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Comparison and simulation-based analysis of the sound field of Dong drum tower buildings

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Abstract

Drum towers are the most prominent cultural markers and the major site for cultural ceremonies in Dong villages. The visibility and audibility of drum towers are important factors influencing the location and construction of buildings in Dong villages. In this paper, the authors map and classify 21 drum tower buildings according to three characteristics: shape of the plan, elevation of the enclosure, and aspect ratio of the longitudinal section. Having used the sound field simulation software Odeon to filter two of the three characteristics that were identical, the authors simulated drum towers with different values of the third characteristic to study the factors influencing their sound field. The correlation between the construction of the drum tower and its characteristics of sound was established, and the characteristics of the sound field as well as their adaptability were assessed by comparing different forms of drum towers. This can provide technical support for the protection and repair of drum towers, their renovation and upgrade, and the construction of new drum towers in the Dong region.

Keywords Dong drum tower, Cultural properties, Shape and combination, Sound field characteristics

Introduction

The Dong people are an ethnic group with a long history and an ancient culture in China. They are descendants of the ancient Yue people, and belong to the Gan Yue and Luo Yue branches [1] that are mainly distributed in parts of Guizhou, Hunan, and Guangxi provinces [2]. A Dong village consists of dwellings, a theater, a fish pond, a Satan (traditional Dong ritual architecture), and drum towers [3]. The drum tower is the tallest, largest, and most beautifully decorated building in the Dong village [4], and is so called because a wooden drum is located on the top floor of the tower. The earliest known drum tower is more than 500 years old, and 439 drum towers have been preserved in the Guizhou area of Nan Dong [1, 5, 6]. They can be divided into two types: temple pavilion type and drum tower buildings [7]. Temple pavilion-type drum towers mainly originate from the Dong branch of the Jiao Dong branch, located in the Yangtze River system, and from the Dan Dong branch of the Xun River basin in the Pearl River system. Drum tower buildings are widely found in all Dong areas [8]. The internal space of the drum tower is divided into a “fire space” and a surrounding space for activity by two columns on the inside and outside [9] that represent access to the spiritual world [10]. The planes of the tower are mostly even. Most of them have one central column (Leigong column) symbolizing the year, four main columns symbolizing the four seasons and the four geographical directions, and 12 side pillars symbolizing the 12 earthly branches and the 12 months of the year [11]. The structure of the drum tower is based on the principle of mechanical leverage, with a chiseled mortise and tenon joints, large and small pillars, squared pillar

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crossings and straight sets, and hinged support systems combined with a pierced layer-by-layer structure [12].The layers are odd in number as this is considered auspicious by the Dong people [13]. The outer eaves panel of the drum tower is usually decorated with two totems of dragons and auspicious clouds as the main motifs. They symbolize the supreme authority of the drum tower in the Dong village. The pigments used in the totems are made of clay unique to the Dong region, and have an anticorrosive effect [14].

The Dong drum tower has political, military, and cultural functions in the Dong village. Politically, the drum tower is a symbol of the rights and domains of the ethnic group, and acts as the political center of the village. It is the site of deliberations and trials, where the matters are dealt with according to the internal conventions of the clan [11, 15]. Its military function is mainly defensive, as a lookout in which wooden drums can be used to send out warning signals. In case of a call for usual deliberations, the beat of the drums is "dong dong dong," which represents the soundscape when the atmosphere is calm [16].When encountering soldiers and bandits engaged in rioting and looting, the drums are struck with an initial heavy blow followed by continuous strikes. In case of fire hazards, the drums are beaten intensively and at intervals, during which the drummer shouts and point to the location of the fire [17]. When important personages arrive or assemble at the tower, the sounds of the drums are long and the beats slow. The cultural nature of the drum tower is expressed in the cultural identity that it establishes for villages, ethnic groups, and families. The Dong people are closely connected with the drum tower throughout their lives. Every important stage of life, such as birth, marriage, and funeral, is celebrated in the drum tower. All 13- to 17-year-old Dong male youths (note that their ages are odd numbers) are assigned names associated with the drum towers of their villages in a grand naming ceremony, and a naming banquet is held to mark their adulthood [18]. That is, they are associated with the drum tower and thus establish a cultural bond with it. This is also a reflection of the cultural function of the drum tower. Therefore, seeing the drum tower and hearing the drums are important considerations for the Dong people in choosing the site of the building. Each drum tower is thus inseparable from the pulse of the Dong village.

The Dong people did not develop writing during their long historical evolution, because of which the drum tower served as the main site for education. Activities such as the transmission of history and culture, the spreading of a national spirit, and the management of daily affairs are carried out in the drum tower through oral transmission [19]. Such verses as "spring with a huge wood buried in the ground for the building, several feet high, singers at night will edge to stay on it [sic]…" [20] and "[sic] trigger men singing, drinking sound, night edge to stay on it, so proud" [21] describe such scenes involving sounds. The social activities recorded in songs of the drum tower have also enriched the field of its sound [22]. Examples include the "the Grand Song of the Dong," "Moon also old," and "Moon also Zuo Lou" [23, 24]. Thus, the sound of the drum tower is indispensable to the culture and life of the Dong people, and many studies have examined its construction and influence on their culture [8, 25–30] as well as its function and meaning [18, 31, 32]. However, no study to date has regarded the drum tower as a building for spectators and examined the characteristics of its sound field, in the context of its role as a cultural building that integrates the assembly, lives, and education of the Dong people, and in light of the cultural attributes of its sounds. Therefore, the authors of this study analyze and compare the characteristics of the sound fields of different kinds of drum towers by classifying typical drum towers in Dong villages into different types and simulating them. This provides a basis for the protection, repair, and construction of such towers.

Materals and methods

Selection of features for the classification of typical drum towers

There are many drum towers in Dong settlements. Because the palm ink masters who built the drum towers had no design drawings, all the structures and dimensions were based on memory, and no particular norms and standards were followed [12]. This resulted in different forms of drum towers. The on-site mapping of 21 typical drum towers with good integrity and the longest history has shown that they are mainly quadrilateral in plan, with a few towers with hexagonal and octagonal plans. The overall height, number of layers of heavy eaves, form of the roof, and form of the plan of these towers were measured as modeling points, and the results are shown in Fig. 1 [11].Its internal structure is shown in Fig. 2. From the perspective of architectural acoustics, the spatial morphology of a building influences the spatial characteristics of its sound field, and the relationships between them is shown in Fig. 3. The planar shape in the figure represents the shape of the viewing space, and reflects the path of reflection of sound in the horizontal space. The aspect ratio of the longitudinal section of the viewing space, i.e., the ratio of the height of the longitudinal section to the length of the bottom edge of the tower, represents the shape of the building cavity and reflects the path of reflection of the sound in the three-dimensional cavity. The enclosure of the façade reflects the degree of sound transmission from the interior of

