EFFECTS OF SURFACE CHARACTERISTICS ON THE ACOUSTIC ENVIRONMENT OF ANCIENT OUTDOOR PERFORMANCE SPACES

K Chourmouziadou University of Sheffield, School of Architecture, Sheffield S10 2TN
J Kang University of Sheffield, School of Architecture, Sheffield S10 2TN

1 INTRODUCTION

Previous research on ancient performances and performance spaces[1-2] has revealed that theatre evolution in Europe was based on changes in design style, and also significantly on material use. Since there is strong evidence that the ancients studied sound and realised the effects of material absorption and reflection,[3-6] they could have considered this during the renovations of the theatres. In oriental countries like China, performances were taking place on temporary stages and later in purpose-built theatres,[7] thus the surrounding conditions in terms of material properties were critical.

The aim of this research is to study the effects of surface characteristics on the acoustic environment of outdoor performance spaces in antiquity. A series of acoustic simulations have been carried out using a ray-tracing program, to study the influence of surface absorption and diffusion on ancient theatres. The simulations are based on commonly used material properties in modern acoustic simulations, as well as a range of possible material coefficients. The hypothesis is that the former may not always be appropriate for ancient theatres, since the surface treatments could be different. In addition to material properties, effects of surface dimensions and the use of enclosures have also been taken into account.

The paper first briefly reviews the development of Chinese and Roman drama and the types of theatre involved. It then presents the results of a series of acoustic simulations in two representative theatres, one Chinese and one Roman. The two theatres are both examples of the first outdoors but enclosed purpose-built performance spaces, with rectangular and semicircular shapes respectively. It is thus interesting to study the effects of surface conditions, as well as their basic acoustic characteristics.

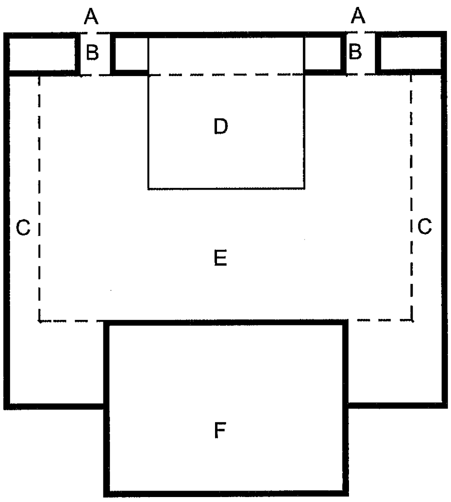
2 ANCIENT PERFORMANCE SPACES

2.1 Chinese theatres

The earliest known Chinese drama was a highly synthetic art, embodying a broad range of different kinds of performance, such as dance, song, music, acting, recitation and acrobatics. Religious ritual and dancing occurred in the shamanistic and court dances of the Zhou dynasty in China. Also, regional rulers, national disunity, decentralised power, invasions, and Buddhism had influenced the development of drama.[7]

There were a number of theatres, probably fairly solid enclosures with a raised stage open to three sides and hemmed in by a low railing or balustrade, in amusement quarters, called wasi, resembling vast fairgrounds or little towns of amusement arcades. The bigger of these theatres were capable of accommodating several thousands spectators. Temporary stages were also constructed for itinerant players, with a variety of boundary conditions.[1-2] The extensive use of wood in Chinese architecture is a major factor for the lack of evidence of many early theatres. A form of theatre, which was an important part of the history of Chinese drama, is the temple stage. Enclosed spaces of monasteries had watching platforms on three sides, while the stage was erected against the main temple hall. Figure 1a illustrates a temple stage in China.

Generally, there were resemblances between the permanent theatres and the temple stages. In the Qing dynasty there were two kinds of fixed public theatre: the xiyuan (play garden), the most popular theatres, and the xizhuang (play establishment or play emporium),[7-8] for selected groups of elite and wealthy customers. The major troupes monopolised the bigger theatres, which organised the performances. The auditorium typically included a central space in front of the stage, spaces to either side of the stage, and a two-level accommodation around the sides. The second floor had verandas, accessible by stairs from the main entrance of the theatre. The official seats were upstairs, to the right and left side and situated nearest to the stage. The stage was about 1-1.2m above the ground, in a square shape with 5-6m sides, usually wooden, with round black-lacquered pillars at the front two corners. Between them, about 3m above the stage, there were one or two horizontal bars, used to assist in the fighting and acrobatics. The three sides of the stage had a low railing, about 30-60cm high. The stage was roofed over with a substantial and sometimes a very elaborate roof. An axonometric view of the theatre that will be used for the simulation is shown in Figure 1b.



