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ACOUSTICS OF THE ROMAN AMPHITHEATRE IN SALONA

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ABSTRACT

Salona was the capital of the Roman province of Dalmatia and, as an important city, had an amphitheatre. Today, in Salona, remains of an ancient Roman amphitheatre exist, in the form of foundations, walls and some arches on the ground floor. To analyze the acoustical properties of Salona's amphitheatre, we made the 3D model, according to the reconstruction provided by the archaeologists. We then performed the acoustic simulation of the amphitheatre to explore its acoustical properties. We performed the simulation using geometrical simulation based on the hybrid image source/ray tracing method. In this paper we present the results of the simulation and discuss them. We analyse the influence of the audience and the velarium on the acoustic properties of the amphitheatre.

Keywords: *acoustic simulation, geometrical simulation, ancient amphitheatre*

1. INTRODUCTION

Today, the biggest sporting events such as football matches take place in stadiums which are designed after Roman amphitheatres. The acoustics do not play as important role in Roman amphitheatres as in Roman and Greek theatres, but it is still an important part in the overall atmosphere and the impression of an event. In [1] authors identify 744 ancient theatres, of which four are in Croatia [2]. According to [3] there were at least 230 Roman amphitheatres scattered around the empire. In Croatia until present time there are identified four of them [4] - the first one in Pula, which is among the best preserved in the world; the second one in Zadar, which is known form historic documents; the third one in Burnum, which was inside a legionaries camp; and the fourth in Salona, which is the subject of this research. Today, in Salona, remains of an ancient Roman amphitheatre exist, in the form of foundations, walls and some arches on the ground floor (Fig. 15).

This paper presents the reconstruction and acoustical simulation of the Roman amphitheatre in Salona. The second chapter presents the previous work in this field, the third one the reconstruction and the modeling of the amphitheatre, and the fourth results of the acoustical simulation.

2. PREVIOUS WORK ON ANCIENT AMPHITHEATRES

The foundations for design of ancient theatres gave Vitruvius in his fifth book [5]. The amphitheatre of Pompei was built in the suburban area between 75. and 70. B.C. It was built like the amphitheatre of Salona on an existing embankment, and had dimensions of 131 m x 102 m with capacity of 20.000 spectators. Bevilacqua [6] analyzed the acoustic characteristics of the amphitheatre of Pompei in an innovative manner using spherical microphone array. The acoustic measurement made with spherical microphone array was visualized and superimposed on spherical video, which enabled to clearly detect from where the reflections of the sound came to the receiver. The main source of the reflections were the stone seats in *cavea*.

Berardi in [7] brings the measurements and simulation of the Roman amphitheatre of Avella, which is parti-

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ally reconstructed. It was built in the 1st century B.C. on top of existing structural walls, with dimensions comparable to the amphitheatre of Pompei. The sound source was situated in the arena, and receivers were scattered over the arena and *cavea*. Measurement results showed significantly better C_{80} and D_{50} values for cavea than arena, caused by the strong reflections from the high wall surrounding the arena. The authors did also the simulation of the reconstructed arena using the Ramsete software and 2 orders of reflections. The simulation produced the acoustical maps showing that T_{30} at 1kHz was around 3.5s for the whole arena when simulated without the audience. With audience it was 0.9s in the arena and 1.5s in the *cavea*. Acoustic map for male voice STI showed that without audience values were fair, fluctuating around 0.6, while with the audience they were good - above 0.6 for the whole amphitheatre.

Iannace in [8] brings the measurement and simulation of the Roman amphitheatre located in Santa Maria Capua Vetere, built between 133. and 83. B.C. Amphitheatre is only partially saved, with most integral sectors on northern and southern side. The measurements were made to calibrate the simulation which was then used for the design of a new stage. Amphitheatre originally had capacity of 50.000 spectators, and dimensions of of $170\,\mathrm{m}$ x $140\,\mathrm{m}$. Two sound sources were positioned at the height of $1.3\,\mathrm{m}$ inside the arena, along the main axis. Receivers were scattered over the arena and *cavea*. Measurements showed that reverberation time T_{30} was around 2s, speech clarity C_{50} was between -2dB to 2dB, which is below the optimal values, and music clarity C_{80} was high, around 6dB. Definition D_{50} was around 40%. All these values show that if used today it would be best suitable for music performance.