Village	Zhaoxing Shangzhai		Zhaoxing Xiazhai		Zhaoxing Zhongzhai	Huanggang					Tangan
Drum Tower Name	Ren	Yi	Zhi	Xin	Li	Liangjing	Baxi	Dangliao	Gaoluo	Baoji	Tangan
Planar form	Quadrilateral	Quadrilateral	Quadrilateral	Quadrilateral	Quadrilateral	Quadrilateral	Octagon	Quadrilateral	Octagon	Quadrilateral	Quadrilateral
Inner column/pc	4	4	4	4	4	4	4	4	4	4	4
External column/pc	12	12	12	12	12	12	8	12	8	12	12
Height/m	21.8	25.8	10.9	25.9	23.1	17.8	18.5	18.8	16	18	20
High viewing space	10.13	15.41	11.13	15.33	13.5	9.4	10.5	9.6	9.6	9.63	9.69
Length of bottom edge/m	11.84	11.84	12.35	14.36	12.06	13.74	11	13.9	11.3	12.21	13.14
Number of heavy eaves layers/story	7	11	7	11	13	13	13	13	13	11	9
Roof form	octagonal saving tip	octagonal saving tip	Four Corner Resting Hill	octagonal saving tip	octagonal saving tip	octagonal saving tip	octagonal saving tip	octagonal saving tip	octagonal saving tip	octagonal saving tip	Four Corner Resting Hill
Building crown	Single	Single	Single	Single	Single	Single	Single	Single	Single	Single	Single

Live View

Village	Zengchong	Xiaohuang			Gaozeng			Luanli	Dali	Zaidang
Drum Tower Name	Zengchong	Xinqian	Xiaohuang	Gaohuang	Shangzhai (Gaomu)	Xiazhai (pomu)	Bazhai	Luanli	Dali	Zaidang
Planar form	Octagon	Quadrilateral	Quadrilateral	Quadrilateral	Quadrilateral	Quadrilateral	Quadrilateral	Hexagonal	Hexagonal	Octagon
Inner column/pc	4	4	4	4	4	8	6	6	6	4
External column/pc	8	12	12	12	12	14	14	6	6	8
Height/m	25	16	16.6	22	21	23.8	21.9	22	21.8	12
High viewing space	12.28	10.12	12.13	10.12	11.28	14.75	15	10.2	10.65	7.85
Length of bottom edge/m	9.71	9.23	11.08	9.23	11.8	12.08	8.41	9.3	10.1	7.54
Number of heavy eaves	13	11	13	11	14	17	13	15	9	7
Roof form	octagonal saving tip	octagonal saving tip	octagonal saving tip	octagonal saving tip	Four Corner Resting Hill	Hexagonal saving tip	Hexagonal saving tip	Hexagonal saving tip	Hexagonal saving tip	octagonal saving tip
Building crown	Double	Single	Single	Single	Single	Double	Single	Single	Single	Single

Live View

Fig. 1 Mapped values of the characteristics of drum towers and their morphologies

the building to the environment, i.e., the amount of sound spillover. The authors used these three characteristic quantities for the classification of the types of drum tower. The results are shown in Table 1. Different types of drum towers were simulated and compared by setting two of the above three characteristics as constant and varying the third.

Fig. 2 Internal structure of Dong Drum tower

Table 1 Classification of characteristics of drum towers in Gulou

Number	Drum tower name	Planar form	Elevation enclosure	Longitudinal profile height-to-width ratio
1	Ren	***Quadrilateral***	0.76	0.86
	GaoLuo	***Octagon***	0.76	0.85
1	ShangZhai (GaoMu)	Quadrilateral	***0.89***	0.96
	Zhi	Quadrilateral	***0.72***	0.90
2	DangLiao	Quadrilateral	***0.81***	0.69
	TangAn	Quadrilateral	***0.70***	0.74
3	XinQian	Quadrilateral	***0.77***	1.10
	GaoHuang	Quadrilateral	***0.85***	1.10
1	Zhi	Quadrilateral	0.72	***0.90***
	TangAn	Quadrilateral	0.70	***0.74***
2	Ren	Quadrilateral	0.76	***0.86***
	XinQian	Quadrilateral	0.77	***1.10***
	XiaoHuang	Quadrilateral	0.77	***1.10***
3	ShangZhai(GaoMu)	Quadrilateral	0.89	***0.96***
	XiaZhai(PoMu)	Quadrilateral	0.90	***1.22***
4	LuanLi	Hexagonal	0.97	***1.10***
	DaLi	Hexagonal	0.97	***1.05***

The drum towers were divided into three groups according to the three features mentioned above. One of the features was set to change, and is represented by a combination of bold and italics in the table, while the other two features were kept constant

Simulations and parameter settings

ODEON16.00 software was used to simulate the sound field. It considers specular and diffuse reflections as well as diffraction, and thus is regarded as among the most accurate softwares for modeling building acoustics based on geometric acoustic algorithms [33]. Its applicability to sound fields in small spaces, urban public open spaces, and semi-open and semi-enclosed spaces has been demonstrated [34–36]. Owing to the diverse architectural forms of the drum tower and the large number of decorative components on the surface of the building, the process of modeling was faceted, and was linearly simplified [37]. The fully enclosed drum tower was treated in the same way as an indoor sound field [38, 39], and the semi-enclosed drum tower was process by using the manual user settings of ODEON [40].The number of sound lines was set on a case-by-case basis [41], and the duration of the impulse response was set to two-thirds of the maximum duration of reverberation to enhance the accuracy of the calculations [42]. The coefficient of material absorption was modified with reference to past research [43], and by consulting the relevant tools [41, 44, 45] of the software [46]. The selected coefficients of absorption are shown in Table 2. The settings of humidity and temperature for each building were consistent, and the local annual average was calculated with reference

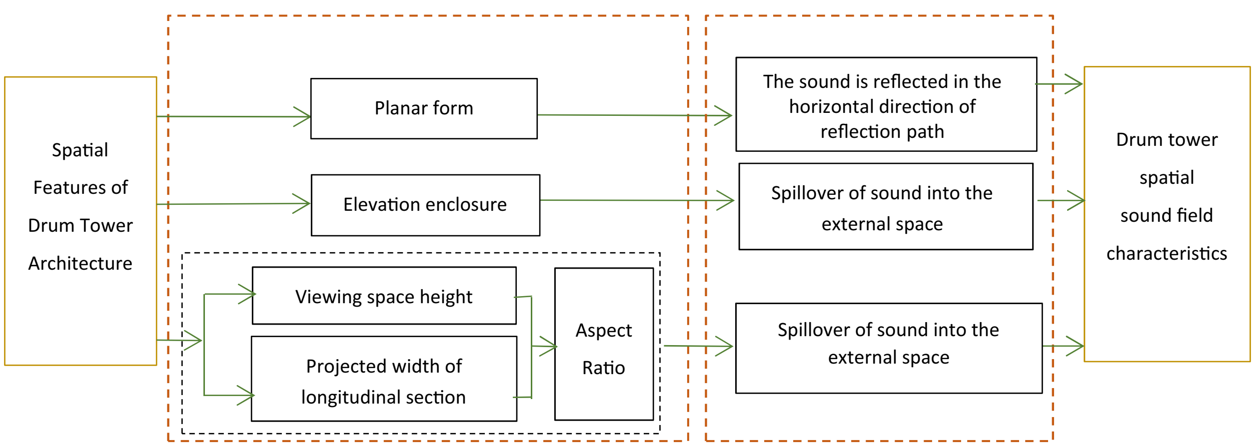

Fig. 3 Spatial characteristics and spatial relationships of the sound field of drum towers

Table 2 Coefficients of sound absorption of materials of the enclosure of the drum tower

Material Name	Sound absorption coefficient for the following frequencies (Hz)						
	63	125	250	500	1 k	2 k	4 k
Hard stone steps	0.01	0.01	0.02	0.02	0.02	0.03	0.03
Masonry	0.21	0.21	0.54	0.74	0.34	0.28	0.42
Interior wood materials	0.05	0.05	0.10	0.11	0.05	0.05	0.05
Wooden arch	0.25	0.25	0.32	0.41	0.53	0.40	0.50

to [47], where the humidity had been set to 80% and the temperature to 18.5 °C. The distance between each measurement point of the drum building and the source point of sound was consistent, and all parameters were calculated according to the ISO 3382–1:2009 standard.