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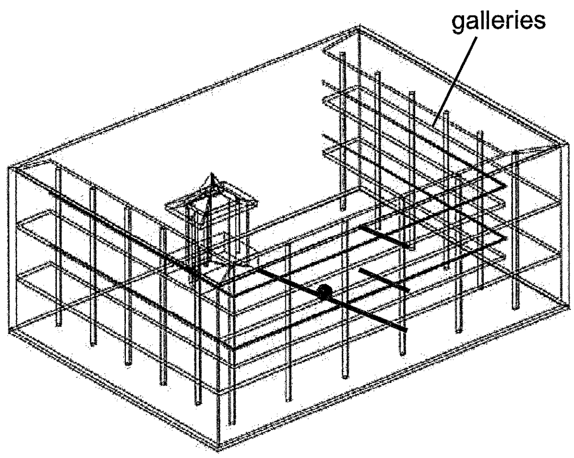


b

__Figure 1.__ Typical permanent theatres in ancient China. __a.__ Plan of stage and surroundings in a City God Temple of Ningro.[7] A, gate; B, passage; C, galleries; D, stage; E, central courtyard; F, main temple. __b.__ Axonometric view of a theatre used for the acoustic simulation. The red dot and red lines indicate the typical receiver and receiver lines used in the simulation.

2.2 Roman theatres

In ancient Rome drama was not connected with religion. Popular plays had neat plots and there was no chorus.[9] According to the literature,[10] up to the early third century B.C. there were no theatres in the Roman state. There were only some wooden stages-come-scaffolding used for the performances of the popular farces or for productions of Etruscan drama. It is believed that the first Roman stage, made of wood, was erected in 364 B.C. at the Circus Maximus for the appearance of a troupe of Etruscan performers.[11] When Romans came into contact with the advanced forms of Greek theatres, an interest in everything connected with letters, art and architecture was developed, particularly in theatre architecture.

Although the Romans preferred hillsides for their plots, the need to build the theatres in the big cities led to new structural methods. The theatres were individual buildings, rested upon stone-built arches. The cavea of the Roman theatre was semicircular, probably for functional and structural purposes. The audience confronted the actors, who were performing solely on the stage. The orchestra pit, made of stone or paved, was occupied with seats for important guests and the stage was wide and high, while the stage floor was often wooden. The back stage wall was increased at the same height as the auditorium and the stage building was decorated with columns and niches. There were vaulted passages at the point where the orchestra pit was connected to the cavea, to make the orchestra pit accessible. The important spectators watched the performances from 'boxes' placed over these passages. Figure 2 shows the plan and the axonometric view of the Roman theatre that will be used in the simulation.