Roman theatres and amphitheatres used *velaria* or awnings to protect spectators from the sun and the heat. The evidence for this are mainly provisions for mounting of wooden masts on which the *velaria* were suspended, found on many still standing theatres and amphitheatres. In Pompei there exists a mural painting of the amphitheatre of Pompei with an awning. Pliny reported that for awnings linen clothes were used. Authors in [9] have performed computer simulation of the theatres of Pompei and Benevento with and without awnings. They inspected the acoustic influence of linen cloth for *velaria* with different density - ranging from $0.5\,\mathrm{kg\,m^{-2}}$ to $2\,\mathrm{kg\,m^{-2}}$. For such cloth they calculated the frequency dependant absorption coefficients which on the low frequency are equal to total absorption, and decrease at 500 Hz and above. The simulation of both theatres of Pompei and Benevento clearly shows the increase of the reverberation time on higher frequencies in the case when *velaria* are present.

In [10, 11] authors present the analysis of the influence of *velarium* to the theatre of Verona. They measured the acoustics of the existing remains of the theatre, which doesn't have *velarium*. They then made a digital model and using the measurements calibrated the simulation parameters of absorption and scattering. Finally they created the model of the original shape of the theatre with the velarium and performed the simulation. Results showed that EDT of the original shape with velarium was between $1.8\,\mathrm{s}$ and $2.6\,\mathrm{s}$, while nowadays it is around $0.5\,\mathrm{s}$. The existing T_{30} is around 1s, while original values were much higher, from $4\,\mathrm{s}$ on low frequencies to $2\,\mathrm{s}$ on high frequencies.

3. ROMAN AMPHITHEATRE OF SALONA

3.1 Historical Background of Salona

Colonia Martia Iulia Salona was the capital of the roman province of Dalmatia. It was situated at the end of a well-protected bay, beside the estuary of the river Salon [2]. Salona was founded in 3rd century BC by the Greeks and became Roman after their conquest of Dalmatia. In the peak of its expansion, it reached over 60 000 inhabitants. The city consisted of the old city - *Urbs vetus*, and the new city which spanned to the east - *Urbs orientalis* and to the west - *Urbs occidentalis*. The amphitheatre (marked in red in Fig. 1) was build in the western part of the city.

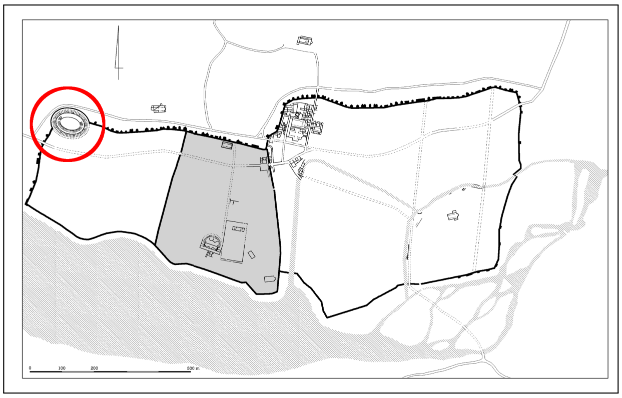

Figure 1. Three parts of Salona, with the position of the amphitheatre marked in red.

3.2 Architectural Features of Salona

The research of Salona started Ivan Luka Garagnin 1805, followed by Frane Carrara in the middle of 20th century [12], and he excavates the eastern entrance to the amphitheatre and some arches of the *cavea* substructures. Famous archaeologist don Frane Bulić has bought the land on which amphitheatre is situated, and continued to excavate. Danish archaeologist Ejnar Dyggve has analyzed all previous excavations and published the results in a famous publication [13]. Franko Oreb in 1981. excavates the center of the arena, and Josipa Ružić discovers the southwestern part of the building and the west gate.

The time when the amphitheatre was built is still under dispute - Dyggve in [13] stated that it was build in the second century A.D. but recent findings show that it was probably built during the dynasty of Flavievs between 70.-96. A.D. [14]. The amphitheatre was first situated outside the city walls, but during the raids of Markomans and Quads in the second part of the second century A.D. it was incorporated in the new city walls. The outer arcade in the northwestern part of the amphitheatre was removed, and in their place the massive fortified wall was built, that was connected to the rest of the fortification ring (Fig. 2).