Selection of characteristic quantities for evaluating the sound field

The drum tower is not a fully enclosed space, and the early decay time (EDT) can be used as an indicator of the quality of sound of the space to characterize changes in the sound energy with changes in its spatial morphology [48]. As a classical index for assessing indoor acoustics, the reverberation time (T30) can also be applied to evaluate the acoustic environment of open spaces [23]. The intensity index (G) was used as a logarithmic ratio to characterize the impulse response in the free field during the propagation of sound [49]. The variation in its magnitude can be used to accurately measure the characteristics of the sound field and assess its homogeneity [50]. Changes in the speech transmission index (STI) [51] can reflect the listener's perception of the clarity of the speech. Linguistic clarity (C50) is also an important index based on the impulse response used to measure the quality of sound in the sound field, and can reflect the level of energy of the reflected sound in relation to time and space [52] to represent its clarity. A weighted level of sound pressure (LAeq) can be used to characterize changes in sound pressure inside the sound field of the drum tower to reflect the changes in sound at different locations in this space.

To ensure the objectivity of the simulations, their results were compared with empirical measurements of the sound field with reference to the requirements of the just noticeable difference (JND) international standard. On-site sound measurement was performed by using the Lehua (AWA6291) sound level meter with a calibration error of ± 0.5 dB.A SONY professional recorder was used to record the on-site source of sound, and the sound of balloon burst was used as the source of the sound of the impulse response.The entire measurement process followed the ISO3382-1 standard. The height of the handheld sound source was 1.5 m, and six receiving points at an equal distance from the center of the drum tower were arranged in each tower. The distance between the source point to the receiving point was at least 1 m, and the height is 1.2 m as specified in the standard.The measured and simulated arrangement of measurement points for the sound field is shown in Fig. 4. The pressure of the source of sound in each octave in the sound field of the drum tower needed to be higher than the background noise of 45 dB for repeated tests of the background noise. The results show that background noise are below 20 dB, while the sound pressure level of the sound source are above 75 dB, the difference between the two meet the requirements of international standards. Live sound recording files after audio editing software Cool edit editing after using the reverberation room calibrated Dirac software for acoustic index analysis, the field measurement data of Huanggang Gaoluo drums building and simulation results error analysis is shown in Fig. 5, it can be seen that according to Table 3 (JND) standard comparison of the two types of results, the simulation results obtained values are within the allowable error, so the accuracy of the results of this simulation experiment can be guaranteed.

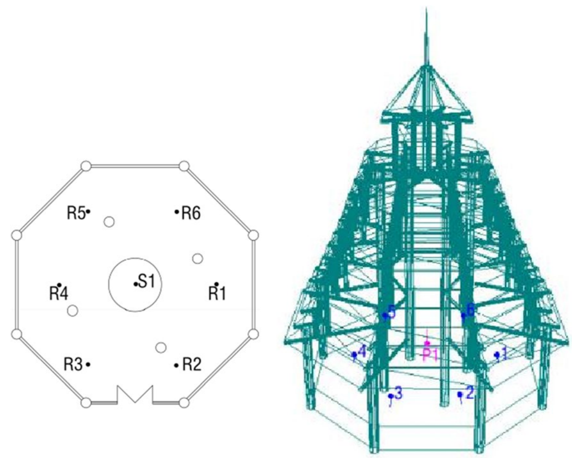

Fig.4 Measured and simulated positions

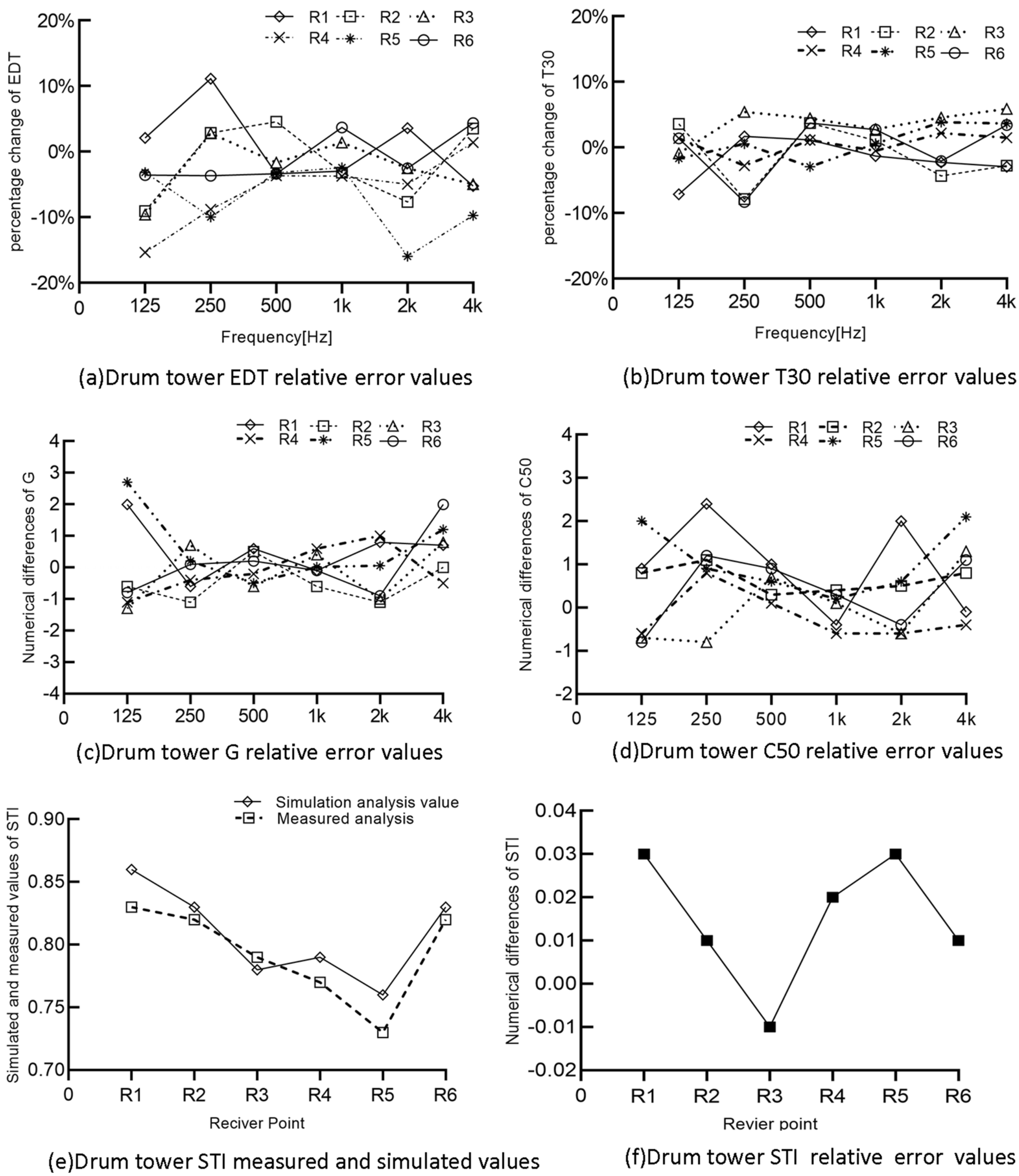

Fig. 5 Error between empirical measurements and the simulated calculations

Table 3 JND of the objective parameters

Parameter	G (0.5–1 kHz)	EDT (0.5–1 kHz)	C50 (0.5–1 kHz)	STI	RT (0.5–1 kHz)	LAeq
JND	1 dB	5%	1 dB	0.03	5%	–