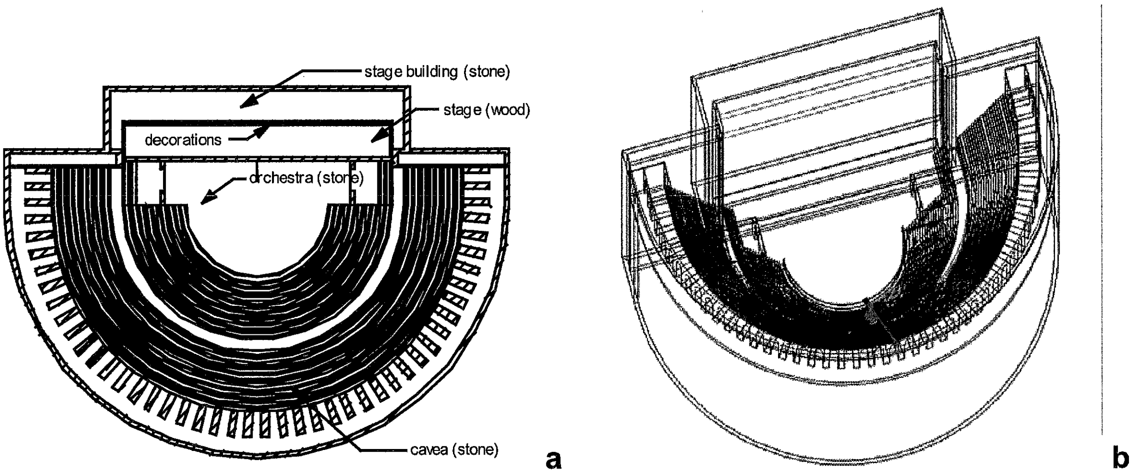


Figure 2. *A typical Roman theatre.* ***a.*** *Plan of the theatre at Aspendus.* ***b.*** *Axonometric view of the theatre used in the simulation. The red dot and red line indicate the typical receiver and receiver line used in the simulation respectively.*

2.3 Comparison between Chinese and Roman theatres

The performances and performance spaces in oriental and western civilisations share many characteristics. The performances took place outdoors but the permanent structures were enclosed spaces, constructed with hard materials. Actors performed on a wooden stage, whilst the audience was seated at several heights. In some cases, the majority of the performance space was covered by a structure made of fabric and ropes. The use of enclosed spaces generally improved the acoustic conditions. The boundaries usually provided useful reflections, depending on the material. Additionally, the ornamentation in these spaces provided diffusion characteristics to the boundaries. The fact that the important guests were occupying the best seats of the theatre, both in western and oriental theatres, reveals that people were familiar with sight lines and distribution of sound, at least by observation. However, in the two civilisations the shape and layout of the theatres were fundamentally different, suggesting that they had different acoustic attributes. The Chinese theatres were simpler than the Roman, in rectangular shapes, and the sound propagation depended on the direct sound and the reflections from the ground, the perimeter (surrounding) walls, and in some cases the roof and two sidewalls of the stage. Whereas in Roman theatres the orchestra pit and the back stage wall were important for providing reflections.

3 ACOUSTIC SIMULATION

This Section presents a series of acoustic simulations investigating the effects of surface characteristics. The simulations are carried out using commercial software Raynoise.[12] For each major surface material, comparisons are made with a range of absorption coefficient a, found from the literature, representing the possible minimum, typical, and maximum, while the other materials retain the typical coefficients, as shown in Table 1.[12-14] Comparison has also been made between with and without diffusion on some boundaries.

Table 1. *Typical surface absorption and diffusion coefficients used in the simulation.*

	Material / Frequency (Hz)	125	250	500	1k	2k	4k
Absorption	Stone	0.01	0.01	0.01	0.01	0.01	0.01
	Wood	0.15	0.11	0.1	0.07	0.06	0.07
	Plaster	0.03	0.05	0.04	0.06	0.08	0.08
	Audience	0.28	0.4	0.78	0.98	0.96	0.87
Diffusion	Stage	0.3	0.2	0.15	0.1	0.09	0.07

The surface materials of the two theatres simulated are presented in Table 2. Both unoccupied and occupied conditions are considered. The former is useful for studying the basic acoustic characteristics of the theatres as well as the acoustic conditions during rehearsals. A point source is positioned near the middle of the stage in both theatres, simulating a single actor. The sound power level of an actor's strong voice is determined by increasing the sound power level of conversational speech[12] by 12dB in each octave band,[15] which becomes 84dB at 125Hz, 76dB at 250Hz, 76dB at 500Hz, 72dB at 1kHz, 67dB at 2kHz, and 47dB at 4kHz. No background noise is applied.

Table 2. *Material properties of simulated theatres.*

Theatre type/ Material	Stone	Wood	Plaster
Chinese	ground floor	galeries	perimetric walls
	-	stage	-
	-	pillars	-
Roman	cavea	stage floor	-
	orchestra	-	-
	peripheral corridor	-	-
	stage building	-	-

The theatre models were first created using Archicad and 3D Studio, as shown in Figures 1 and 2, and then imported into Raynoise for the acoustic simulation. The core of Raynoise is a hybrid algorithm combining the image source method and the beam-tracing method.[12] The calculation parameters were carefully selected based on the pilot study.[2] The number of rays varies, depending on the model's complexity, from 10,000 to 100,000. Typically the reflection order is 50, the time window is 2s for the Chinese theatre and 10s for the Roman theatre, and the dynamic range is 90dB. Acoustic indices considered in the simulation include sound pressure level (SPL), reverberation time (RT30), and speech transmission index (STI). The reverberation time is used in this research for comparative studies, given that the index has been mainly applied for evaluating enclosed indoor spaces.