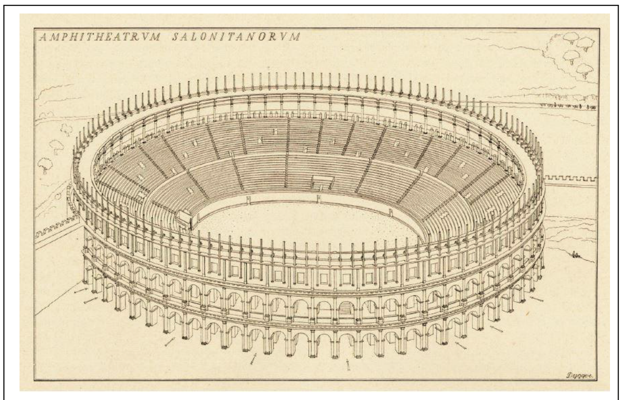

Figure 2. The reconstructions of the amphitheatre incorporated in the city walls, by Ejnar Dyggve [13].

The amphitheatre of Salona was 126 m long and 102 m wide. The long axis of the amphitheatre had the east-west direction, with an angular shift of 4 degrees. The dimensions of the arena were 65 m by 40 m, and the *cavea* was raised 2.4 m from the level of the arena. The *cavea* started with a corridor 1.5 m wide. The lower two parts of the *cavea* were seated, with seats 0.7 m wide and 0.4 m high. The seated parts of the *cavea* were divided by a corridor 1 m wide. The third part of *cavea* was a gallery for standing spectators, 6.3 m wide and 5.5 m tall. All over the *cavea* there were 48 entrances to the *vomitoria*, that were 2.1 m tall and 1.5 m wide. It is estimated that the amphitheatre had capacity of 17.000 spectators.

The outer facade of the amphitheatre was divided in three tiers, two of them with arches and the third one with rectangular openings. Amphitheatre was in function till the sixth century, and after that was used as a fortress. In 1647. the Venetian governor of Dalmatia ordered its destruction in order to prevent the Turks from using it as a fortress.

4. RECONSTRUCTION AND SIMULATION OF AMPHITHEATRE

4.1 Modelling of amphitheatre

Ejnar Dyggve in his publication [13] presented reconstruction of the amphitheatre in the form of perspective, floor plan and several cross sections. We first georeferenced the Dyggve's floor plan to the areal photo [15] in GIS system, and proportionately sized the cross sections. From the floor plan and the cross sections we extracted the amphitheatre dimensions presented in the previous section. We then created the 3D model of the theatre in SketchUp software (Fig. 3).

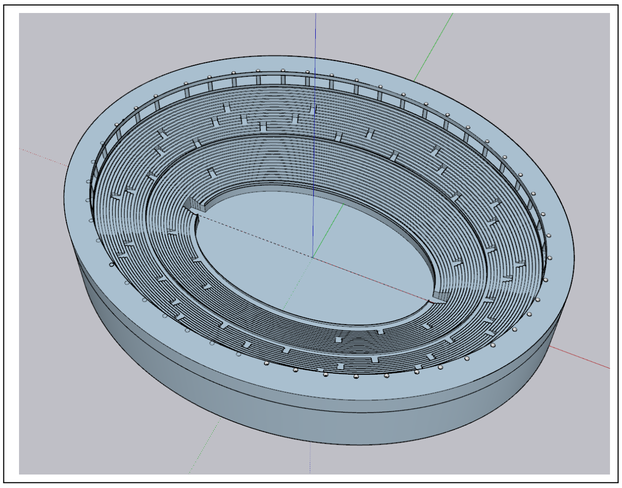

Figure 3. Model of amphitheatre of Salona.

4.2 Simulation of amphitheatre

The simulation of the amphitheatre was performed in Odeon software version 14.05 [16]. Odeon uses geometric simulation techniques of ray-tracing and image sources to perform simulation of specular and diffuse reflections and the diffraction of sound. We exported the model of the amphitheatre from Sketchup to Odeon using the SU2Odeon extension. We set the materials for the model according to Dyggve's reconstruction [13], and simulations of similar amphitheatres [6–11]. The acoustical properties of used materials are presented in Tab. 1.