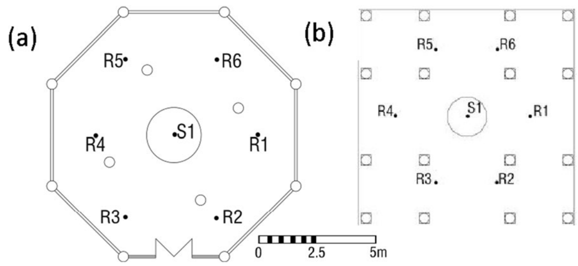

Fig. 6 Huanggang Gaoluo (**a**) Zhaoxing Rentuan (**b**)

points of the Huanggang Gaoluo Drum Tower (octagonal) and the Zhaoxing Rentuan Drum Tower (quadrilateral), as shown in Fig. 6.

The results of simulations of the Huanggang Gaoluo and the Zhaoxing Rentuan Drum Towers are shown in Fig. 7. The patterns of variations in the EDT, T30, and C50 with the frequency were the same at each measurement point in the two drum towers. The EDT of the Gaoluo Drum Tower had the largest value at 125 Hz and the smallest at 500 Hz. The difference in values between the measurement points was small. The value of EDT of

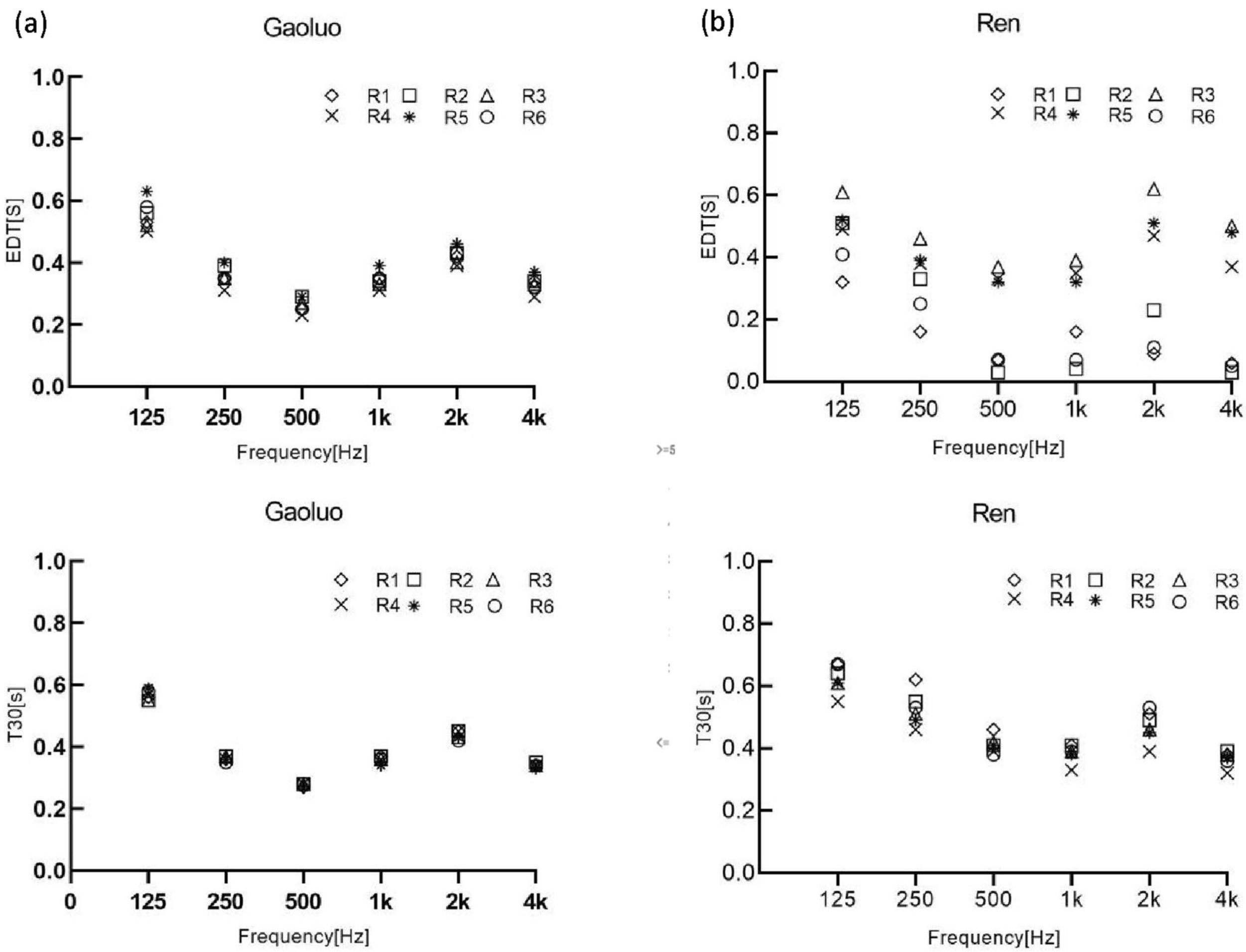

Fig. 7 Objective indicators of the simulated sound fields of Huanggang Gaoluo (**a**) and Zhaoxing Rentuan (**b**)

Results

Comparison of sound fields of drum towers with different planar shapes

The enclosure of the elevation and the aspect ratio of the longitudinal section were approximated as the screening conditions. The authors then compared the planar forms and the distributions of the simulated measurements the Zhaoxing Rentuan Drum Tower was the largest at 125 Hz, and then decreased gradually with an increase in the frequency of sound. After a short rise at 2 kHz, its value decreased with the increase in frequency. The values of T30 of the Gaoluo Drum Tower were 0.27–0.59 s, and smaller values were recorded at each measurement point at 500 Hz and 4 kHz.The maximum value was

Table 4 STI values of the drum towers

Name		Measurement point					
		R1	R2	R3	R4	R5	R6
Gaoluo	Numerical value	0.81	0.8	0.81	0.82	0.78	0.81
Ren		0.87	0.86	0.86	0.84	0.86	0.87

obtained at 125 Hz. The value of T30 of the Zhaoxing Rentuan Drum Tower was 0.34–0.66 s, slightly higher than that of the Gaoluo Drum Tower. Its value at each measurement point was the lowest at 1 kHz and 4 kHz, and was the largest at 125 Hz. However, the difference in values between the measurement points was larger than that of the Gaoluo Drum Tower, and was the most significant at 250 Hz and 500 Hz. Its value of C50 at 500 Hz was the largest, and was the smallest at 125 Hz, where the value at measurement point R2 was the lowest in each frequency band. The value of C50 at 500 Hz was the largest, and was the smallest at 125 Hz. The difference between the measurement points in the high-frequency band was small.