3.1 Chinese theatres

Given the large area of wooden surfaces in the Chinese theatre, comparison is made between three absorption coefficients for wood, 0.04, 0.2 and 0.4, across 125-4kHz.[12-14] Figure 3 show the SPL along a receiver line and the RT30 at a typical receiver, as illustrated in Figure 1. From Figure 3a it can be seen that the SPL is reduced by about 2.3dB on average when a is changed from 0.04 to 0.2, and by 2.1dB on average when a is changed from 0.2 to 0.4. If the wooden surfaces are considered as diffusely reflective, with diffusion coefficients from Table 1, the SPL is reduced by almost 2dB. It is noted that at receivers near the boundaries, with increasing source-receiver distance, the SPL increases on the ground floor and the first floor gallery, but decreases on the second floor gallery. This is mainly due to the different reflection patterns at different positions, as shown in Figure 4. Under occupied conditions the SPL variations are less than those above, but the tendency is similar. Compared to unoccupied conditions the SPL is generally about 5-7dB lower.

For RT30, the effect of a is more significant than that for the SPL. This is because the SPL is mainly determined by the direct sound and early reflections, whereas the RT30 depends on multiple reflections. Since the theatre is enclosed and rectangular in shape, the RT30 is rather long under unoccupied conditions, about 2-3.5s. Figure 3b shows that by changing from a=0.04 to 0.2 the

RT30 is reduced by 4-10%, and from a=0.2 to 0.4 the RT30 reduction is 9-15%. Further calculations show that for the receiver line the difference in RT30 caused by using different absorption coefficients for wood becomes greater with decreasing source-receiver distance. With the presence of an audience the differences between different wood coefficients diminish significantly. This is expected, because the audience absorption is dominant in the space, especially when multiple reflections are considered.

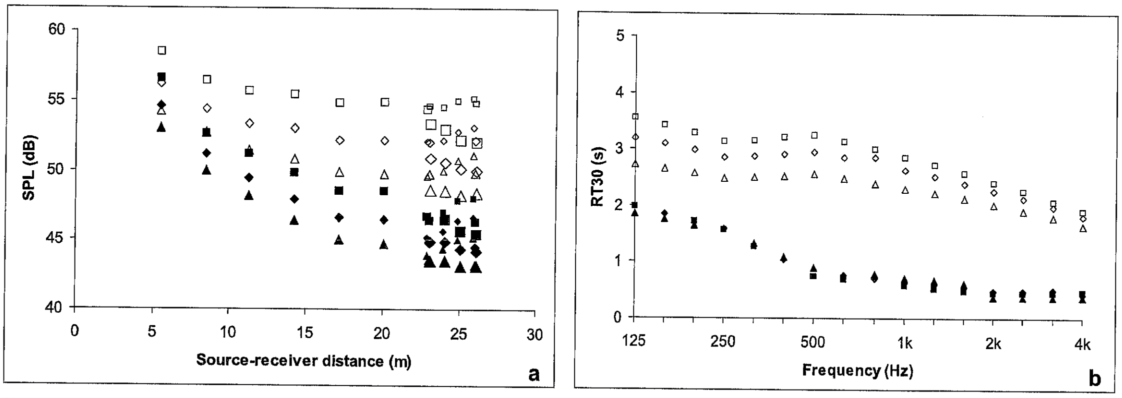


Figure 3. *Comparison between three absorption coefficients for the wooden surfaces in the Chinese theatre.* ***a.*** *SPL (dB) at 500Hz along the receiver lines as illustrated in Figure 1b.* ***b.*** *RT30 (s) at the typical receiver (see Figure 1b). Open symbols, unoccupied condition; solid symbols, occupied condition. ■ and □, a=0.04; ♦ and ◊, a=0.2; ▲ and Δ, a=0.4. In* ***a*** *the receivers on the first and second floor galleries (beyond 20m from the source) are presented with smaller and greater symbols respectively, compared to the ground floor.*