Table 1. Materials used in simulation.

	Abs.						*Scat.*
f[Hz]	**125**	**250**	**500**	**1k**	**2k**	**4k**	
Stone I	0.01	0.01	0.01	0.01	0.02	0.02	*0.6*
Stone II	0.01	0.01	0.01	0.01	0.02	0.02	*0.8*
Audience	0.51	0.64	0.75	0.8	0.82	0.83	*0.6*
Sand	0.15	0.35	0.40	0.50	0.55	0.80	*0.4*
Awning	1.00	1.00	0.16	0.04	0.01	0.01	*0.4*

We defined two stone materials, based on the Odeon's marble material. The *Stone I* material was used for seats and gallery and we set the scattering coefficient for this material to 0.6. The *Stone II* material was used for walls that were in front of the corridors in *cavea*, and the front of the gallery, and we set its scattering coefficient to 0.8, since Dyggve presumed they were decorated with stone ornaments. The *Audience* material was assigned to the *cavea* when it was full of spectators. We used the Odeon's audience material with the lowest absorption, because the seats were made of stone. To the arena we assigned the Odeon's sand material, with 0,4 scattering. We also created the virtual roof on the top of the theatre and assigned to it 100% absorption to simulate the open roof. The same absorption was assigned to all doors in the theatre. In the case when we simulated the *velarium* we assigned to it the *Awning* material, as a heavy awning textile material ($1\,\mathrm{kg\,m^{-2}}$) [9]. In simulation, air conditions were set according to ISO standard [17] - temperature of 20°C, and relative humidity of 50%.

The positions of sources and receivers are shown in Fig. 4. We created two sources inside the arena (shown in red), at the height of $1.5\,\mathrm{m}$ above the surface of the arena. The source P1 was positioned at the intersection of the major and minor axis of the ellipse and the source P2 was near the rim of the arena. Six receivers were positioned in the *cavea* (shown in blue), two in the lower part of the *cavea*, two in the upper part of the *cavea*, and two in the gallery. The height of the receivers was $0.8\,\mathrm{m}$ above the seat for the first four (seating) receivers, and $1.5\,\mathrm{m}$ for two (standing) receivers in the gallery. Because of the symmetry of the elliptical plan of the amphitheatre, we covered only one quadrant with receivers.

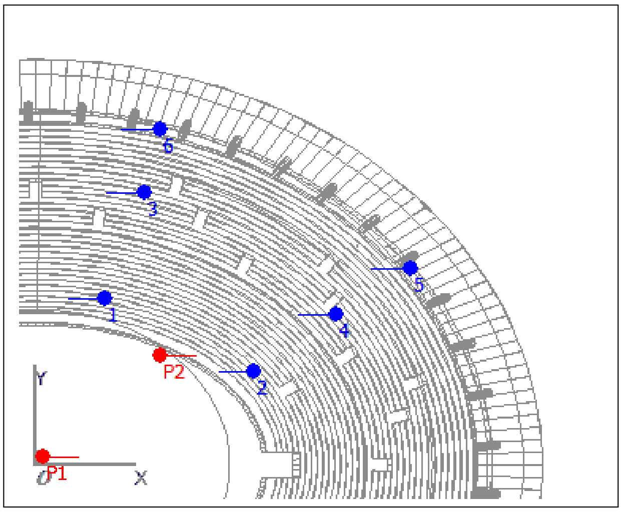

Figure 4. Position of sources (red) and receivers (blue) for the simulation of amphitheatre of Salona.

