THE ACOUSTICS OF THE "NUOVO TEATRO COMUNALE" IN CAGLIARI

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1. ABSTRACT

In 1967, the Cagliari municipality started building a new Opera House, to replace the 19th century theatre, destroyed during the Second World War.

After an initial stage, the works were interrupted due to lack of funds, and restarted only in 1985. Only when the works were taken up again was the acoustic consultant contacted, who therefore intervened on an already partly constructed building. It soon became clear that the room shape was problematic from an acoustic point of view.

Thus, a 1:50 scale model was built on which the first reflection acoustic field was studied. A series of experimental measurements was also carried out inside the structure. From these experiments it became clear that the shape of the hall needed to be changed. In particular, the inclination of the side walls had to be varied in order to increase the number of useful reflections in the central area of the main floor.

The work inside the hall was finished in 1993, but the stage equipment necessary for the production of operas is still missing. In order to make it possible for the theatre to be inaugurated, an acoustic chamber was designed and built. This means that the hall can be used for symphony concerts.

The theatre was inaugurated in September 1993 with a concert conducted by Riccardo Muti.

In this paper, the Authors present the experimental results obtained throughout the whole project development, until the present situation with the acoustic chamber.

2. DESIGN HISTORY

2.1 Description of the hall

In the initial project, the hall was characterised by a widely open fan-shaped plan. The galleries had an asymmetrical shape, and were very deep. The hall was intended to have at least 1600 seats, divided between stalls and two galleries. The shape of the ceiling had not yet been defined. The materials covering the walls, floor and ceiling, were also undefined, but a general idea to introduce wood panels in certain places was already present.

The gross hall volume was 16000 m^3, the stage volume was about 23000 m^3, and the proscenium was 16 m large and 9 m tall. The maximum distance between any listener and the stage was less than 40m, as the hall is very high (20 m) but not very long (35m). The surface of the orchestra pit is 106 m^2, the total surface occupied by seats (including corridors) is 1357 m^2. The ratio between the total surface occupied by seats and the number of seats, that is 0.81 m^2/seat, and the ratio between the hall volume and the number of seats, that is 9.6 m^3/seat are remarkable. In fig. 1 the original plan shape of the room is shown.

2.2 First studies on a scale model

Initially, a 1:50 scale model was built in order to study the acoustic behaviour of the hall, in particular the first reflections. The model was in fact built with cardboard-covered polyurethane boards, and therefore there was no similarity in the absorption coefficients. In order to study the first reflections, a spark source was used as sound source, and a miniature hydrophone as detector, due to its wide frequency response (up to 200 kHz, which means 4 kHz in reality), sampling the signal through a digital storage oscilloscope.

From the results of this study and the analysis of the project, it became clear that it was impossible to ensure enough first reflections in the central area of the stalls and in certain zones of the galleries, particularly the rear part of the second gallery.

The lack of first reflections was a result of the excessive angle of the side walls with respect to the central axis of the hall.

An attempt was made to correct this lack of early reflections by introducing in the model some acoustic reflectors placed on the side walls: their inclination and position were adjusted using a small light source, as the reflectors were built with small glass mirrors. In addition, various shapes of the ceiling were tested.

