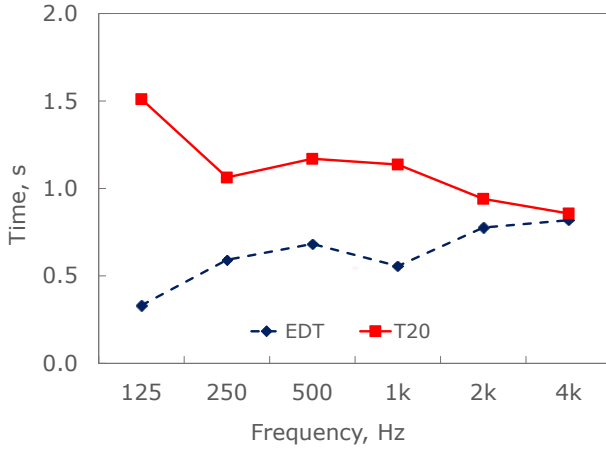


Fig. 4. Measured results of Early Decay Time (EDT) and Reverberation Time (T_{20}).

Given the morphological configuration of the existing conditions of the theatre, lacking in most important constructions like the scenic building, the EDT parameter averaged to 0.8 s across all the selected spectrum, as shown in Fig. 4, is mainly due to the absence of the scenic building that would be representing a favorable surface for the early reflections [12].

In terms of reverberation time, Fig. 4 indicates an averaged value of T_{20} close to 1.1 s. The presence of bricks instead of marble finishes on the seats of the *cavea*, the reduced volume due to lack of the *summa cavea* covered by soil and the incompleteness of the ambulatory contribute altogether to the outcome value. This result is considered very good to be an open-air theatre [13], whereas usually this is found inside any closed performing arts space of similar volume size.

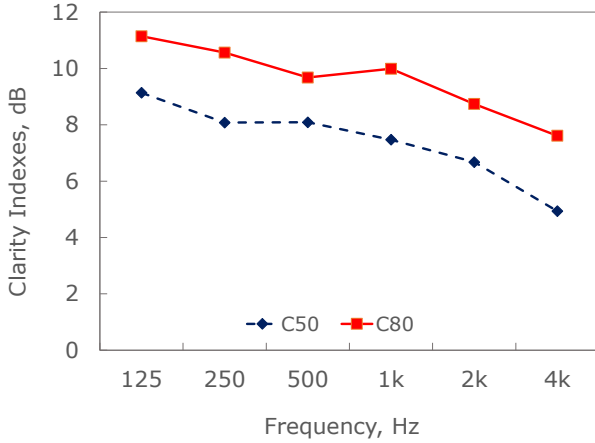


Fig. 5. Measured results of clarity indexes (C_{50} and C_{80}).

Fig. 5 shows that the speech clarity index (C_{50}) falls into the good target as defined by literature (i.e. ≥ 3 dB) [14]. This means that the prose performance is well perceived by the listeners, related to both male and female voices.

In terms of music (C_{80}), the outcomes ranging around 9 dB across all the frequency spectrum may be resulting too far from the upper range limit outlined by literature [15]. Translated in other words, this outcome means that the music would be very clear, especially at low frequencies.

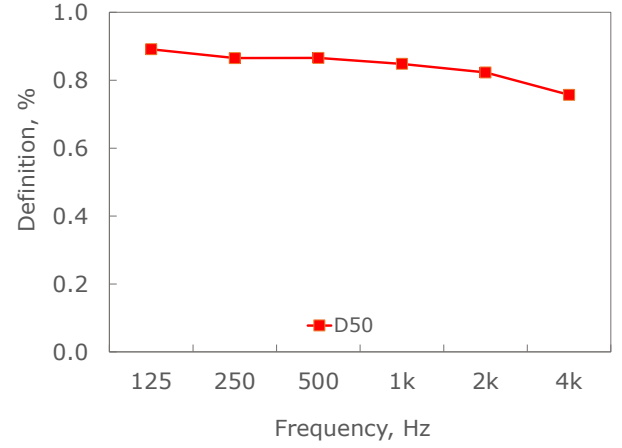


Fig. 6. Measured results of Definition (D_{50}).

Fig. 6 indicates a D_{50} around 0.9 (i.e. 90%) as the averaged value across all the spectrum. This outcome means that the overall acoustics of the Roman theatre of Benevento is more suitable for speech performance than musical shows [16].

B. Acoustic analysis of 3D sound maps

The employment of the spherical array microphone (i.e. em32 Eigenmike®) for the acoustic measurements allowed the elaboration of sound maps obtained for each source-receiver combination [17]. These maps have been created by shooting some moments of the video flowing the recorded IR.