In the Odeon software we set the "precision" parameters, with impulse response length of 2000 ms, 432 720 late rays, max reflection order of 10 000, transition order of early reflection set to 2, 100 early scattered rays per image source, and with screen diffraction turned on. We performed the simulations of the amphitheatre of Salona with three configurations:

- configuration 1 (C1) corresponded to the amphitheatre without audience and without *velarium*
- configuration 2 (C2) corresponded to the amphitheatre with full audience and without *velarium*
- configuration 3 (C1) corresponded to the amphitheatre with full audience and with *velarium*

4.3 Results and discussion

4.3.1 Influence of the audience

We first present the simulation results for source P1, with and without the audience. This simulation was performed

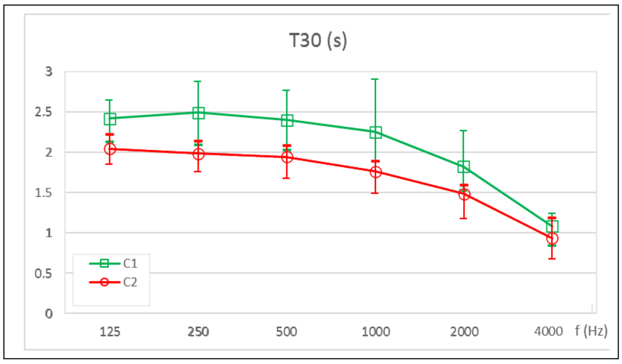

Figure 5. Reverberation time, with (C2) and without (C1) audience. Results are for source S1, without *velarium*.

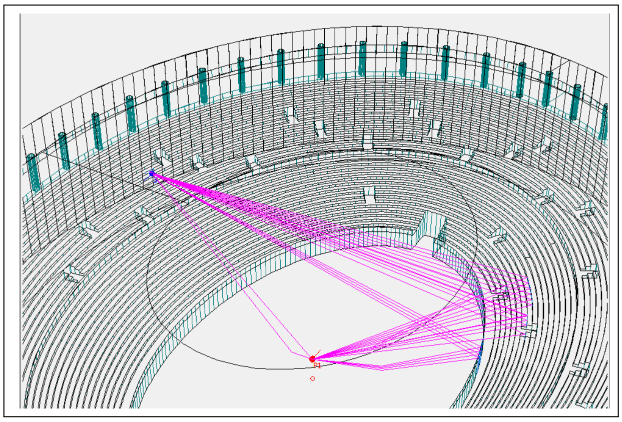

Figure 6. Sound rays up to second order of reflection.

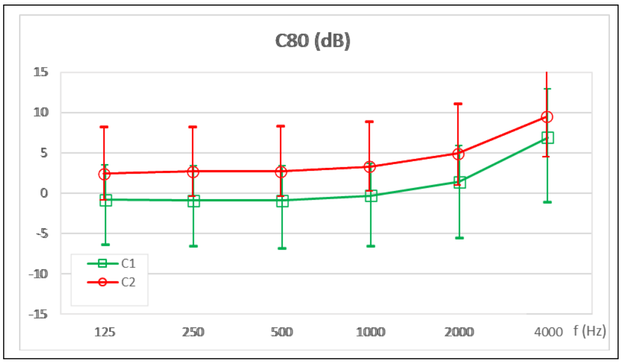

Figure 7. Clarity, with (C2) and without (C1) audience.

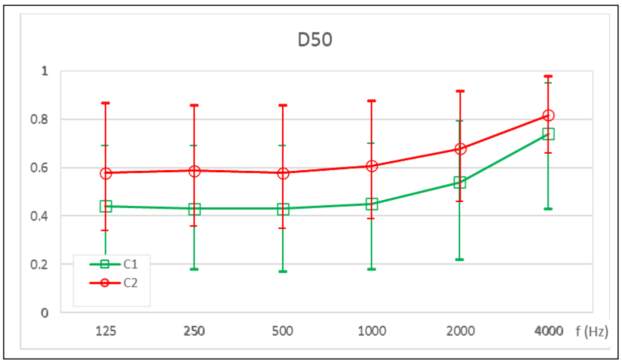

Figure 8. Definition, with (C2) and without (C1) audience.

without *velarium*. Results are presented in octave bands, with region ±1 JND shown with dashed lines. Reverberation time T_{30} (Fig. 5) for empty audience (C1 – green line) is around 2.5 s for lower frequencies, and decreases towards 1 s for high frequencies. When the amphitheatre is full of audience (C2 – red line) reverberation time is around 2 s on lower frequencies, about half a second lower due to the audience absorption.

If we analyse the rays of sound produced by the simulation (Fig. 6) we can see that shortly after the direct sound comes the first reflection from the sand floor of the arena. Besides this reflection, there is a strong focusing effect of second reflections coming from the opposite arena wall and seats in the *cavea*.

