Acoustic Design of the Philharmonic Hall in the Shanghai Oriental Art Center

WANG jingbo, ZHANG kuisheng

(Shanghai Modern Architectural Design (Group) Co., Ltd. Shanghai, 200041)

Abstract: The Shanghai Oriental Art Center opened officially on July 2005 is one of the largest performance art centers in the domestic. It mainly consists of the 2000 seats philharmonic hall, the 1100 seats opera house and the 330 seats chamber music hall, and several rehearsal facilities. It has been become one of the most important landmark buildings in Shanghai as well in PuDong new district. In this paper it is mainly elucidated the features of the architectural acoustics design of the 2000-seat philharmonic hall, the largest specially designed for music performance venue. It is also covered the objective acoustical measurement results and a bit of subjective acoustics evaluation from all circles after opening.

Key words: Philharmonic Hall; Room Acoustics Criteria; Building Acoustics Index

INTRODUCTION

The Shanghai Oriental Art Center, opened officially on July 2005, is one of the leading performing arts and cultural facilities in Shanghai and mainland of China. It was designed by French architect Paul Andreu and ADPi, in closed collaboration with the local architects & engineers----ECADI(East China Architectural Design & Research Institute Co., Ltd.). The complex includes the 2000 seats philharmonic hall, the 1100 seats opera house, the 330 seats chamber music hall, and several rehearsal facilities. The overall floor area is 39,964 square meters.

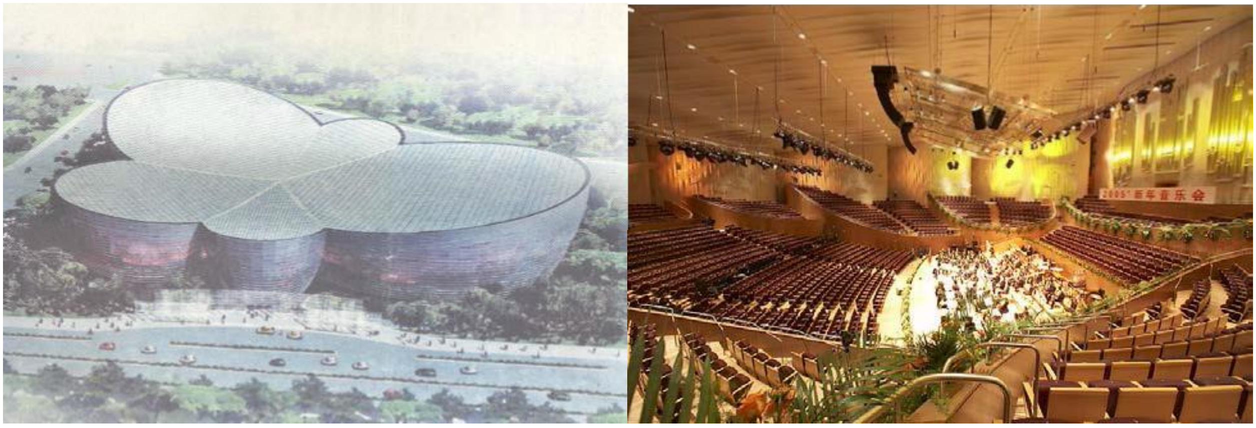

Figure 1. A bird’s-eye view of OAC (archi. rendition) & interior of the Philharmonic hall

The building merges architectural artistry with functionality. The five interconnected hemispherical halls or 'petals', which resemble a butterfly or butterfly orchid from above, with each 'petal' belonging in turn to the entrance of individual hall.

As an acoustical consulting team affiliated to the Shanghai Modern Architectural Design (Group) Co., Ltd, we were commissioned by ECADI and client respectively as the local acoustical consultant, we were involved in this project as early as the phase of preliminary design, mainly focused on some issues related to sound insulation, noise & vibration control of mechanical facilities, computer simulations for three main halls on room acoustics, acoustical consulting for detailed design in construction phase and final acoustic measurements. In this paper only the topics of room acoustics are focused.

Mr. Jean Paul Vian from CSTB, France worked as an acoustical expert for architect Paul Andreu in supporting of architectural competition and preliminary design, he also supervised the overall construction phase, co-organized and participated in the first acoustical measurement for philharmonic hall. The author presents this article not only to retrospect the overall progress in building this art center, but also to pay the tribute to Mr.Vian, an unforgettable and respectable mentor.

Acoustic consideration for philharmonic hall

The philharmonic hall is mainly aimed at the symphonic repertoire from classical to contemporary period. The ground plan shape is elliptical shape with a quasi central stage. The maximum length is 53 meters, and the maximum width is 42 meters, with the audience seated around the central stage. It is the so called style of vine yard, as the classical vine yard concert hall, the Berlin Philharmonie Hall. As to the large scale concert hall, the two concert hall forms considered appropriate for the best acoustic characteristics are the terraced (vine yard) and the parallel-sided hall (shoe box). One of the obvious features of vineyard concert hall is that the audience in each terrace can receive the unobstructed direct sound, and the significant early reflections for musicians and the audience in stall is provided by the front side wall of each terrace. The intimacy in view of acoustics and sightline between musician and audience is developed so naturally that the vineyard layout for audience has become one of the successful styles for large scale concert hall. The plan and longitudinal section of the Philharmonic hall is showed on Figure 2.