The results regarding STI will correspond to RT30 since no background noise is considered. For unoccupied conditions, although increased absorption by the wood results in shorter RT30, thus increased STI, the STI variation is less than 0.1. With an audience the STI is generally good, around 0.6 with various wood absorption coefficients. The definition with a=0.04 is around 40% at low to middle frequencies and around 80% at high frequencies, whereas with a=0.4 these values are 65% and 95% respectively.

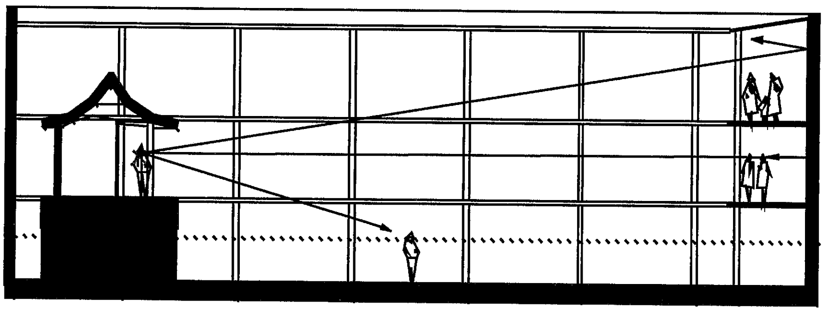
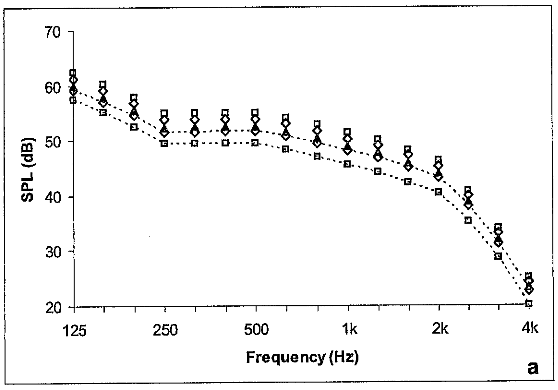


Figure 4. *Cross-section of the Chinese theatre showing reflection paths.*

For the surrounding walls, three conditions have been simulated, a=0.02, 0.1 and 0.3. Both occupied and unoccupied conditions are taken into account. For the latter, a diffusion coefficient of 0.5 is also considered for the surrounding walls at all frequencies. Figure 5 shows the SPL at the typical receiver and the RT30 along the receiver line. Between a=0.02 and 0.3, the SPL difference is only 1dB. In contrast, the difference caused by considering diffusion is rather significant, 5dB with a=0.02 and 2dB with a=0.1. With an audience the SPL is reduced by 2-4dB at the receiver. Again, under occupied conditions the effect of the absorption coefficient of the surrounding walls on the SPL is less significant than that under unoccupied conditions.

For reverberation, with a=0.02 for the surrounding walls, the RT30 is generally over 3s on the ground floor, 2.3-2.8s on the first floor, and 2.2-3.0s on the second floor. By increasing the absorption of the surrounding walls to 0.1 the RT30 becomes shorter, by 0.5-1.3s. However, when a diffusion coefficient of 0.5 is applied to these surfaces with a=0.02, the RT30 is reduced by 1.4-2.7s, which is more significant than increasing absorption coefficient. As expected, with an audience the RT30 becomes shorter, around 0.9s with a=0.02, 0.8s with a=0.1, and 0.6s with a=0.3. The STI along the receiver line at 500Hz is 0.3-0.6 under unoccupied conditions and 0.6-0.8 under occupied conditions. With an audience the definition is also considerably increased, especially at middle to high frequencies, although the influence of surface a seems insignificant.