On lower frequencies clarity C_{80} (Fig. 7) is around 0 dB without an audience, and 2.5 dB with a full audience. As expected it increases on higher frequencies. According to this values such an amphitheatre would suit well for performances of operas, as is the case with the famous amphitheatre of Verona which is today one of the best venues for opera performances in the world. Definition D_{50} (Fig. 8) is around 45% for empty and 60% for the full audience, except on higher frequencies where its value increases.

We compared these results with the measurements of the remains of the existing amphitheatres (Fig. 9) in Santa Maria Capua Vetere [8] and Avella [7]. In the first amphitheatre the reverberation time T_{30} on 1kHz is 0.3 s lower than in our simulation and in the second amphitheatre it is one 1 s lower. The cause for this discrepancy is the fact that the measured amphitheatres are not well preserved which is especially the case for the second one, where only earth remains exist, without any stone cover. The

Figure 9. The remains of the existing amphitheatres in Santa Maria Capua Vetere (left) and Avella (right).

clarity C_{80} is for the first theatre 5 dB and for the second 10 dB vs. 4 dB in our case. The definition D_{50} is for the first theatre 40% and for the second one 90% vs. 45% in our case.

4.3.2 Influence of the velarium

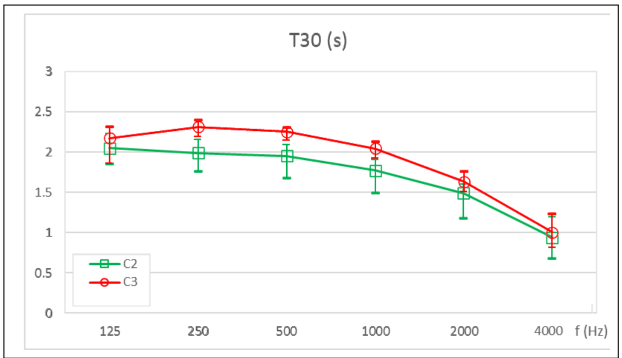

Figure 10. Reverberation time, with (C2) and without (C1) *velarium*. Results are for source S1, with audience.

Next, we explored the influence of the *velarium* on the acoustics of the amphitheatre. We defined the *velarium* as an elliptic ring with the hole in the middle (major axis 24 m, minor axis 19.3 m), and assigned it *Awning* material from Tab. 1. The results clearly show that *velarium* did have an influence on the acoustics of the amphitheatre. With *velarium*, reverberation time T_{30} (Fig. 10) increased ba about 0.3 s in the middle frequencies. On the lowest frequencies the influence of the *velarium* is negligible due to its total absorption, and on the high frequencies it is lower due to the higher air absorption. The clarity C_{80} (Fig. 11) with *velarium* is lower about 3 dB because of the late reflections. Definition D_{50} (Fig. 12) is decreased

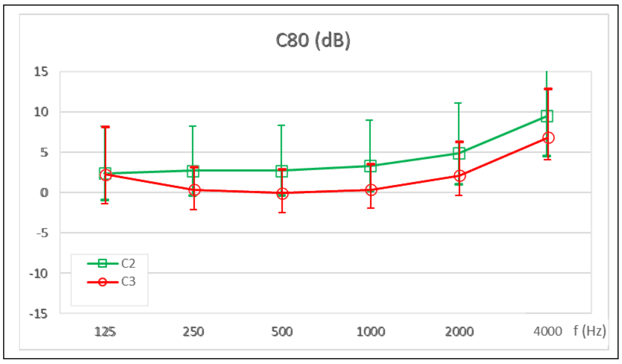

Figure 11. Clarity C80, with (C2) and without (C1) *velarium*.