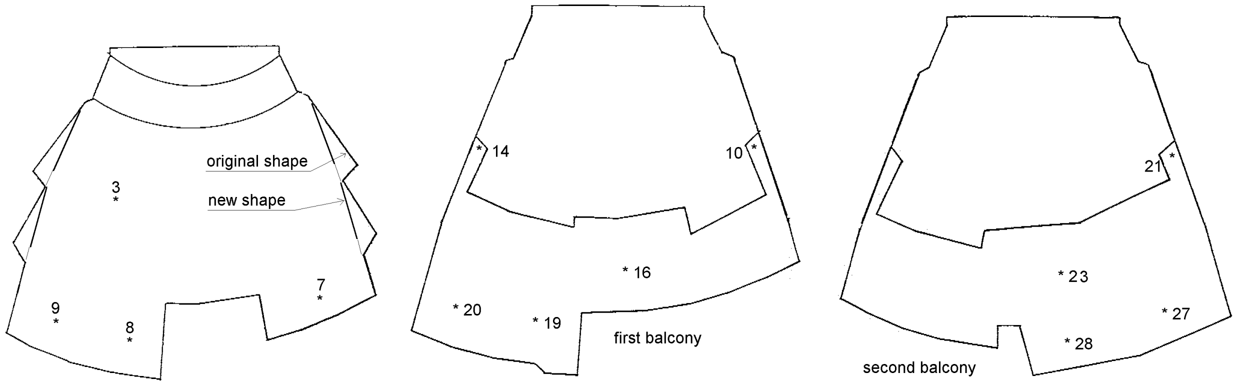

Fig. 1: Plan of the theatre with the old and the new design of the side walls

2.3 Modification of the shape of the hall

The architectural consultant was not happy with the proposed acoustic reflectors. Also the proposal of introducing Schroeder's diffusors [1] on the side walls was discarded for aesthetical reasons. Thus it was decided to reduce the angle of the side walls as shown in fig.1. Further solutions were also proposed to improve the early reflection acoustic field. For example, the slope of the gallery parapet and the back wall of the hall were modified (fig.2).

It was decided that the ceiling should be flat, made of gypsum board, and with an inclination of 9 degrees. Five large circular holes were made, which contain the lighting system.

The two walls at the sides of the proscenium, which already existed in the initial project, were of considerable importance for the acoustics, as they were the continuation of the stage: their inclination was checked both with the scale model and with a geometric construction of the image source for various source positions on the stage.

3. THE ACOUSTIC PROJECT OF THE THEATRE

3.1 Design criteria for reverberation

Having defined the shape of the room in the first part of the study, it was still necessary to give detailed indications on the choice of covering materials, seats, furnishing, etc.

Taking into account that the theatre was initially designed for opera, emphasis was given to the clarity of sound coming from the stage (singers), while that coming from the orchestra pit was sustained by an adequate reverberation.

According to the most recent theories developed by Ando and Cremer, [2,3] the aim was to obtain optimum values for the main acoustic parameters: minimum values of IACC (inter-aural cross correlation) by means of early reflections coming mainly from the sides; clarity index between 0 and 2 dB; center time between 90 and 120 ms.

The optimal reverberation times for each frequency band are shown in figure 3. The values are slightly higher than those of other opera houses in Italy, because the latter are usually considered too dull by critics and musicians. This characteristic is probably due to the series of successive restorations which have increased the amount of sound-absorbing materials, such as curtains, velvet upholstery, padded seats, etc. [Commins, 4].

For these reasons, no special absorbing materials were introduced in the room, choosing to install a wooden floor, wood panels over part of the concrete walls, and gypsum panels on the ceiling and underneath balconies.

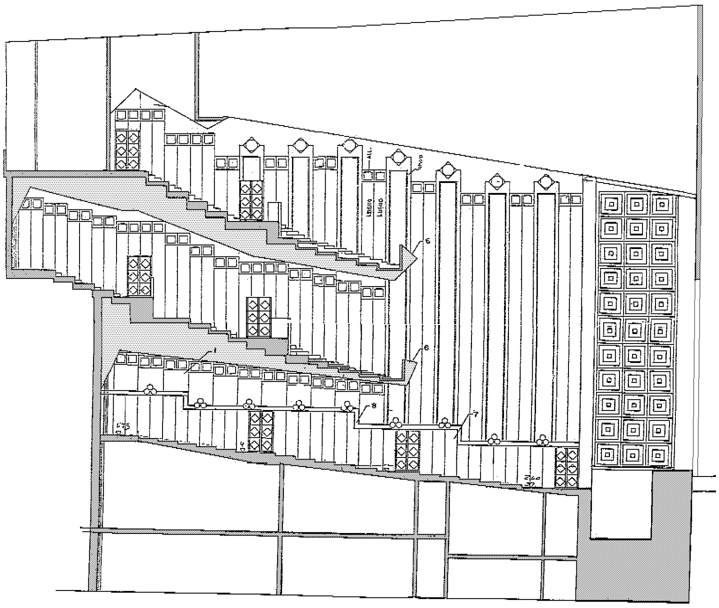

Fig. 2: Vertical section of the Theatre

3.2 Final adjustment of the reverberation by proper choice of seats

The only highly sound-absorbing material in the hall is the audience, since the wooden floors, the walls (concrete, wood and gypsum) and the ceiling (gypsum) show low absorption coefficients for medium and high frequencies.