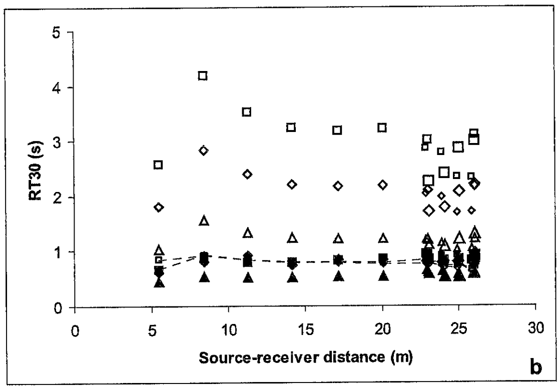


***Figure 5.** Comparison between three absorption coefficients for the surrounding walls in the Chinese theatre. **a.** SPL (dB) at the typical receiver (see Figure 1b). **b.** RT30 (s) at 500Hz along the receiver line (see Figure 1b). Dotted line, with a diffusion coefficient of 0.5 at all frequencies; open symbols, unoccupied condition; solid symbols, occupied condition. ■ and □, a=0.02; ♦ and ◊, a=0.1; ▲ and Δ, a=0.3. In **b** the receivers on the first and second floor galleries (beyond 20m from the source) are presented with smaller and greater symbols respectively, compared to the ground floor.*

In the above calculations the absorption coefficient is 0.01 for the floor, simulating marble. A calculation has also been made with a=0.02 and 0.1. The results show that under unoccupied conditions the maximum difference is 0.4dB in SPL and 0.15s in RT30.

3.2 Roman theatres

The Roman theatre, as mentioned above, was structured on stone arches and its basic material was usually marble. There are however examples of other material used, such as limestone. It is thus useful to study the acoustic properties with different characteristics of stone surfaces. Three absorption coefficients, 0.01, 0.02, and 0.1, are considered across 125-4kHz.[12-14] In many cases the enclosure of the stage in Roman theatres was decorated, so that these surfaces are regarded as diffusely reflective in the simulation, with the diffusion coefficients shown in Table 1.

Figure 6 shows the SPL at a typical receiver and the RT30 along a receiver line, as illustrated in Figure 2. From Figure 6a it can be seen that the SPL variation with different absorption coefficients is generally insignificant. Under unoccupied conditions, when a is changed from 0.01 to 0.02, the SPL is reduced by only 0.2-0.3dB. From a=0.02 to 0.1 the SPL reduction is 1.3-1.6dB. Under occupied conditions the SPL variation between different a values is almost unnoticeable. By comparing the simulation results in the Chinese and Roman theatres it is noted that the effects of different a on the SPL generally have a similar tendency, although the effects depend on the surface area, as expected.

For reverberation, like in the Chinese theatre, the effect of a is greater than that for the SPL, as can be seen in Figure 6b. The RT30 reduction is about 2-5% when changing from a=0.01 to 0.02, and about 15-30% from a=0.02 to 0.1. This, in terms of absolute values means that RT30 can be estimated as 2.6s on average if the stone is simulated as marble (a=0.01) and 2.1s on average if it is simulated as brickwork (a=0.1). Under occupied conditions the RT30 is lower, as expected, but the RT30 values with a=0.01, 0.02 and 0.1 are almost identical. This result is useful from the design viewpoint.

The STI results correspond to RT30 since no background noise is considered in the simulation. For unoccupied conditions the STI is around 0.4 for all a values, whereas for occupied conditions the STI is about 0.5 at low frequencies and 0.7 at middle to high frequencies, which are generally good in terms of speech intelligibility.