This different approach in evaluating the data analysis process is obtained by a combination of the multichannel microphone with the panoramic camera (i.e. Rico Teta V, capturing a 360° image herein represented in an equirectangular view). The 32 microphone signals have been processed by extracting 122 high directivity virtual microphones with the addition of the Spatial PCM Sampling (SPS). Thereafter, it was possible to detect the direction of arrival of the sound rays as they were captured from every direction by the microphone.

The colors shown in the map overlay indicate a high level of sound energy, given in red tinge, and poor energy sound wave represented in blue-violet shades. Fig. 7 shows an illustration of the direct sound.

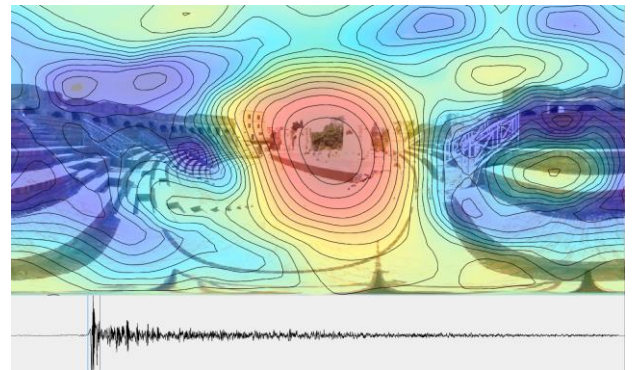


Fig. 7. Acoustical map showing the direct sound arriving to the receiver placed in the *ima cavea*.

The strong sound energy of the direct ray has been captured by Fig. 7, where it is possible to detect the sound source placed onto the *scenae* level.

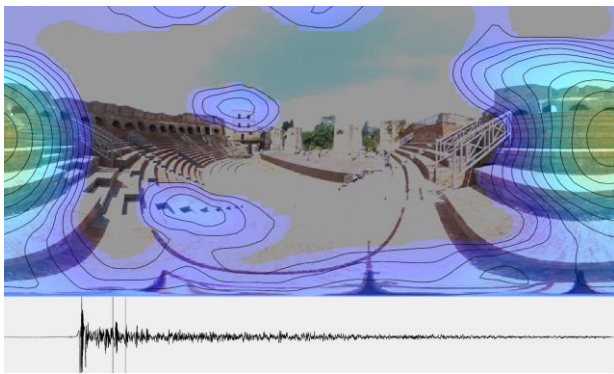


Fig. 8. Acoustical map showing the reflections moving upwards onto the steps.

Fig. 8 shows the early reflection moving upwards onto the steps of the *ima cavea* as the steps are the only reflecting surface that the sound can hit.

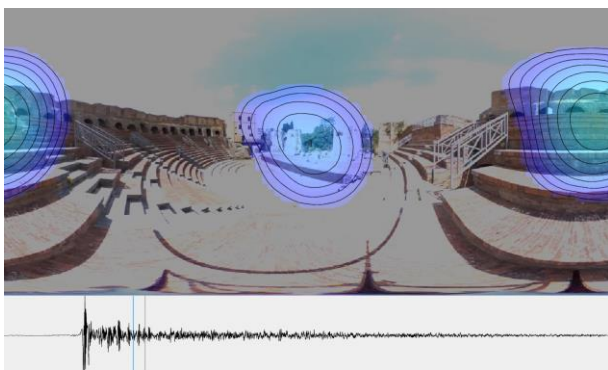


Fig. 9. Acoustical map showing the late reflections at the center of the equirectangular view.

A few milliseconds after the previous shot, as it is possible to see in the bar at the bottom of the picture, Fig. 9 shows the presence of an echo recognized as a late reflection [18]. This reflects the so-called *circumsonant* sound as defined by the Vitruvium calling what actually the acousticians nominate a focusing effect due to a concave surface [2][13].

VI. CONCLUSIONS

This paper deals with the acoustic behavior of the Roman theatre of Benevento after the last restoration works undertaken in 2018 and by using the last generation of equipment.

The reconstruction of the existing architectural features has been made by the analysis of historical documents related to archaeological discoveries, natural and human disasters, to be included the restoration works started during the 20th century.

Based on a traditional approach reflecting the graphs of the main acoustic parameters, the overall acoustics of the Roman theatre of Benevento is more suitable for prose than musical

performance. However, the outcomes match the targets set for unroofed theatres and having similar lacks in construction elements (e.g. partial erection of the scenic building and of the *ambulacrum*, the missing *summa cavea*, etc.).

The analysis of the 3d maps shows the direction of arrival of the sound rays. As such, some shots taken from the video-overlay elaborated from the 32 microphone signals focus on the direct sound, on the early and late reflections obtained by the IR. This innovative approach completes the understanding of the acoustic behavior of a performance arts space.

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