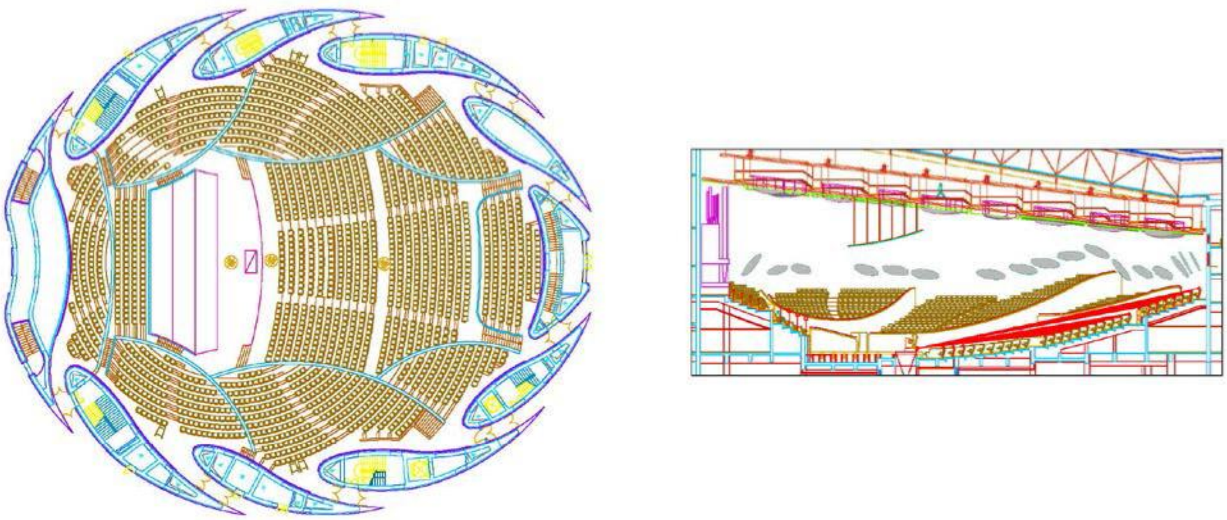

Figure 2. Plan and longitudinal section of the Philharmonic hall

The wall of concert hall are enclosed by eight fish-shaped reinforced concrete cores in which the mechanical ducts can be installed, and the corridor is also organized within it. The interior reflective ceiling is an inclined plan with diffusing treatment to provide smooth ceiling reflections over the audience, it is higher on the end of the performance area, and lower on the rear end of the hall. Most of the audience area receives early lateral reflections from the side walls that surround them, including the walls behind due to their orientation and the diffusive reflectors spread on the lower part of the walls. The front of the terrace blocks are organized to provide early reflections for both musicians and the audience in the front stage and main seating area.

Five blocks of large elliptic stage reflectors which are fully adjustable for the height and the inclination, are hung above stage around the height of 12 meters, to provide good connection between different parts of musicians.

The distance to the stage for all audience is reasonable short, the average distance to the podium on stage is 17 meter for the whole audience, so as to achieve the appreciated intimacy both in view of acoustics and sightline. The ceiling height is 16 meters above the performance stage, and the overall average height is 11meters above the listener's head position.

The acoustical effective room volume amounts to approx. 24000m3, the volume falls to each seat amounts to approx. 12m3/seat. If the number of musicians & chorus is considered, the volume falls to each seat amounts to approx. 10.6m3/seat.

On the performing stage area, by changing the height of the elevated platform, the stage can offer different settings to satisfy any grand symphony orchestra and meet the best choruses' performance requirements. It boasts one of the largest pipe organs in mainland of China, equipped with an 88 diapasons

5-layer hand controlled keyboard pipe organ made by Rieger, Austria.

Both the wall and the ceiling is made of massive GRG, all sections are prefabricated in moulds off site, then are fixed to the steel frame. Some fine-scale irregularities were formed on the GRG panel surface, both for acoustics and aesthetics. The front of the terrace blocks are made of wooden style, the plywood glued tightly to the MDF board. The floor is covered with two layers of thick wood fixed on timber frame mounted on the concrete floor slab.

In order to allow for variation in the reverberation time (RT), 66 blocks of highly absorbing baffles are hidden in the ceiling and randomly spread around the ceiling. All these baffles are motorized for up and down motion, and are prefabricated panels covered by fire-resistance fabric. The overall absorbing area is large enough to correspond to the required absorbing area for the variation of RT from 2.1s to 1.6s theoretically.

Each section of the fish-shaped enclosed wall of concert hall has the diffusive property, especially for lower frequency, with a few of diffusive reflectors spread on the lower part of these wall. These reflectors are fabricated by thick frosted glass (thick sandblasted sheet glass), and be designed to be rotated flexibly to tune the orientation of reflections.

Originally a large elliptical stage reflector or stage canopy was designed to be hung above the stage. During the construction phase, this idea was transformed into five blocks of long oval reflectors, and each block was composed of peaces of laminated glass.

The chairs are wooden appearance with the surfaces not covered by a sitting person, such as the back of the back rest, the lateral surfaces as well as the arm rest, including the back rest which reaches above shoulder height, being sound reflecting. In such a way, the absorption area of the occupied chairs is as close as possible to that of the unoccupied ones. From the acoustic point of view, too large seat width and row spacing shall be avoided. The average row spacing is 0.90m and the seat width is 0.56m.

Objective room acoustics criteria and room acoustical computer simulation

For the philharmonic hall, the following criteria which are defined in the standard ISO3382 were adopted.

Table 1. Room acoustics criteria for the hall

Reverberation Time (RT)	variable 1.6 s ~ 2.1s, mid frequency
Early Decay Time (EDT)	1.4 s ~ 1.8s, mid frequency
Clarity (C80)	-3 dB~ 1dB, mid frequency
Early Lateral Energy Fraction (ELEF)	0.15~0.30
Total Relative Sound Level or Strength (G)	⩾3dB
Background Noise	NR--20

For the room acoustical simulation, Odeon was used (Mr. Vian’s team used the Epidaure developed by CSTB to present the results of simulation in the preliminary design). A 3D geometric model was created that included the detail required of the software, but was not of high geometric fidelity. For example, the audience area of each terrace was treated as a single slope surface, to avoid too many strips and steps. All the curved surfaces split into a series of plane surfaces with reasonable dimension size, especially for the main curved surfaces. Using the current computer ray-tracing techniques combined with other non-specular (mirror) reflection model method, and using a reasonable transition order and coefficient of absorbing and scattering, the value or the tendency obtained from simulation and the statistical predicted reverberation time closely match. In the computer model, the omni-directional source was set on stage, microphone positions are spread over one half in the hall due to the symmetry. Figure 3 is the geometric model of the hall with ceiling baffles down.

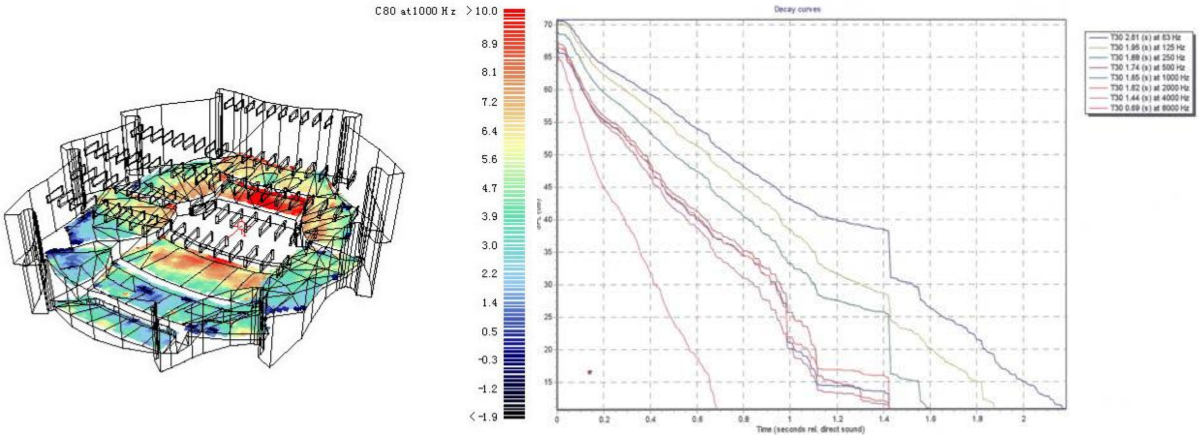

Figure 3. The geometric model of the hall and decay curve with ceiling baffles down