The values of STI of the two drum towers are shown in Table 4. Both were above 0.75, and the differences in values between their measurement points were small. The STI at each measurement point of the Gaoluo Drum Tower was lower than that of the Rentuan Drum Tower. The values of LAeq of the Gaoluo Drum Tower and the Rentuan Drum Tower exhibited the same pattern of variation with the frequency of sound, i.e., The maximum values at middle and high frequencies were higher than that at a low frequency. The difference in values between measurement points was significant at 500 Hz, and the results are shown in Fig. 8. The LAeq of the Gaoluo Drum Tower gradually decreased along its outer edge after a sudden drop at its inner column. The LAeq of Rentuan Gulou exhibited a significant reduction near the diagonal of the plane, and decreased uniformly from inside to outside at the other locations. The value of G of each measurement point for the two drum towers is shown in Fig. 7. The values of G between the measurement points of the Gaoluo Drum Tower were large, among which the value of G at R5 was smaller than those at the other measurement points. The difference in the values of G between measurement points R1 and R4, and the remaining measurement points was large as well. However, the difference in G at the same measurement point at different frequencies was small.

Comparison of sound fields of drum towers with different façade enclosures

The Huanggang Dangliao Drum Tower and Tang'an Drum Tower, which had similar planar forms and aspect ratios in the longitudinal section but different enclosures of the façade, were selected for comparison. They also

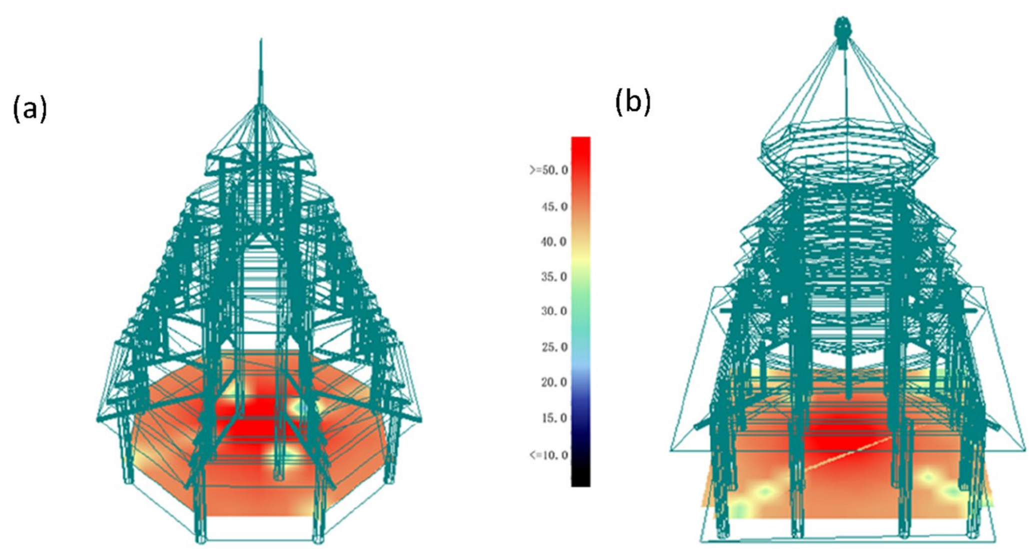

Fig. 8 Distribution of LAeq values for the Huanggang Gaoluo (**a**) and the Zhaoxing Rentuan Drum Towers (**b**)

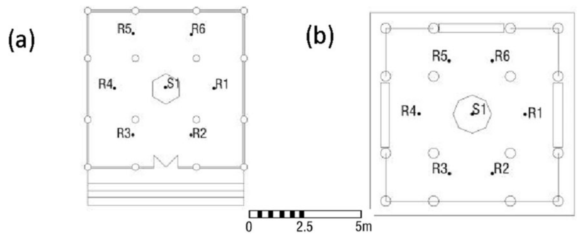

Fig. 9. Huanggang Dangliao (**a**) Tangan (**b**)

satisfied the screening conditions. Figure 9 shows the distributions of their simulated measurement points.

The results of the simulations are shown in Fig. 10. When the pattern of variations in the EDT with the frequency of sound tended to be the same for each measurement point in the drum tower, the difference in values between the measurement points was small. The EDT was the smallest at 500 Hz, and the difference in its values between measurement points was large. The EDT at each measurement point of the Tangan Drum Tower was inconsistent with changes in the frequency of sound, i.e., it gradually decreased after 250 Hz, but the decline at each measurement point was different. The minimum values at R3 and R6 were obtained after having remained stable in the low range of frequency. When the R4 measurement point in the drum building at 125 Hz-500 Hz, R1 measurement point at 125 Hz T30 value is the highest and higher than the average, the rest of the measurement point in each frequency band under the value of lower and different points between the difference is small. The pattern of variation in the values of T30 at different frequency bands tended to be the same at each measurement point of the Tangan Drum Tower, with the smallest values at 1 kHz and 4 kHz, and minor differences between the measurement points.

The value of C50 at 500 Hz was the largest, and was the smallest at 125 Hz, where the value at measurement point R2 was the lowest in each frequency band. The value of C50 at 500 Hz was the largest, and was the smallest at 125 Hz. The difference between the measurement points in the high-frequency band was small. The values of STI of the two drum towers are shown in Table 5, and all of them were above 0.75. The difference in its values between the measurement points was small. The difference in STI between the measurement points of the Tangan Drum Tower was large. The smallest value at measurement point R2, located at the entrance, was 0.76, and the largest value at R3, located at the west entrance, was 0.90. Except for measurement point R2, the values of the STI at all other measurement points were higher than those of the Tangan Drum Tower.

The patterns of distribution of the values of LAeq at different frequencies of sound of the Dangliao Drum Tower and Tangan Drum Tower were the same, i.e., the middle frequency yielded the largest value, and larger values were obtained at high frequencies than at low frequencies. The difference between the measurement points was more significant at 500 Hz, and the results are shown in Fig. 11. The value of G at each measurement point of the Tangan Drum Tower varied consistently with the frequency of sound, as shown in Fig. 10, with the smallest values at 500 Hz and 4 kHz, and the largest value at 125 Hz.The difference in values between the measurement points was small. The values of G of the Tangan Drum Tower were not significantly large, except at measurement point R2, at which it was significantly smaller than in the entire frequency band. The difference in its values between the other measurement points was small.

Comparison of sound fields of drum towers with different aspect ratios of longitudinal section

We compared the Shangzhai Gaomu Drum Tower and the Xiazhai Pomu Drum Tower, with similar planar forms and elevation enclosures but different aspect ratios in the longitudinal section, as shown in Fig. 12.

The results of simulations of the Shangzhai Gaomu Drum Tower and the Xiazhai Pomu Drum Tower are shown in Fig. 13. The regularity of variations in the EDT with the frequency of sound was the same for both drum towers. Their EDTs were the shortest at 500 Hz and the longest at 125 Hz. The difference in the EDTs between the measurement points decreased gradually with the increase in the frequency of sound, and was the most significant at 250 Hz. The overall EDT of the Pomu Drum Tower was slightly longer than that of the Gaomu Drum Tower, except at R1, which tends to be the same with frequency, i.e., the maximum at 500 Hz and the minimum at 125 Hz. But the difference between the values gradually increased with the frequency.The variation in the value of T30 with frequency was not significant at any measurement point of the Gaomu Drum Tower, and the difference in values between measurement points was small. The overall value of T30 of the Pomu Drum Tower was slightly higher than that of the Gaomu Drum Tower, and its values varied significantly between measurement points with the frequency of sound. The pattern of variation tended to be consistent, i.e., the minimum value was obtained at 500 Hz and the maximum at 125 Hz. The difference between the values at the measurement points was small.