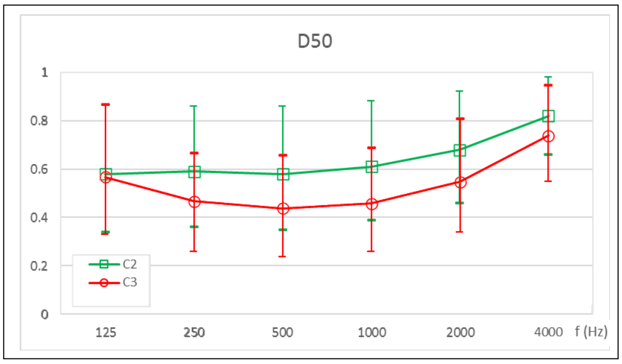

Figure 12. Definition D50, with (C2) and without (C1) *velarium*.

to almost 40% for middle frequencies also due to the late reflections coming from the *velarium*.

The results of the simulation are consistent with the findings of [9] and [10, 11] which also showed that *velarium* causes reverberation to increase. However direct comparison cannot be made, because the cited papers simulated theatres instead of amphitheatres.

4.3.3 Influence of the source and receiver position

Finally, we analysed the influence of the source and receiver position on the acoustics of the amphitheatre. Results presented in previous cases were all for the first source P1, that was centered in the middle of the arena. The second source P2 was located near the 3.23 m high arena wall (Fig. 4). The influence of such geometry can be seen on the results shown in Fig. 13. Definition D_{50} is significantly lower on all frequencies. On 1kHz definition for P1 is 45% and for P2 only 20%. The reason for this is

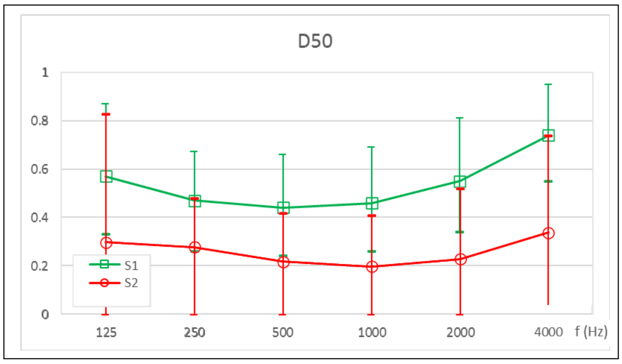

Figure 13. Comparison of definition D50 for two sources: P1 (green line) and P2 (red line), for full aphitheatre with velarium.

the occlusion of early reflections caused by the wall of the arena.

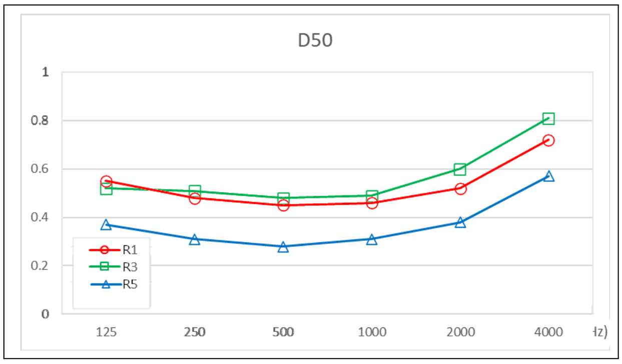

Figure 14. Comparison of definition D50 for three receivers R1 (green line), R3 (red line) and R5 (blue line), for full amphitheatre with velarium.

Fig. 14 shows the definition D_{50} for three different positions of receivers. Receivers R1 and R3 were situated in the lower and the upper part of the *cavea* respectively, and receiver R5 was in the gallery (Fig. 4). Results for R1 and R3 are similar, with definition for R3 being little increased on higher frequencies. On the other hand the receiver R5 has significantly lower definition - on 1kHz it is 30% for R5 vs. 50% for R3. This is due to the greater number of later reflections coming from the walls of the gallery where R5 is positioned.

5. CONCLUSION

In this paper we present the simulation of the amphitheatre of Salona (Fig. 15). We modeled the amphitheatre according to the findings of E. Dyggve [13] and using computer simulation analysed the influence of the audience, *velarium* and positions of source and receivers on the acoustics of the amphitheatre. The results show that *velarium* slightly decreased the clarity and definition, and that the listeners in the lower and upper *cavea* did have significantly higher definition than those in the gallery of the amphitheatre.

The overall results are in good accordance with the measurements of existing amphitheatres, and show that if the amphitheatre of Salona was preserved, it could well be used for open-air opera performances, similar to the amphitheatre of Verona.

Figure 15. The remains of the amphitheatre of Salona.

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