The room acoustics simulation of this hall is investigated the following issues: (1) the influence to room acoustics criteria caused by the reflector above the stage; (2) the calculated room acoustics criteria range under the absorbing and reflecting status by the movable up and down baffles on the ceiling; (3) the influence to room acoustics criteria caused by the front shape of the terrace located on the stage and stall area. According to coefficient of the potential materials used in the hall, and the scattering property be taken into consideration, each surface will be given a specific scattering coefficient. The average simulation value of RT from 13 points is given in Table 2. Other room acoustics criteria at 1000Hz under three conditions are given in Table 3.

Table 2. The average simulation RT under two conditions

frequency(Hz)	125	250	500	1k	2k	4k
RT30 (S)---- baffles up	2.37	2.29	2.23	2.17	1.89	1.63
RT30 (S)---- baffles down	1.99	1.81	1.70	1.69	1.65	1.42

Table 3. Other room acoustics criteria at 1000Hz under three conditions

receive point	ceiling baffles move up, with reflector above stage				ceiling baffles move up, without reflector above stage				ceiling baffles move down, with reflector above stage			
	EDT	C80	G	ELEF	EDT	C80	G	ELEF	EDT	C80	G	ELEF
1	1.73	3.5	2.4	0.049	1.14	4.9	1.6	0.059	0.93	7.0	1.4	0.051
2	1.36	3.6	3.2	0.196	1.03	4.9	2.3	0.214	0.80	7.0	2.1	0.194
3	1.49	-1.7	2.1	0.163	1.27	1.1	-0.1	0.167	1.00	3.0	-0.6	0.165
4	1.61	2.2	1.8	0.216	1.19	3.3	0.7	0.244	0.94	4.8	0.3	0.235
5	2.04	-1.1	1.4	0.179	2.00	-0.8	-0.9	0.130	1.05	2.5	-2.2	0.116
6	2.11	-1.0	0.3	0.173	1.64	0.9	-1.6	0.223	0.96	3.2	-2.3	0.146
7	1.25	6.7	3.9	0.016	0.65	9.4	3.0	0.005	0.69	9.0	3.1	0.002
8	1.72	2.0	1.5	0.101	1.22	4.1	0.2	0.090	0.93	5.3	0.0	0.088
9	1.67	3.0	1.2	0.118	1.39	4.5	0.3	0.111	0.97	6.0	-0.2	0.122
10	1.78	2.5	0.7	0.062	1.41	4.1	-0.1	0.052	1.13	5.5	-0.8	0.054
11	1.78	1.7	0.9	0.125	1.39	2.9	-0.5	0.114	1.18	4.3	-0.6	0.109
12	1.86	1.4	0.6	0.140	1.44	2.9	-0.9	0.138	1.25	4.0	-1.4	0.080
13	1.97	0.7	0.6	0.136	1.37	2.3	-0.6	0.137	1.21	1.8	-2.4	0.097

From the Odeon simulation it is obvious that

- Under the condition of reflector installed and ceiling baffles are moved up, all the values of strength of 13 points are larger than the ones without reflector, and the value of each point is large than 0dB. While the value of clarity of each point with reflector is smaller than the value without reflector, the values are approaching the expected. The change of clarity has an apparent coherence with the EDT.
- It is demonstrated that the role of reflector is not only to increase the strength on most audience area, but also to decrease the clarity on those area (become more reverberant). The reason of the value of clarity at several points is more high is related to the closed position to the sound source, it is predominant

by the strong reflections after direct sound.

▪ Under the ceiling baffles totally move down, the value of strength and EDT is smaller than the condition of the baffles totally move up. While the value of clarity under the condition of baffles down, is increased obviously.

▪ Under the condition of absorbing (baffles down), the energy decay of RT has the property with the double slope decay as expected in the range of mid to high frequency, i.e. it is decayed more fast in the early while decayed more slowly in the late part. It is expected to boast the high clarity meanwhile with the required resonant.

Early lateral reflections play a prominent role in concert hall listening, the perceived apparent source width (ASW), one of the components for spaciousness, which is predominantly determined by the early sound. Generally the value of ELEF should be in the range of 0.2—0.3 to acquire the reasonable spatial impression. From the results of simulation, the ELEF is approached to or larger than the value of 0.2 on the areas closed to the front wall of terrace, whereas it has little influence by the ceiling status. As the vineyard hall, the front wall of each terrace has a much more role in improving the ELEF. The relative lower ELEF on the area just faced the stage has much high clarity of music and reasonable strength with those can be compensation the lacking of part of spatial impression.

It can be deduced that the influence to ELEF by the downwards terrace front varies in the receive points, and it is obvious that ELEF can not be increased by the diffusive treatments. In fact, comparing to direct sound, if the discrete lateral reflection is too strong or the arriving time is too early, the false localization and tone coloration could occur.

Objective acoustic measurement

The groundbreaking held on April 2002 marks the start of construction on OAC. The detailed design & construction lasted three years for this prestigious project, and the construction of philharmonic hall was finished firstly on the end of 2004. The final acoustic measurement was carried out on Dec. 7,8 and 9., Mr. Jean Paul Vian from CSTB and our team work together to take the room acoustics measurement, on empty and occupied condition, as well to tune some acoustical elements for the expected target. Local Shanghai Symphony Orchestra and Shenzhen Symphony Orchestra based on Shenzhen, South China, were invited by client to performing for the first time in this hall, which also to provide the chance for acoustic measurement. On the March 2005 our team undertook the commissioning measurement covered of the philharmonic hall, opera house, chamber music hall, and rehearsal facilities. Part of results of the measurements on the mentioned two phases is shown below.