The overall value of C50 was higher than that of the Pomu Drum Tower, but both have similar patterns of variation with frequency, i.e., both are maximum at 500 Hz and 4 kHz. The values of STI of both drum towers were above 0.75, as shown in Table 6, while the difference

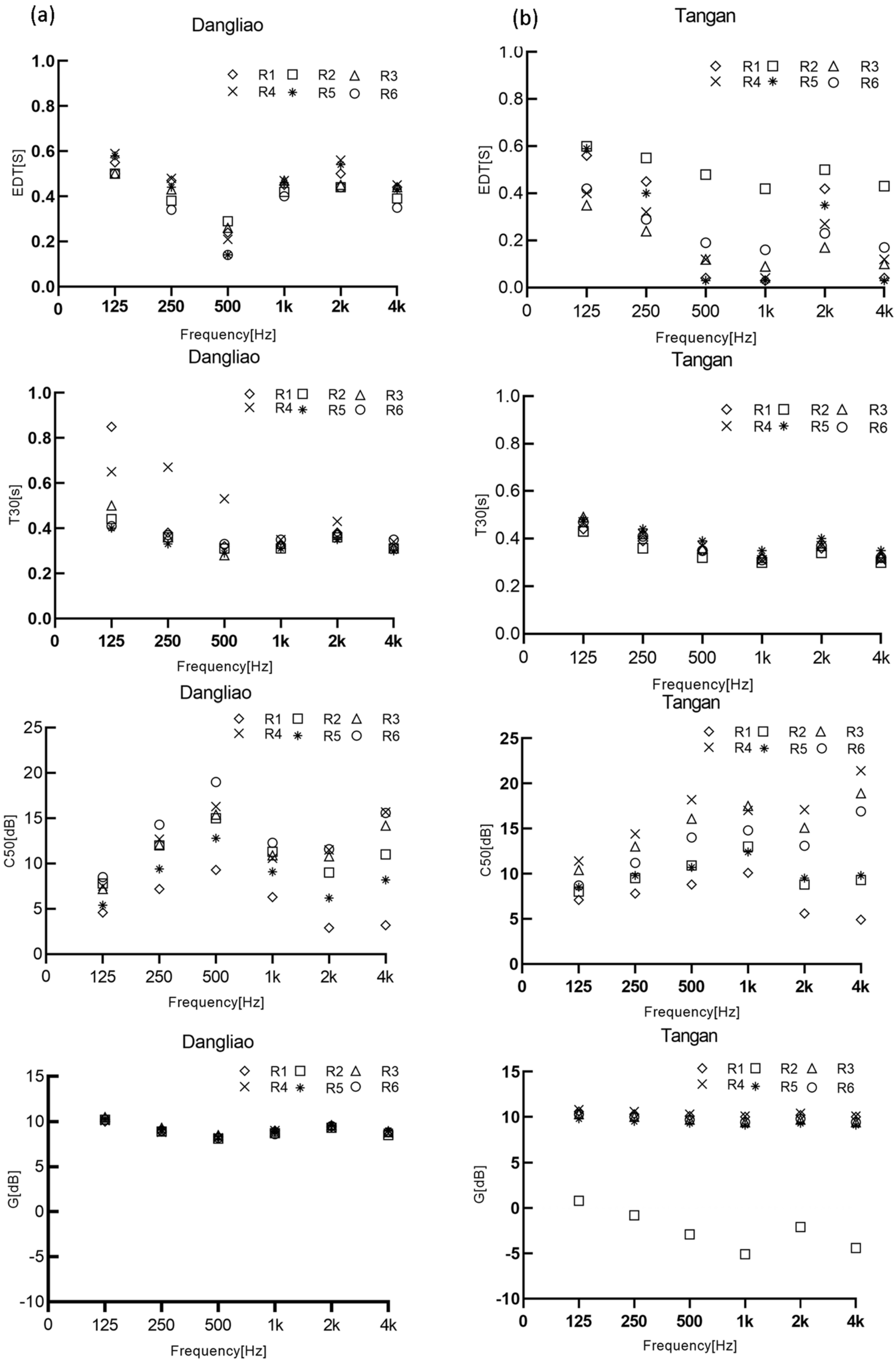

Fig. 10 Objective indicators of the simulated sound fields of Huanggang Dangliao (**a**) and Tangan (**b**)

Table 5 STI values of the drum towers

Name		Measurement point					
		R1	R2	R3	R4	R5	R6
Dangliao	Numerical value	0.83	0.81	0.83	0.82	0.84	0.85
Tangan		0.88	0.76	0.9	0.89	0.89	0.88

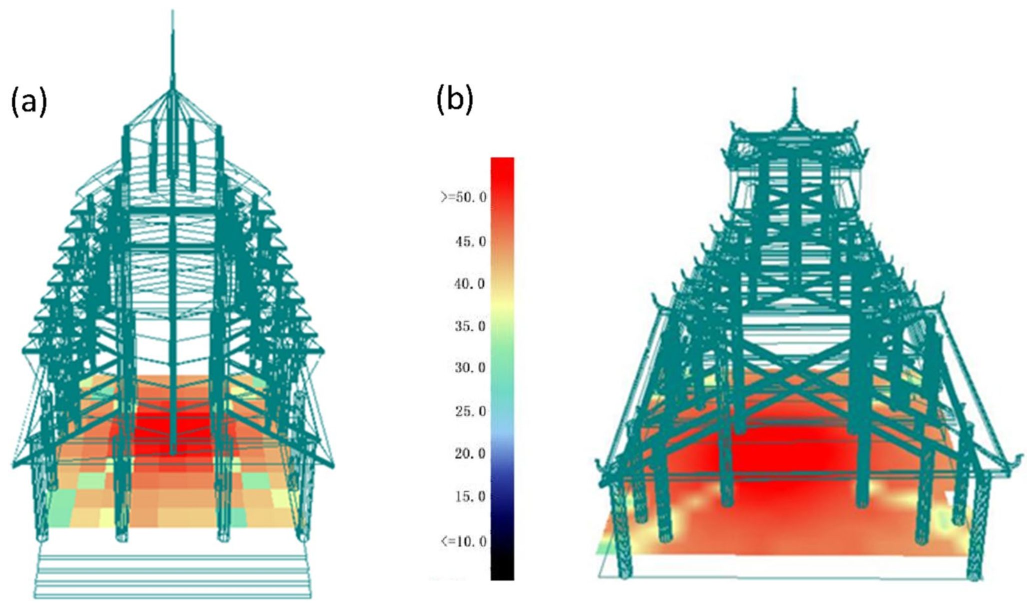

Fig. 11 Distributions of LAeq values of Huanggang Dangliao (**a**) and Tangan (**b**)

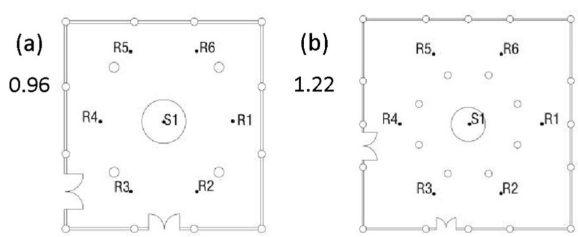

Fig. 12 Shangzhai Gaomu (**a**) Xiazhai Pomu (**b**)

in STI values between the measurement points of the Gaomu Drum Tower was small. The difference in STI between the measurement points of the Pomu Drum Tower was larger, while its average STI was lower than that of the Gaomu Drum Tower.