Before positioning the seats, their sound absorbing properties were measured in a reverberation chamber according to ISO/354. Fig.4 shows the value of the equivalent absorption area A per seat in octave bands obtained from a matrix of 3x4 seats placed in the reverberation chamber, and surrounded with a reflecting frame. It can be noted that the stalls seats exhibit a large absorption peak at low frequency, probably due to the resonant behaviour of the air conditioning cavity under the seats.

The initial calculation of the reverberation time according to Sabine's relation, for a volume of 16000 m^3 and with the absorption values of the materials mentioned above, gave values very close to the optimum ones fixed in the project, as shown in fig. 3.

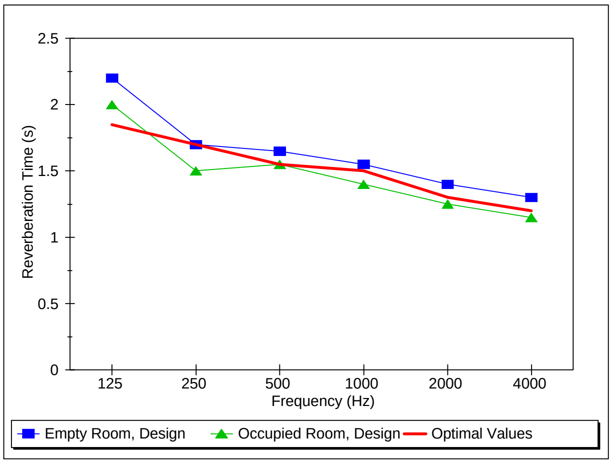

Fig. 3: Reverberation times at design stage computed with Sabine's formula

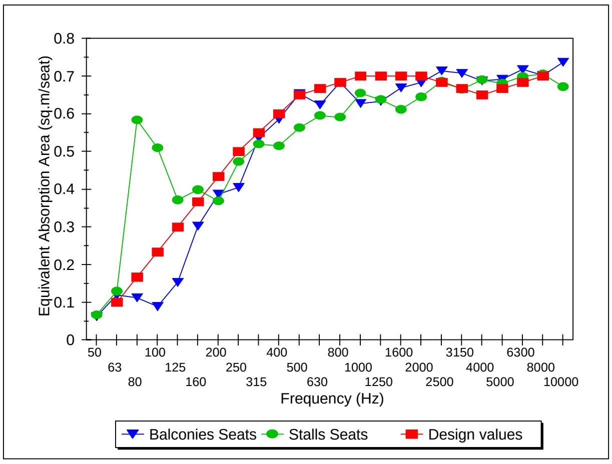

Fig. 4: Equivalent absorption area of seats measured in a reverberation chamber

3.3 Structural solutions for sound insulation improvement

The outside noise is mainly due to road traffic, and partly to the noise of aeroplanes in the nearby airport. The insulation from the street is guaranteed by the position of the hall within the building: it is in fact surrounded by rooms, which separate it from the outside. Only the back wall of the stage is an outer wall of the building. Furthermore, the entrance doors of the hall are all double, and some are separated by a corridor.

3.4 Reduction of noise emission from HVAC systems

The HVAC system was designed to respect the curve PNC=20 dB. The distribution of the conditioned air takes place through the back of each seat and through small openings in the ceiling for the galleries. The speed of the outcoming air is extremely slow.

Nevertheless, at the first start of the HVAC system the noise was considerably higher than that expected, due to some fans not properly insulated. It was necessary to add silencers and resilient mounts to reduce the emitted noise.

In fig. 5 the curve PNC 20 (29 dBA) is compared with the average experimental data measured at a number of points in the stalls, which show that after the treatment the background noise is about 35 dB/A, 6 dBA above the value fixed in the project, probably due to the noise of the ingoing and/or outcoming air in the gallery openings. This results was obtained with the maximum flow rate in the ducts, that is normally not required to achieve the desired thermoigrometric conditioning, so during normal operation no noise can be perceived coming from the HVAC system.

3.5 Corrections of acoustic defects

The only acoustic defect already identified during the study with the scale model regards an echo coming from the back wall of the hall. In order to eliminate it, the wall was treated with sound absorbing material: a 50 mm thick mineral wool panel, covered with a thin perforated steel sheet, and a soft 10 mm carpet.