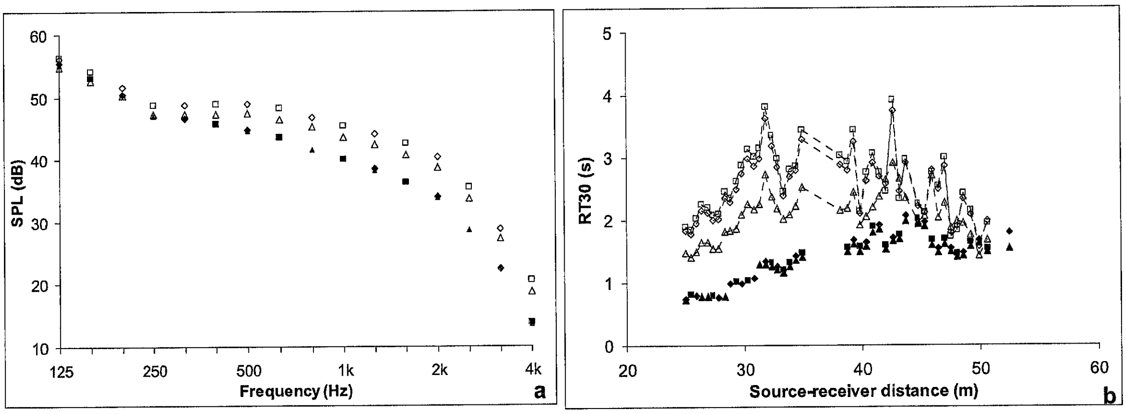


Figure 6. *Comparison between three absorption coefficients for the hard materials in the Roman theatre.* ***a.*** *SPL (dB) at the typical receiver as illustrated in Figure 2b.* ***b.*** *RT30 (s) at 500Hz along the receiver line (see Figure 2b). Open symbols, unoccupied condition; solid symbols, occupied condition. ■ and □, a=0.01; ♦ and ◊, a=0.02; ▲ and Δ, a=0.1.*

If a diffusion coefficient of 0.5 is applied to the audience at all frequencies, the SPL is slightly reduced, by 1-3dB, while the RT30 is shortened by a maximum of 0.5s.

Simulations have also been made with various possible absorption coefficients for the wooden surfaces in the Roman theatre. Since the surface area is rather small, the effect of using various absorption coefficients is insignificant.

4 CONCLUSIONS

The effects of using a possible range of surface characteristics have been examined through a series of computer simulations, for both Chinese and Roman theatres. Three absorption coefficients have been used for every surface, representing possible minimum, typical and maximum values. Diffusion has been applied where appropriate. Generally speaking, the simulations have shown that alterations in surface characteristics affect mostly the unoccupied conditions, and the effects are less on SPL and more on reverberation. The results in both types of ancient performance space show similar tendencies.

In the Chinese theatre a large amount of wooden surfaces was used, and the influence of using a range of absorption coefficients is up to 5dB. The influence is greater under unoccupied conditions than occupied conditions, as mentioned above. It is interesting to note that the effect on SPL varies at different receivers, due to the reflection paths. In terms of the surrounding walls the SPL variation with different a is insignificant, especially when the theatre is occupied. Conversely, the SPL is considerably decreased if the surfaces are regarded as diffusely reflective. In the Roman theatre the maximum difference in SPL caused by the possible range of stone absorption is 1.6dB under unoccupied conditions and is almost unnoticeable under occupied conditions. In both theatres audience absorption reduces SPL by about 6dB, and this increases with increasing source-receiver distance.

The effect of surface characteristics on reverberation is generally greater than that on SPL. The RT30 under unoccupied conditions in the Chinese theatre could be rather high, about 2-3.5s, if the surfaces are regarded as geometrically reflective and a low absorption coefficient is given. Using a larger possible absorption coefficient, especially for surrounding walls, can greatly reduce the reverberation, by over 50%. Applying diffusion coefficients can also bring a considerable reduction in RT30. As expected, under occupied conditions the variation in reverberation caused by different surface characteristics is less than that under unoccupied conditions. In the Roman theatre, with an audience there is almost no change in RT30 with a range of stone absorption coefficients. In both theatres the STI under occupied conditions is more than 0.6 with various surface characteristics, which is rather good in terms of intelligibility. Definition is also high.

With the same sound source the SPL at 500Hz in the Chinese theatre is about 43-56dB with an audience and 45-58dB without, and in the Roman theatre these values are generally lower, 39-47dB and 40-51dB respectively. The main reason for the differences is that the Chinese theatre is a smaller size and there are more early reflections. The Roman theatre however has a longer reverberation - in the Chinese theatre the RT30 is about 0.5-1s with an audience and 1-4s without, and these values are 0.7-2s and 1.4-3.9s in the Roman theatre. This is essentially because in the Roman theatre the volume is larger and materials are harder.

5 ACKNOWLEDGEMENTS

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