The pattern of distribution of values of LAeq in different frequency bands was the same for the Gaomu Drum tower and the Pomu Drum Tower, i.e., the largest values were obtained a medium frequency, and values at high frequencies were larger than those at low frequencies. The difference between the measurement points was the most significant at 500 Hz, and the results gradually decayed from inside to outside along the center, as shown in Fig. 14. The LAeq of the Gaomu Drum tower was large, as was the distance between the location of attenuation and the center, than that of the Pomu Drum Tower. The patterns of distribution of the values of G of the two drum towers were similar, and the small difference in values between their measurement points is shown in Fig. 13.

Discussion

The planar shape of a structure has a limiting effect on the propagation of sound in it in the horizontal direction. The above comparisons of drum towers of different shapes showed that listeners in the quadrilateral drum tower experienced clearer sound, and the small difference in sound pressure at different locations of the tower indicated that the sound field was more uniform. The sound energy decayed more uniformly in the octagonal drum tower over time, and the reverberations in it were closer to those in an acoustically well-designed hall [42]. The overall quality of the sound field in the quadrilateral drum tower was slightly better than that in the octagonal

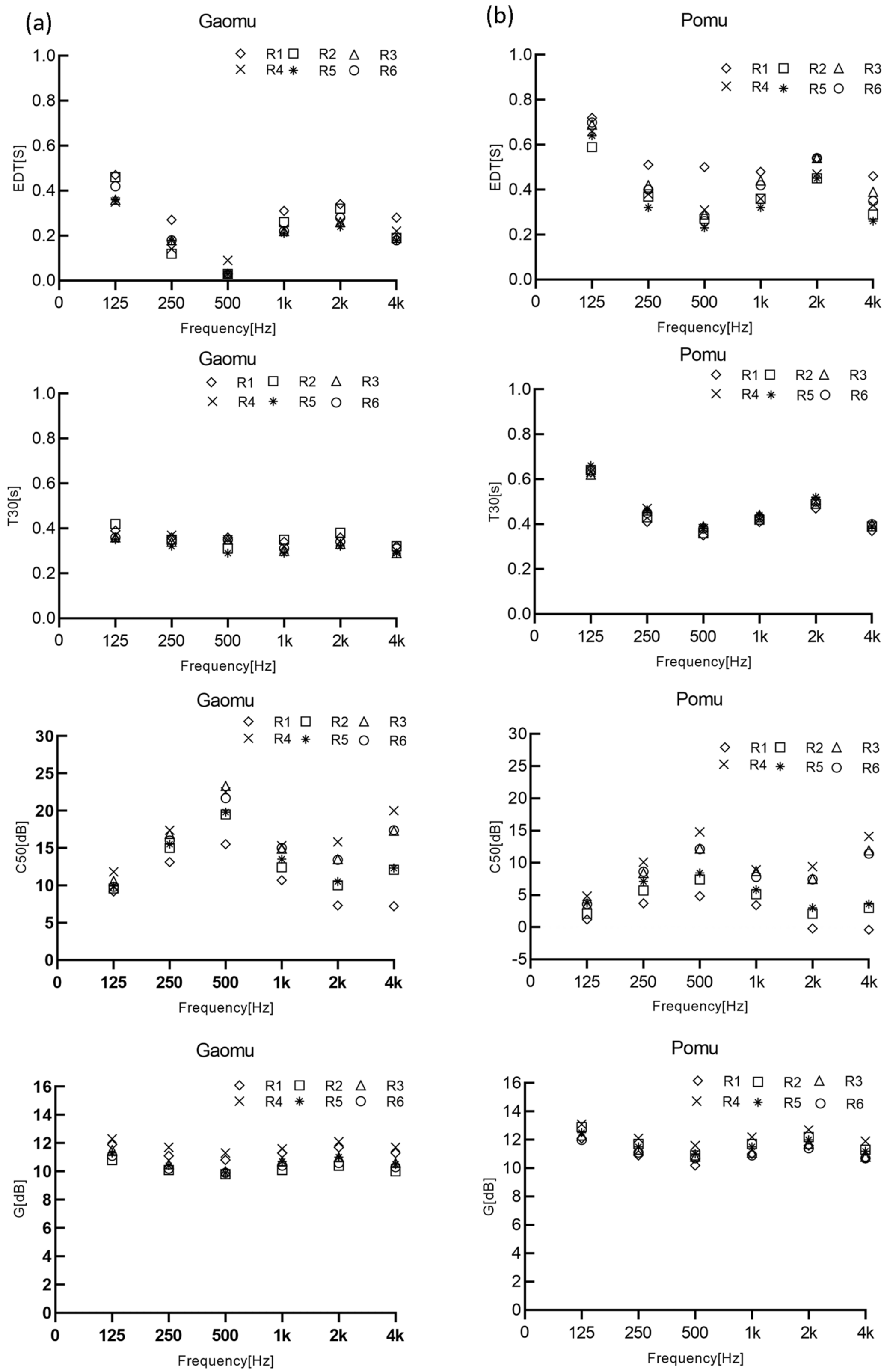

Fig. 13 Simulated values of the Shangzhai Gaomu (**a**) and Xiazhai Pomu (**b**) drum towers

Table 6 STI values of the drum towers

Name		Measurement point					
		R1	R2	R3	R4	R5	R6
Gaomu	Numerical value	0.88	0.9	0.89	0.89	0.9	0.9
Pomu		0.77	0.82	0.8	0.82	0.83	0.81

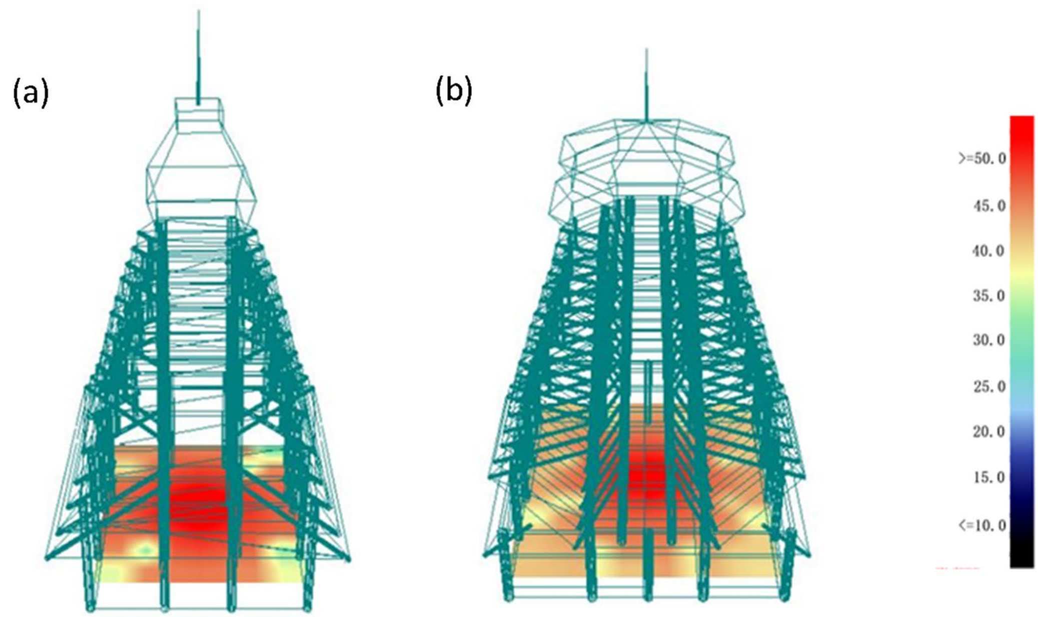

Fig. 14 Distributions of LAeq values of Shangzhai Gaomu and (**a**) Xiazhai Pomu (**b**)