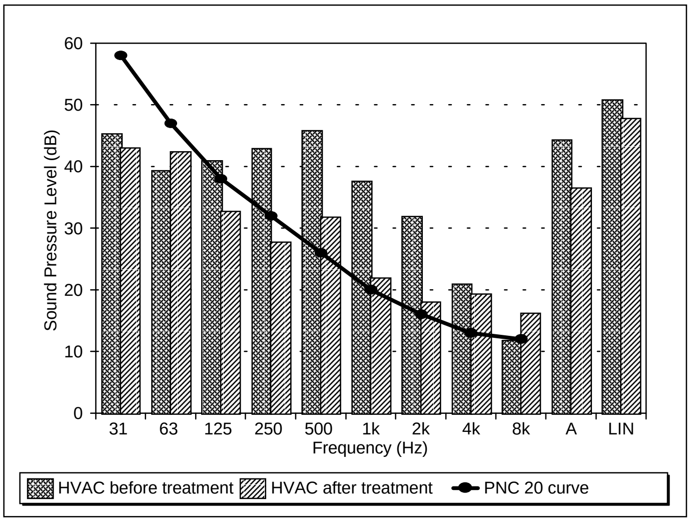

Fig. 5: Experimental HVAC noise levels before and after treatment compared with PNC-20 curve

4. DESIGN AND REALISATION OF THE ACOUSTIC CHAMBER

After furnishing the hall it became clear that, due to lack of funds, it was not possible to acquire the stage machinery and devices necessary to perform operas. It was therefore decided to inaugurate the hall with a series of classical concerts. However, this required the use of an acoustic chamber on the stage.

4.1 Design criteria

The design of the acoustic chamber was carried out by trying to ensure the best possible listening conditions not only for the audience, but also for the musicians. With regard to the audience, the acoustic chamber had to exclude an excessive reverberation coming from the empty stage, and to increase the useful early reflections in the hall. With regard to the musicians, an attempt was made to create an environment which would allow them to hear each other while still enabling them to perceive the acoustics of the hall. The chamber was built with surfaces that are sound-diffusing at middle and low frequencies, obtained with recesses of different depth.

The plan of the chamber was also chosen taking into account the need to re-direct the sound energy towards the hall, while at the same time diffusing it inside the chamber itself (fig. 6). The vertical section (fig.7) shows the shape of the ceiling of the chamber, which also includes the lighting system, and its inclination.

5. RESULTS FROM EXPERIMENTAL MEASUREMENTS

5.1 Measurement techniques

The measurements were conducted in the hall with two different measuring techniques: the first is the MLSSA system, which employs a portable PC fitted with an A/D board, that generates the Maximum Length Sequence signal. This steady-state signal is amplified and reproduced through an omnidirectional loudspeaker, while the receiving microphone is moved to the various measuring positions. At each point, 1 minute of MLS response was recorded on a DAT recorder, and then these recordings were post-processed on the PC deconvolving a 64k-points, 22.05 kHz sampled impulse response through the asynchronous cross-correlation capability of the MLSSA system.