Table 4. Results of the measurements under different conditions

measuring condition	mid frequency of octave band						notation
	125	250	500	1k	2k	4k	
Reverberation Time (RT)							
unoccupied, baffles up—ceiling reflecting	2.1	2.0	2.0	1.9	1.8	1.5	F+C*
occupied, baffles up—ceiling reflecting	2.0	1.9	1.9	1.8	1.8	1.5	F+C
unoccupied, baffles down—ceiling absorbing	1.9	1.9	1.8	1.7	1.7	1.4	F+C
unoccupied, baffles up—ceiling reflecting	2.04	1.98	2.0	1.9	1.76	1.25	C**
unoccupied, baffles down—ceiling absorbing,	1.95	1.87	1.85	1.77	1.64	1.24	C
Early Decay Time (EDT)							
unoccupied, baffles up—ceiling reflecting	2.1	1.9	1.9	1.8	1.8	1.4	F+C
occupied, baffles up—ceiling reflecting	1.7	1.7	1.6	1.6	1.6	1.4	F+C
unoccupied, baffles down—ceiling absorbing	2.1	1.7	1.7	1.6	1.6	1.2	F+C
unoccupied, baffles up—ceiling reflecting	1.93	2.05	1.99	1.77	1.63	1.13	C
unoccupied, baffles down—ceiling absorbing,	1.88	1.83	1.7	1.56	1.5	1.12	C
Clarity (C80)							
unoccupied, baffles up—ceiling reflecting	-3.0	-1.1	1.1	1.4	0.9	1.9	F+C
occupied, baffles up—ceiling reflecting	-3.2	0.0	1.6	2.0	2.0	2.4	F+C
unoccupied, baffles down—ceiling absorbing	-3.4	-0.8	2.0	2.0	2.0	3.3	F+C
unoccupied, baffles up—ceiling reflecting	-1.74	0.10	1.17	1.00	1.80	2.71	C
unoccupied, baffles down—ceiling absorbing,	-1.06	0.36	2.39	2.61	2.49	3.03	C

* F+C means done by CSTB and our team on Dec. 7--9, 2004.

** C means done by our team on Mar. 25, 2005.

The mid-frequency RT on the unoccupied and occupied is 2.0s and 1.9s respectively which is the suitable and satisfied criteria for this hall, the relative flat spectrum of RT is not a bad situation. It is rather favorable for giving a very clear and precise acoustics suitable for classical and 20th century repertoire. Clarity, EDT and LE are all within the expected design target, and are corresponding to excellent values, rather homogeneously spread over the entire audience area.

From the day of its official inauguration on July 1st 2005 till now, OAC has hosted many high-level performances. A famous and well-traveled conductor made his comment on OAC upon seeing the season's calendar during his visit in 2009 "It's whether classical or popular, Chinese or Western, public or commercial purpose amazing to find such an international level venue in Shanghai" Some counterparts both from the domestic and abroad also give their appreciation for the acoustics as well as the interior. Of course few performers from local orchestra ensemble who have been accustomed to playing under an orchestra shell in multi-function theatre need to adapt the acoustics when playing on stage in this vine yard concert hall on the first time.

References

1. Michael Barron "The current state of acoustic design of concert halls and opera houses'' ACŨSTICA 2000, TECNIACŨSTICA MADRID 2000
2. ISO 3382 (1997) "Acoustics - Measurement of the reverberation time of rooms with reference to other acoustical parameters"
3. Leo L. Beranek, "Concert and opera halls: how they sound" (1996, published by Acoustical society of America, ISBN 1-56396-530-5)
4. J.H. Rindel, "Computer simulation techniques for the acoustical design of rooms - how to treat reflections in sound field simulation" ASVA 97, Tokyo, 2-4 April 1997. Proceedings p. 201-208.
5. Wang JingBo "Acoustical computer simulation for the philharmonic hall of the oriental art center in Shanghai" Construction & Design for Project, ISSN 1007-9467/CN11-3914/TU, 2003.03.

兩個水景劇院的建聲設計與音質模擬
Architectural Acoustical Design and Acoustic Simulation of Two Waterscape Opera Houses

宋擁民，章奎生

SONG Yong Min, ZHANG Kui Sheng

（上海現代建築設計（集團）有限公司 章奎生聲學設計研究所，上海 200041）

(Zhang kui-sheng Acoustic Design and Research Studio, Shanghai 200041，China)

Abstract: An overview on the architectural design of two waterscape theaters is summarized. One named Jiading Poly grand theater which built beside Yuanxiang Lake in Shanghai and the other named Sanya Serenity Coast concert hall built on the intersection of small East China Sea and Luhuitou Bay. The main ideas and acoustic targets of acoustic design on 1500-seats opera house in Poly Grand Theater and 1300-seats opera house in Sanya Serenity Coast concert hall are introduced in detail, so the approaches to make satisfied acoustic are. Then acoustic simulation analysis was done in both two opera houses with Odeon which is the room acoustics program. Meanwhile, 1/10 scale-model test of 1500-seats opera house was done. Preliminary acoustics evaluations on those two waterscape grand theaters based on computer simulations were given.

Key words: Opera house; Acoustic simulation; Scale-model test; Acoustic evaluation

摘　要：概述了建於遠香湖湖畔的上海嘉定保利大劇院和建於小東海與鹿回頭灣交匯處的三亞半島音樂廳兩個水景劇院的建築概況，重點介紹了保利劇院 1500 座歌劇廳和半島音樂廳 1300 座歌劇廳的音質設計思想、技術指標及建聲措施，並對兩個水景劇場進行了廳堂音質電腦類比分析，同時還完成了保利 1500 座歌劇廳 1:10 聲學縮尺模型試驗，最後依據電腦空滿場類比結果對兩個劇場的音質進行了初步評估。

關鍵詞：歌劇廳; 音質電腦類比; 縮尺模型試驗; 音質評價

1 劇院建築概況

上海嘉定保利大劇院是世界級建築大師安藤忠雄先生在中國設計的首座大型文化設施項目，保利置業集團參與承建。劇院面向遠香湖，基地北側為白銀路，西側為規劃中的環湖路，東側和南側臨遠香湖。建成後的保利大劇院將會成為上海首座“水景劇院”和嘉定新文化地標。在簡單的幾何學構成的空間中，呈現出如萬花筒一般豐富多變的面貌。透過萬花筒，各種顏色的斷片相互重迭反射，幻化出華麗而變化多端的光影效果。劇院淋漓盡致地利用水景資源，各個建築物之間利用圓形空間融匯貫通，在人行天橋上交錯對應。整個劇院坐落在 100×100×50m的建築體塊中，包含一個 1500 座歌劇廳和一個 400 座多功能廳，能滿足歌舞劇、交響樂、話劇、綜藝演出以及其他現代劇種演出的需要，具備接待世界優秀表演藝術團體演出的條件和能力，圖 1 為保利劇院水景效果圖。