drum tower.This explains one of the reasons why there are far more quadrilateral drum towers than octagonal ones in Dong villages.To overcome the shortcomings of the sound fields of the two planar forms, the authors suggest increasing the number of reflective surfaces in the viewing space of the quadrilateral drum tower to improve the effect of reverberations. As the octagonal planar form satisfies the aesthetics of the Dong people in terms of construction and decoration, its sound field should be improved by changing the aspect ratio of the enclosure of the facade.

The surface enclosure has a limiting effect on the ratio of reflection to transmission of sound in the sound field. A comparison of the two enclosures of the facade of the drum tower showed that the tower with a larger facade underwent a more stable change in sound energy, and had a more uniform sound field and clearer sound at different locations within the drum tower. The drum tower with a smaller façade enclosure had a good reverberation effect, and the differences in the magnitudes of sounds experienced at different locations were smaller. Therefore, the dimensions of the enclosure of the façade should can be changed according to the specifics of the drum tower by using easily removable materials to enhance the reverberation effect and make the sound field more uniform.

The aspect ratio of the longitudinal profile has a limiting effect on the direction of propagation of sound in space. The comparison of drum towers with different aspect ratios showed that sound in the tower with a larger aspect ratio varied less with time, and the reverberation times at different locations in the space varied greatly,but were all short. Therefore, the drum tower can provide a relatively stable reverberation effect, and the volume of the sound at different locations decreases from its center to its edges. The sound field was also more uniform. The drum tower with a smaller aspect ratio provided clearer sounds, and the difference in sounds between locations was not significant. The overall quality of the sound field of the drum tower with a large aspect ratio was slightly better. Engineers should thus appropriately increase the aspect ratio of new drum towers that are constructed, and the height of the platform of the wooden drum placed inside existing drum towers should be altered to change its aspect ratio and thus improve the reverberation effect, uniformity of the sound field, and clarity of the sound.

Conclusion

The quality of the sound field of a quadrilateral drum tower is slightly better when the enclosure of its facade is consistent with the aspect ratio of its longitudinal section. Among the variables reflecting sound quality, the STI and C50 at different locations within the quadrilateral tower had smaller differences but larger values, changes in the values of G were not prominent. However, differences in the EDT and T30 between the measurement points of the tower were large, and this led to a poor reverberation effect. The changes in T30 and EDT at different locations in an octagonal drum tower tended to be consistent, but differences in the values of G and LAeq at different measurement points were large. The value of C50 was small, because of which the sound field was not uniform and the resulting sounds were unclear.

When the aspect ratio of the longitudinal section of the drum tower was consistent with its planar shape, the EDT values at different locations of the tower with a larger enclosure of the facade were large, and had the same trend of change. Differences in the values of STI, C50, but those in T30 were large, and values of LAeq decayed significantly from the center of the tower to the outside. The reverberation effect was thus poor, and there were significant differences in the magnitude of sound at different locations. The difference in T30 at different positions in the drum tower with a small enclosure of the facade was not significant, and the decay in the value of LAeq from the center to the outside was not prominent. However, the differences in the values of C50, LAeq, and G at different positions were significant, because of which the clarity of sound and the uniformity of the sound field in the drum tower were poor.

When the enclosure of the facade was consistent with the planar shape, the quality of the sound field of the drum tower with a large aspect ratio in the longitudinal section was good. The values of C50 and the STI at different locations in the drum tower with a small aspect ratio were large. However, the values of the EDT and T30 were small, and those of G at different locations were different such that the reverberation effect and the uniformity of the sound field were poor. The values of EDT and T30 at different locations in the drum tower with a large aspect ratio in the longitudinal section were high. However, the value of C50 was small and LAeq gradually decayed from inside the tower such that the clarity of sound was poor. Moreover, there were significant differences in the intensity of sound experienced by listeners at different locations.

The results of the simulations showed that the value of STI of the drum towers under different constraints was above 0.75, which reflects excellent intelligibility of sound. Moreover, few drum towers in the Dong region have hexagonal and octagonal planar forms. Therefore, in this study, when screening the three variables, the two groups of “façade enclosure” and “aspect ratio of longitudinal section” for quantitative purposes are missing hexagonal and octagonal plan forms. In future work, the authors plan to collect more data on drum towers with polygonal floor plans to further generalize the results of this study.This study focuses on the sound field simulation of ancient Chinese buildings, because of the small research on the sound absorption of ancient building materials, coupled with the inability to disassemble for laboratory mapping, some of the errors in the experiments are considered reasonable, and the study aims to characterize the sound scene, and does not follow the evaluation criteria of the sound quality of modern halls to evaluate the merits of their sound field.

The study can provide a sound field research perspective for the future construction and protection of drum towers in the Dong ethnic area, which can be protected in three dimensions: plan form, façade enclosure and different aspect ratios of longitudinal section. And extend the protection from purely external surface protection to the "interior", enriching the comprehensive protection strategy of the Dong ethnic drum towers.

Acknowledgements
The work was supported by the Youth Project of the National Natural Science Foundation of China (51808356), the Humanities and Social Sciences Fund of the Ministry of Education (22YJA760058), and the Hebei Province University Humanities and Social Sciences Research Youth Top Talents Project (BJS2022008).

Author contributions
LM: conceived and designed the experiments, performed the experiments, analyzed and interpreted the data, contributed reagents, materials, analysis tools or data, wrote the paper. JM: performed the experiments, analyzed and interpreted the data, contributed reagents, materials, analysis tools or data, wrote the paper. XZ: performed the experiments, analyzed and interpreted the data, contributed reagents, materials, analysis tools or data. BL: conceived and designed the experiments, analyzed and interpreted the data, contributed reagents, materials, analysis tools or data. JN: performed the experiments, analyzed and interpreted the data, contributed reagents, materials, analysis tools or data.

Funding
The work was supported by the Youth Project of the National Natural Science Foundation of China (51808356), the Humanities and Social Sciences Fund of the Ministry of Education (22YJA760058), and the Hebei Province University Humanities and Social Sciences Research Youth Top Talents Project (BJS2022008).

Availability of data and materials
Data will be made available on request.

Declarations

Ethics approval and consent to participate
Our research paper "Comparison and Simulation-based Analysis of the Sound Field of Dong Drum Tower Buildings", written by Linqing Mao, Jianjun Ma,Xin Zhang, Bin Liu and Jianzhuang Niu, contributes to your journal. All the authors of this article guarantee that: (1) The study complies with the relevant ethical codes; (2) Oral informed consent was obtained from all participants in the study; (3) Truthfulness of thesis content.

Consent for publication
Not applicable.

Competing interests
The authors declare that they have no conflict of interest.

Received: 18 July 2023 Accepted: 20 September 2023
Published online: 03 October 2023

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