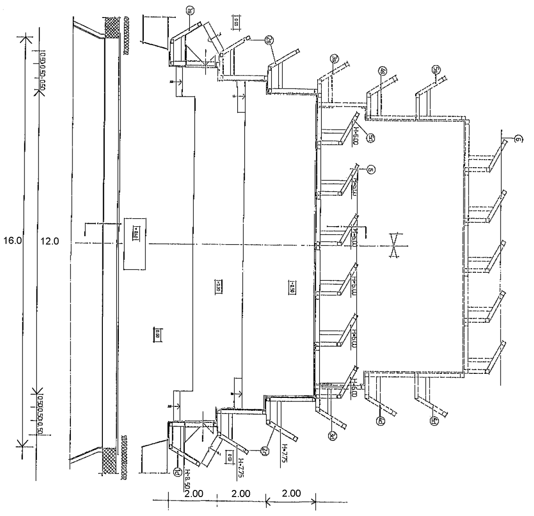

Fig. 6: Plan of the acoustic chamber

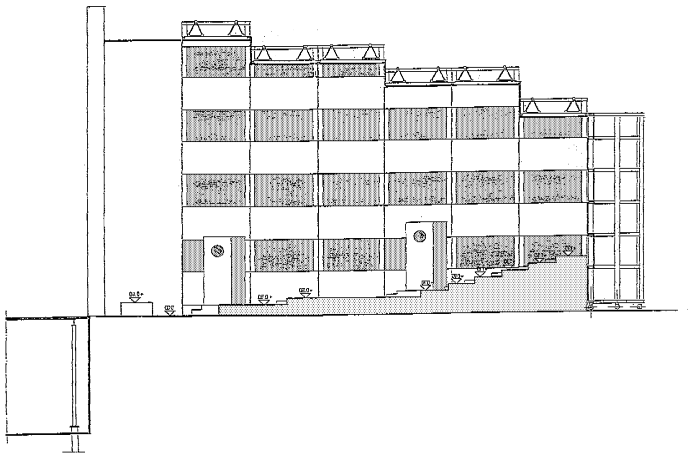

Fig. 7: Vertical section of the acoustic chamber

The second measuring system makes use of a blank shot gun with an omnidirectional diffuser. The shots were recorded through a binaural microphone, worn by one of the authors, connected to a stereo DAT recorder. These recordings were processed on a 2 channel real-time 1/3 octave acoustic analyser to obtain reverberation times through backward integration of the impulse responses. These binaural impulse responses were also digitally converted in MLSSA format, enabling direct comparison of the results obtained with the different techniques.

In addition to the T_{20} reverberation times, the MLSSA software was used to recover the following acoustic parameters in octave bands (according to ISO/CD 3382): C_{50}, C_{80}, D_{50}, EDT, t_s.

An attempt was made to calculate the value of IACC from binaural measurements, but the results obtained with gun shots exhibit a wide spread of values, so these data were discarded.

Two different measuring sessions were conducted in 1993: the first (March) was carried out without the acoustic chamber on the stage, the room being almost completely finished; the second (September) was done with the acoustic chamber on the stage, completely ready for the first concert. Another difference concerned the orchestra pit: in March its floor was at the lower level (the position for opera), while in September it was raised at the stage level, becoming a continuation of it. For this reason it was not possible to maintain the same source positions in the two measurement sessions, although the receivers were the same.

5.2 Results without the acoustic chamber

Two positions of the sound source were considered in this case: inside the orchestra pit and in the middle of the stage. For each of them, measurements were taken in 28 points evenly distributed around the main floor and in the balconies, plus 6 points on the stage.

In fig. 8 the reverberation times obtained with four different source-receiver arrangements are shown: it can be seen that the reverberation of the empty stage dominates the acoustic response of the hall, producing values significantly higher than those expected at the design stage (fig. 3). Being T20 measured with only the first part of the sound decay, the values in the room are lower than those measured on the stage: this means that the stage-room system behaves as two coupled spaces with very different absorption, and accordingly double-slope decays are found in the hall.

The main acoustic parameters, reported in table 1, are consistent with these evaluations: the early-to-late ratios are too low, the center time and EDT are too high. Also manually inspecting the impulse response it is possible to notice the lack of energy near the direct wave, and then a long and strong reverberant decay starting very late.

These results were not very encouraging, and it was clear that it was impossible to inaugurate the theatre in such conditions.

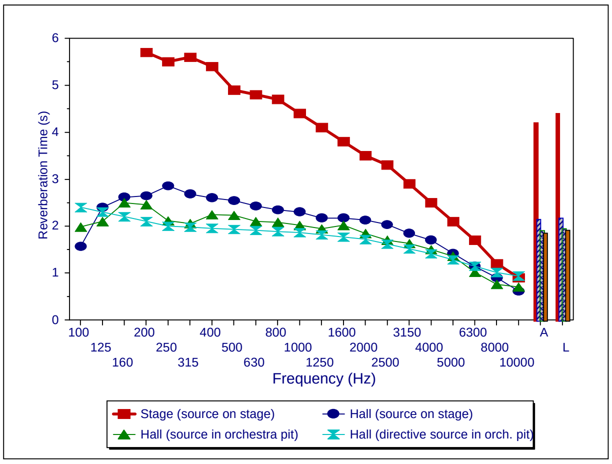

Fig. 9: Reverberation times with the acoustic chamber (September ‘93)