半島音樂廳是安藤忠雄先生在中國的第二個演藝建築作品，由三亞鹿回頭旅遊區開發有限公司投資承建。項目基地位於小東海與鹿回頭灣交匯處，擁有一片美麗而開闊的海景。建築群由半島音樂廳和美術館組成，音樂廳和美術館均以“海”作為設計主題，以國際化元素融合海南本土特色，打造“浮於海上”的建築物，寓喻“通向大海，通向世界”。音樂廳與美術館通過連廊聯接，當從陸地上的音樂廳往海上的美術館方向看，整個建築仿佛一座海上的大門；反之，從美術館往音樂廳方向看，又仿若陸地上

的大門。半島音樂廳坐落在 90×90×30m的建築體塊中，包含 1300 座的歌劇廳和 300 座的音樂廳，圖 2 所示為半島音樂廳鳥瞰圖。

圖 1 上海嘉定保利劇院水景效果圖

圖 2 三亞半島音樂廳鳥瞰圖

2 保利劇院 1500 座歌劇廳音質設計

歌劇廳觀眾廳建築平面呈馬蹄形，舞臺大幕線至最遠處 31.14 米，最寬處 31.68 米，最高點距地 20.1 米。池座 23 排（含樂池 3 排）最大高差 4.2 米；一層樓座 7 排，最大高差 2.4 米；二層樓座 5 排，最大高差 2.32 米。圖 1 和圖 2 分別為劇場觀眾廳池座平面及縱剖面。

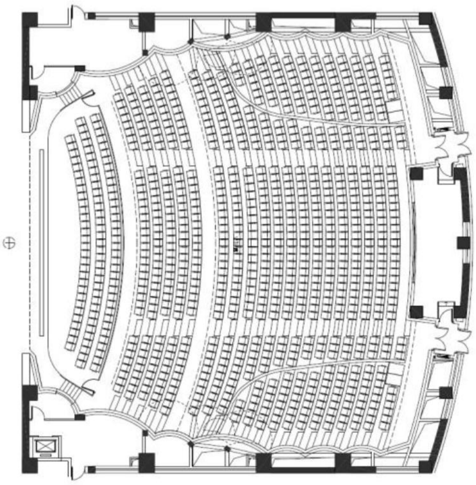

圖 3 歌劇廳池座平面圖

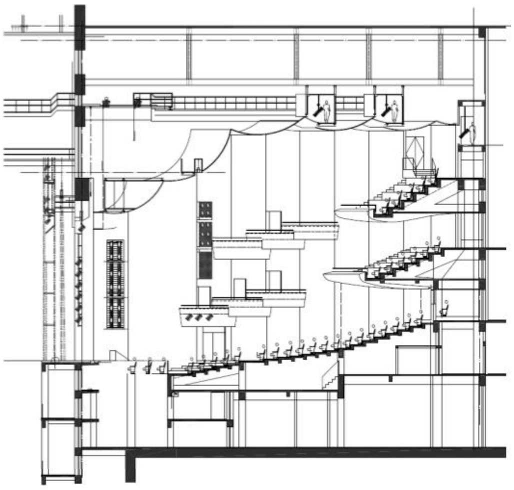

圖 4 歌劇廳剖面圖

2.1 音質設計原則及指標

歌劇廳雖然要滿足歌舞劇、交響樂、話劇、綜藝演出以及其他現代劇種演出需求，但功能上以歌劇、交響樂為主，因此，觀眾廳音質設計原則確定為“自然聲為主兼容擴聲”，歌劇及交響樂演出採用自然聲，其他演出形式使用擴聲系統。基於此原則，音質設計要求做到體型新穎合理、混響合適、廳內響度足夠、聲場擴散良好、有豐富的前次反射聲、廳內無聲缺陷及本底噪音足夠低等。因此，音質設計將以混響時間 *RT*、明晰度 C_{80}(3)、清晰度 D_{50}、聲場分佈不均勻度 ΔLp、側向反射因數 *LF*、背景噪音級 *BNL* 等幾個參量作為最主要的技術指標。

依據歌劇廳規模和容積，並參考相關規範[1]確定歌劇廳音質設計目標值如表 1 所示。

表 1 歌劇廳音質設計技術指標

RT	C_{80}(3)	D_{50}	*LF*	ΔLp	*BNL*	*G*
1.50±0.1s	-1～+3dB	≥50%	≥0.20	≤±3	≤NR-20	≥0dB

2.2 音質設計技術措施

觀眾廳地面選用實木地板實貼地面安裝。吊頂採用增強纖維預製石膏板（即 GRG 板），板的面密度要求達到 40Kg/㎡以上。側牆對劇場前中區而言是十分重要的早期聲反射面，這些牆面能向池座前區的觀眾席提供足夠的早期反射聲能，提高觀眾位置上聽音的空間感。因此該部位的牆面聲學要求盡可能厚實、堅硬，主要起聲反射作用，充分利用聲能而盡可能減少聲吸收。為此在原有結構牆面外實貼（或外包）實木，實木面層結合裝修做裝飾處理，既美化裝修，又起到擴散作用。觀眾廳後牆預留安裝可調混響裝置的空間，當可調混響裝置起反射作用時，滿足歌劇使用要求；當可調混響裝置起吸聲作用時，滿足話劇及會議使用要求；而當可調混響裝置起反射作用時，且在舞臺安裝音樂反聲罩時，滿足交響樂使用要求。欄板則要求在混凝土結構外側實貼（或外包）實木，木材表面可做凹凸紋飾或藝術處理。為增加牆面的擴散性能改善廳內聲場分佈，在側牆面設計了凹凸槽型擴散體的構造。圖 5 所示為歌劇廳牆室內設計效果圖。

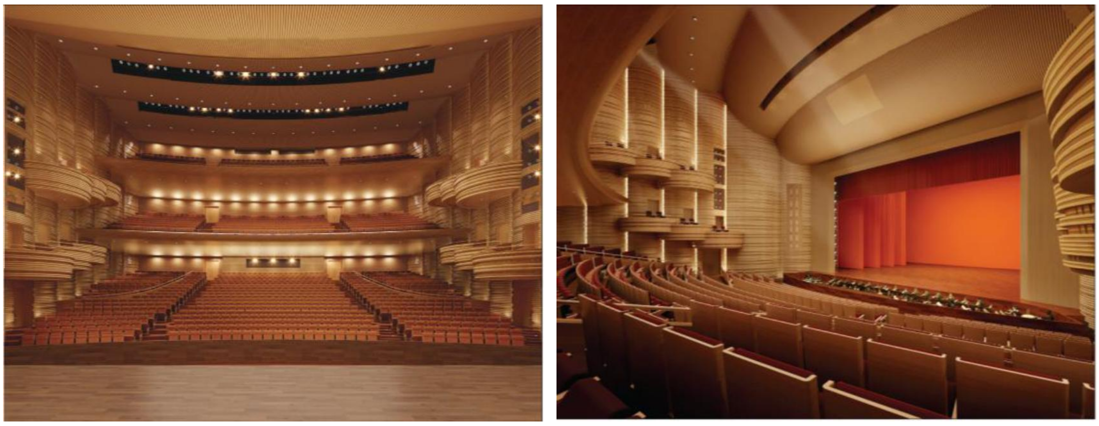

圖 5 歌劇廳室內設計效果圖

2.3 觀眾廳音質電腦類比

在觀眾廳的音質設計中進行了聲場電腦類比分析，目的是優化平剖面體型、計算音質參量並作音質預測評價。類比分析採用 Odeon9.0 室內聲學類比軟體，它兼有聲像法和聲線法的功能。採用 Odeon 軟體進行室內音質電腦類比的步驟為：首先建立實際廳堂符合聲學軟體要求的三維幾何模型，然後對三維幾何模型的所有三維面或三維網格佈置聲學材料，將材料聲學特性參數值輸入電腦軟體，就形成了三維聲學模型。最後由軟體按幾何聲學法則來模擬聲波在廳堂內的傳播規律並得到聲場的特性。圖 6 為電腦類比中聲學模型的效果圖，圖中顏色深淺代表表面材料吸聲性能的優劣。表 2 和表 3 分別為劇場觀眾廳滿場及空場兩種條件下各音質參量的模擬結果。

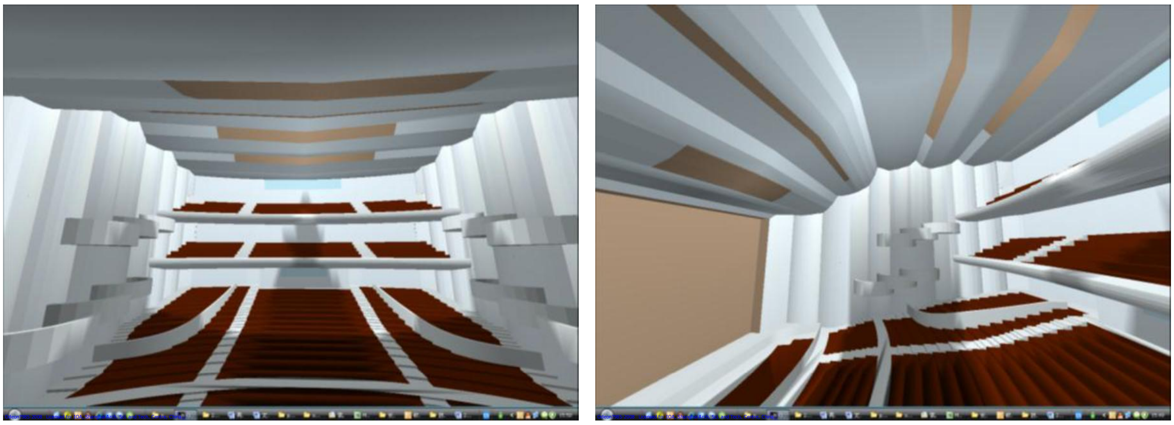

圖 6 歌劇廳聲學模型效果圖

表 2 歌劇廳滿場音質模擬結果

參量	倍頻帶中心頻率 *f*（Hz）					
	125	250	500	1000	2000	4000
T_{30} /s	1.65	1.50	1.53	1.50	1.43	1.24
EDT /s	1.63	1.49	1.52	1.47	1.37	1.14
C_{80} /dB	1.5	2.0	1.9	2.0	2.5	3.7
D_{50}	0.48	0.51	0.50	0.52	0.54	0.59
LF	0.22	0.22	0.23	0.22	0.22	0.21
G /dB	4.9	4.3	4.2	3.8	3.2	1.9
ΔLp /dB	±3.3	±3.2	±3.0	±3.0	±3.1	±3.4

表 3 歌劇廳空場音質模擬結果

參量	倍頻帶中心頻率 *f*（Hz）					
	125	250	500	1000	2000	4000
T_{30} /s	1.78	1.67	1.69	1.7	1.64	1.38
EDT /s	1.77	1.67	1.68	1.70	1.60	1.31
C_{80} /dB	1.0	1.4	1.2	1.1	1.4	2.6
D_{50}	0.43	0.45	0.44	0.43	0.44	0.49
LF	0.23	0.23	0.23	0.23	0.23	0.23
G /dB	5.2	4.8	4.7	4.6	4.0	2.7
ΔLp /dB	±3.2	±3.1	±2.9	±2.8	±2.9	±3.2

從表 2 可知，除聲場不均勻度 ΔLp 略高於設計要求值外，其他參量均在設計要求範圍內。這說明觀眾廳的體形設計、材料選擇均是合適的。同時從反射聲序列的模擬結果看，廳內反射聲組織也比較合理，前 50ms 內均有相當數量的反射聲，而初始延時間隔 ITDG 為 13ms。

2.4 聲學縮尺模型試驗

為進一步檢驗觀眾廳的音質效果，製作了 1:10 的聲學縮尺模型。模型的頂面及牆面均採用 GRG 製作，GRG 乾燥後表面噴木紋漆。由於整個觀眾廳僅觀眾席座椅吸聲，因此，座椅吸聲性能對觀眾廳音質影響很大。為此，首先按 1:10 比例用亞克力製作骨架，再在 1:10 模型混響室對座椅坐墊及靠背材料進行測試，使某一頻率的吸聲性能符合設計要求。通常，一種材料或構造是很難保證幾個頻帶的吸聲性能都符合設計要求的。顯然只要不斷更換座椅的材料，是可以確保進行全頻帶縮尺模型試驗的，但材料遴選的工作量實在太大，為此，本模型試驗僅對 1000Hz 的各聲學參量進行測試。圖 7 為歌劇廳 1:10 縮尺模型完工後的內景圖。

在此縮尺模型內按照相關規範[2]進行縮尺模型試驗，並對高頻空氣吸收進行補償[3]，模型試驗的測試結果如表 4 所示。

圖 7 歌劇廳 1:10 縮尺模型內景圖

表 4 歌劇廳滿場 1:10 縮尺模型試驗結果（1000Hz）

參量	*RT* (s)	*EDT* (s)	*G* (dB)	D_{50} (%)	ΔLp (dB)	C_{80} (dB)
測試值	1.57	1.47	1.29	50.9	±3.6	2.43