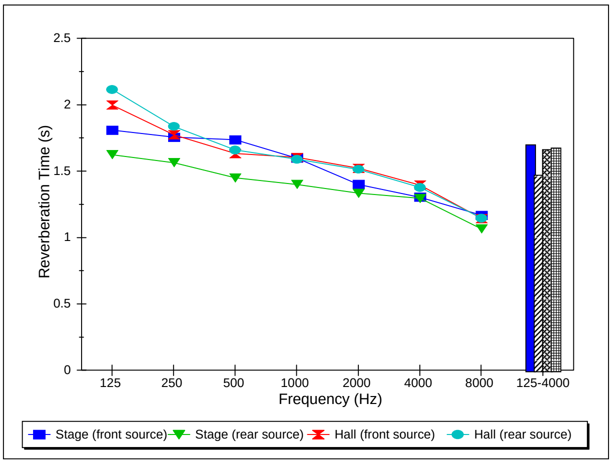

Fig. 8: Reverberation times without the acoustic chamber (March ‘93)

5.3 Results with the acoustic chamber installed.

These measurements were conducted a few hours before the inaugural concert: also in this case two source positions were considered, the first at the beginning of the proscenium (outside the acoustic chamber), and the second in the rear part of the acoustic chamber.

Fig. 9 shows the reverberation times measured in the hall (28 points) and in the stage enclosure (12 points), both with the front and rear source position explained above. The values are significantly lower than the previous ones, even if they are still a little greater than the design values; however it must be considered that the room was empty, and an audience of 1200 introduces a significant absorption area. So it can be stated that the project goal was successfully achieved.

The main acoustic parameters are reported in table 1, to make easy the comparison with the values obtained before the installation of the acoustic chamber.The improvement is evident, as the early reflection field was reinforced, while the late reverberating tail disappeared. The manual inspection of impulse responses reveals strong, early reflections coming within 20 ms from the direct wave in almost all positions.

The observation of the responses inside the acoustic chamber is particularly interesting: although the direct wave is very strong, due to the small source-receiver distance, early reflections coming from side walls and ceiling are evident, with short arrival times and random delays. This means that the musicians receive reflected waves in a diffused environment, avoiding the “shoe box” effect (i.e. flutter echoes) caused by rectangular enclosures.

Table 1: Main acoustic parameters, overall values (125-4000 Hz).

		without acoustic chamber					**with acoustic chamber**				
Point	**Location**	**C50**	**C80**	**D50**	**ts**	**EDT**	**C50**	**C80**	**D50**	**ts**	**EDT**
3	stall	-3.02	2.02	31.3	110	1.716	-1.26	1.1	42.1	115	1.925
7	stall	-0.11	2.62	45.9	99	1.445	4.22	6.75	71	67	1.184
8	stall	-1.31	5.85	40.7	83	0.843	1.06	4.08	53	83	1.427
9	stall	2.56	4.5	60.6	84	1.39	3.66	5.64	66.7	72	1.255
10	1st balcony	-2.61	-0.42	35.1	137	1.971	0.11	1.51	49.9	107	1.923
14	1st balcony	-1.39	0.29	41.6	134	1.995	-0.2	0.89	48.1	114	1.845
16	1st balcony	0.04	2.51	46.7	101	1.565	3.81	6.31	62	70	1.278
19	1st balcony	1.2	4.29	52.6	90	1.214	-0.25	2.82	47.2	92	1.347
20	1st balcony	2	5	58	81	1.1	0.56	2.68	49	96	1.498
21	2nd balcony	0.49	1.4	51.3	112	1.874	0.08	1.37	49.3	105	1.85
23	2nd balcony	0.21	2.14	49.7	105	1.702	2.09	4.24	59.4	79	1.363
27	2nd balcony	-0.5	2.64	43.6	109	1.579	-0.16	3.01	46.9	94	1.319
28	2nd balcony	0.57	3.1	50.8	102	1.604	0.75	3.97	50.7	88	1.274

6. CONCLUSIONS

The results of the experimental measurements agree well with the first subjective judgements expressed by the audience after the inauguration concert: the hall is very live, the music is brilliant (due to the adequately high reverberation time), the sound envelops the listener (thanks to early lateral reflections), the frequency response is almost flat. Both the audience and the performers expressed their satisfaction about the acoustics of the hall.

Obviously some positions were better than others: the judgements regarding the balconies, which initially were considered the most problematic due to their tunnel-like shape, were particularly good.

7. REFERENCES

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