將縮尺模型試驗結果與電腦類比結果對比可以看出，縮尺模型試驗結果與電腦類比結果基本吻合，除聲場不均勻度 ΔLp 外其他參量均在設計要求範圍內，這再次驗證了觀眾廳的體形設計、材料選擇均是合理的。而從反射聲序列的模擬結果看，廳內反射聲組織也比較合理，前 50ms 內均有相當數量的反射聲，而初始延時間隔 ITDG 為 3ms。

3 半島音樂廳 1300 座歌劇廳音質設計

1300 座歌劇廳觀眾廳建築平面為簡單不等邊多邊形，最長處約 33.0m，最寬處約 29.2m，最高處約 18.8m。池座 981 座分 29 排（升降樂池 4 排）排布，前後高差 5.7m；二層樓座 151 席分 7 排排布，高差 2.4m；三層樓座 48 席分 2 排，高差 0.6m。三層樓座後部佈置 4 間 VIP 室，聲光控制室佈置在池座後部。圖 8 和圖 9 分別為歌劇廳建築平剖面。

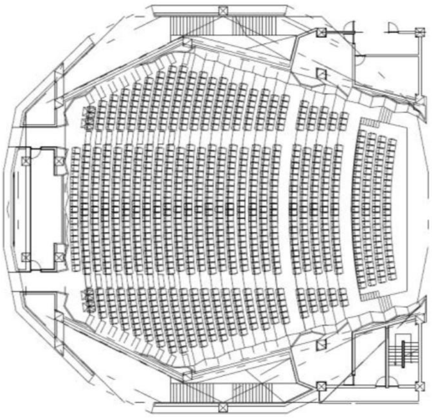

圖 8 歌劇廳池座平面圖

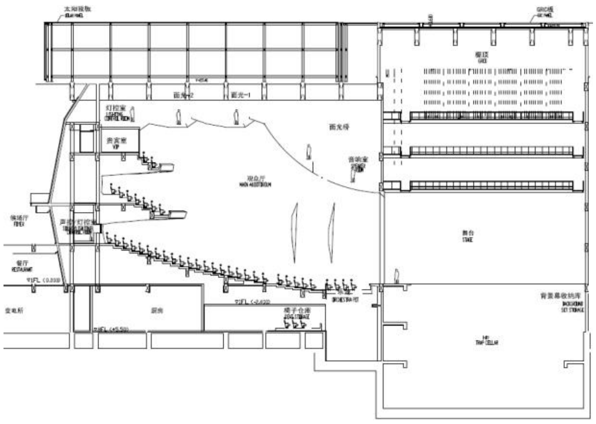

圖 9 歌劇廳縱剖面圖

3.1 音質設計

歌劇廳在功能上要滿足歌舞劇、話劇、綜藝演出以及其他現代劇種演出需求，但以歌劇為主，因此，觀眾廳音質設計原則確定為“自然聲為主兼容擴聲”，基於此原則並依據劇場規模和容積，確定歌劇廳音質設計目標值如表 5 所示。

表 5 歌劇廳音質設計技術指標

RT	$C_{80}(3)$	D_{50}	*LF*	*ΔLp*	*BNL*	*G*
1.50±0.1s	-1～+3dB	≥50%	≥0.20	≤±3	≤NR-20	≥0dB

為滿足上述音質指標要求，在設計中明確劇院的吸聲完全由座椅提供，而其他表面不作吸聲處理。為此，觀眾廳地面採用實鋪木地板，吊頂天花採用增強纖維預製石膏板，GRG 板的面密度要求達到 40Kg/m^2 以上。而側牆及後牆均在原有結構牆面外幹掛 GRG 板，而板的面密度要求達到 45Kg/m^2 以上。

3.2 觀眾廳音質電腦類比

按照相同的建模方法對觀眾廳建立電腦聲學模型，模型效果如圖 10 所示。在此電腦聲學模型內，採用 Odeon 進行歌劇條件下空滿場聲場模擬，結果如表 6 和表 7 所示。

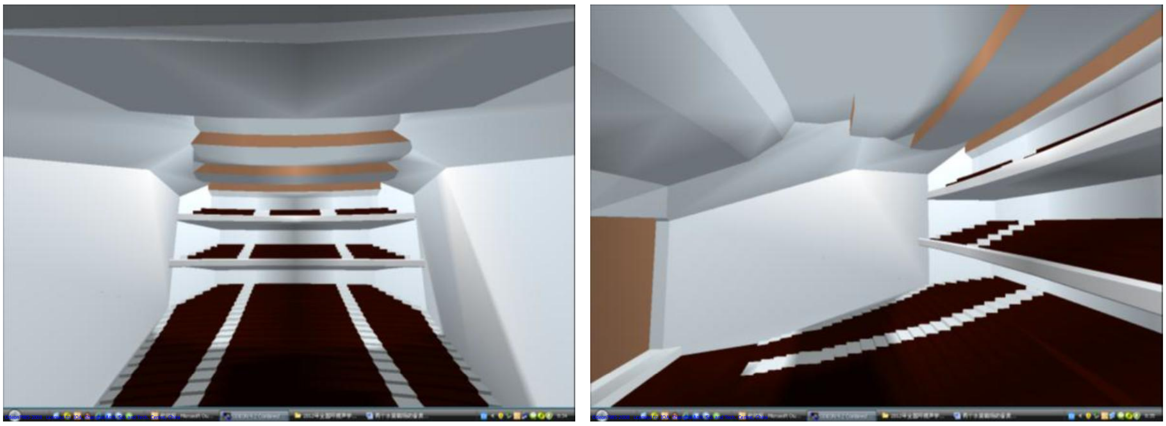

圖 10 歌劇廳聲學模型效果圖

表 6 歌劇廳滿場音質模擬結果

參量	倍頻帶中心頻率 *f*（Hz）					
	125	250	500	1000	2000	4000
T_{30} /s	1.67	1.62	1.62	1.62	1.59	1.41
EDT /s	1.66	1.58	1.57	1.49	1.49	1.29
C_{80} /dB	2.7	2.9	2.8	2.8	2.6	3.3
D_{50}	0.53	0.53	0.52	0.52	0.50	0.53
LF	0.20	0.20	0.22	0.23	0.23	0.23
G /dB	5.1	4.8	4.5	4.1	3.9	3.1
Δ*L*p /dB	±1.2	±1.1	±1.2	±1.2	±1.3	±1.5

表 7 歌劇廳空場音質模擬結果

參量	倍頻帶中心頻率 *f*（Hz）					
	125	250	500	1000	2000	4000
T_{30} /s	1.78	1.75	1.76	1.76	1.74	1.53
EDT /s	1.76	1.7	1.67	1.63	1.61	1.37
C_{80} /dB	3.0	3.1	2.9	3.0	2.7	3.5
D_{50}	0.55	0.55	0.54	0.53	0.52	0.55
LF	0.21	0.22	0.23	0.23	0.24	0.23
G /dB	5.9	5.6	5.4	5.0	4.8	4.1
Δ*L*p /dB	±1.2	±1.1	±1.1	±1.2	±1.2	±1.4

由表 6 可知，除混響時間略超出設計要求範圍外，其他參量均在設計要求範圍內。這說明觀眾廳的體形設計、材料選擇基本上是合理的。考慮混響時間的頻率特性不好，將在縮尺模型試驗過程中再次驗證座椅選擇的正確性。同時反射聲序列的模擬結果也表明，廳內反射聲組織也比較合理，前 50ms 內均有相當數量的反射聲，初始延時間隔 ITDG 為 3ms。

4 音質評估

分別依據兩個歌劇廳觀眾廳空場及滿場條件下的電腦類比結果，將這兩個水景劇場與世界上其他 14 個歌劇院的音質指標[4]分別進行關聯度分析[5]，表 8 所示為 16 個劇院的基本資料，對這 16 個劇院的音質參量進行初值變換，在分辨係數 ρ=0.5 的條件下，計算其等權關聯度及關聯序，結果如表 9 所示。

表 8 參與關聯度分析的 16 個劇場的基本參數

劇院名稱	V /m3	N /座	RT(o) /s	EDT /s	C_{80}(3) /dB	G /dB	1-$IACC_{E3}$	ITDG /ms	BR	備註
上海嘉定保利劇院	11307	1575	1.51	1.69	1.2	4.6	0.68	13	1.04	JP
三亞半島音樂廳歌劇廳	11069	1347	1.62	1.65	2.9	5.2	0.67	3	1.02	SS
布宜諾賽勒斯科隆歌劇院	20570	2487	1.56	1.72	1.1	2.4	0.65	18	1.23	BA
德雷斯登森珀歌劇院	12480	1284	1.60	1.83	0.8	2.7	0.72	20	1.23	DS
米蘭阿拉斯卡拉歌劇院	11252	2289	1.24	1.14	3.6	-0.3	0.48	16	1.26	MS
東京新國立歌劇院	14500	1810	1.49	1.70	1.6	1.7	0.65	20	1.07	TN
巴黎加涅爾歌劇院	10000	2131	1.18	1.16	4.6	0.7	0.50	15	1.31	PG
布拉格國立歌劇院	8000	1554	1.23	1.17	3.1	2.2	0.64	16	1.39	PS
維也納國家歌劇院	10665	1709	1.36	1.43	2.7	2.8	0.60	17	1.19	VS
紐約大都會歌劇院	24724	3816	1.47	1.52	1.7	0.5	0.62	18	1.07	NM
薩爾茨堡節日歌劇院	14020	2158	1.50	1.80	1.5	1.2	0.40	27	1.11	SG
阿姆斯特丹歌劇院	10000	1689	1.30	1.30	1.9	1.7	0.55	32	1.30	AM
倫敦皇家歌劇院	12250	2157	1.20	1.35	4.5	0.7	0.53	18	1.07	LO
漢堡歌劇院	11000	1679	1.23	1.35	2.2	1.3	0.45	34	1.12	HS
柏林國家歌劇院	10800	1900	1.36	1.60	0.7	1.2	0.39	33	1.30	BD
芝加哥民眾歌劇院	23000	3563	1.51	1.49	2.1	0.3	0.53	41	1.32	CC

注：除 RT 與 BR 為滿場結果外，其餘音質參量均為空場結果。同時除保利劇院與三亞音樂廳外，其餘劇院資料均來自文獻 4。

表 9 關聯度分析結果

		BA	DS	MS	TN	PG	PS	VS	NM	SG	AM	LO	HS	BD	CC
嘉定保利劇院歌劇廳	關聯度	0.90	0.87	0.75	0.88	0.75	0.79	0.83	0.86	0.82	0.77	0.76	0.75	0.77	0.75
	關聯序	1	3	13	2	14	7	5	4	6	9	10	12	8	11
半島音樂廳歌劇廳	關聯度	0.91	0.90	0.89	0.91	0.89	0.91	0.92	0.90	0.88	0.87	0.89	0.87	0.86	0.87
	關聯序	3	6	7	4	9	2	1	5	10	11	8	12	14	13

從表 9 可見，保利劇院音質模擬結果與布宜諾賽勒斯科隆歌劇院、東京新國立歌劇院的音質參量之間的關聯度最接近，在文獻 4 中對這兩個劇院的音質評價很高。而半島音樂廳歌劇廳音質模擬結果與維也納國家歌劇院、布拉格國立歌劇院的音質參量之間的關聯度最接近，而文獻 4 對這兩個劇院的音質評價也較高。

5 結語

作為安藤忠雄先生在中國設計的兩個文化建築開篇之作，嘉定保利劇院和三亞半島音樂廳均由國內外最強的設計團隊來完成，尤其對聲學設計給予了足夠的尊重與支持，這無疑為這兩個水景劇院建成後獲得優良音質提供了技術保障。而從專業的建聲設計、音質類比及聲學縮尺模型試驗結果來看，嘉定保利劇院的音質預計可以與布宜諾賽勒斯科隆歌劇院及東京新國立歌劇院相媲美。而半島音樂廳歌劇廳音質預計可以與維也納國家歌劇院及布拉格國立歌劇院相媲美。目前這兩個水景劇院正在建設中，相信只要按照專業設計團隊的要求來施工建造，可以預期這兩個水景劇院建成後不僅會因為其水景而成為當地的文化地標，還會因為其優美的音質而成為當地演藝建築的新貴。

參考文獻

[1] GB/T50356-2005，劇場、電影院和多用途廳堂建築聲學設計規範[S]；

[2] GB/T50412-2007，廳堂音質模型試驗規範[S]；

[3] 莫方朔，盛勝我，廳堂音質縮尺模型測試中空氣聲吸收的修正[J]，聲學技術，2006，25（S）：365-366；

[4] Leo Beranek，Concert Halls and Opera Houses (Second Edition)[M]，555~558；

[5] 宋擁民，章奎生，關聯度分析在東方音樂廳音質評價中的應用[J]，聲學技術，2008，27(2)：247~250。