Front. Eng. Manag. 2022, 9(1): 170–176
https://doi.org/10.1007/s42524-021-0177-x

SUPER ENGINEERING

Jiulin LI, Limin CHEN, Hao XU, Jianlin WANG

Green Construction of National Speed Skating Oval

Keywords super large-span cable net structure, CO_2 Transcritical Direct-cooling Ice Making System, dynamic high-precision construction measurement, green construction, National Speed Skating Oval

1 Background

As the basic principle of the world economy, environment, and social development, sustainable development is the focus of the international community today. In the Olympic Agenda 2020 published by the International Olympic Committee (IOC), sustainable development was officially listed as one of the core concepts of the Olympic Games. Since the beginning of the bid, the concept of "athlete-centered, sustainable and economical" was proposed, which was highly consistent with the idea of the Olympic Agenda 2020. To implement the concept of holding "green" Olympic Games and meet the sustainability requirements of the IOC, the Organizing Committee of Beijing Winter Olympic Games issued a series of documents related to the sustainability of sports venues such as Sustainability Policies for 2022 Beijing Winter Olympic Games and Winter Paralympic Games, and strived to realize the sustainable development of sports venues in the whole life cycle of planning and design stage, construction stage, operation stage, and post-game utilization.

Received September 16, 2021

Jiulin LI (✉)
Tsinghua University, Beijing 100084, China; Beijing Urban Construction Group Co., Ltd., Beijing 100088, China; Beijing National Speed Skating Oval Management Co., Ltd., Beijing 100101, China
E-mail: lijiulin@bjucd.com

Limin CHEN, Jianlin WANG
Beijing National Speed Skating Oval Management Co., Ltd., Beijing 100101, China

Hao XU
Beijing Urban Construction Group Co., Ltd., Beijing 100088, China

Take the Beijing competition area as an example. There are six competition venues, while only two of them are newly-built. All the reconstructed venues are legacies of the 2008 Beijing Olympic Games. Efforts were made to improve the facilities and comprehensive performance of the venues, realizing the multifunction conversion of the venues, and avoiding building new permanent or temporary venues, thus the land and energy resources were saved, and the impact on the social environment was reduced. In the newly-built venues, the National Speed Skating Oval is located in the Olympic Park, capitalizing on the land estate of the 2008 Beijing Olympic Games; and the Shougang Big Air was constructed in the Shougang Industrial Park in Shijingshan District, making full use of the industrial heritage, so that the government did not have to allocate additional land resources for new venues. In the process of the construction and renovation of the sports venue, to practice the concept of holding "green" Olympic Games, information technology was fully used to realize smart construction and intelligent operation and maintenance, the resource utilization of solid waste and the use of clean energy were realized to the greatest extent, and the efficient and green prefabricated construction technology was used.

The National Speed Skating Oval (also known as "Ice Ribbon", Fig. 1) is the iconic venue of 2022 Beijing Winter Olympic Games, reusing the hockey and archery venues of the 2008 Beijing Olympic Games, with an area of 126000 m^2 and a total of 12038 seats. Designed to be green and clean, the National Speed Skating Oval has obtained the three-star certificate of green building design label, and implemented green and sustainable concepts in the whole process of design, construction, and operation. As a typical building with a large-span structure, to meet the shape and function demands and in consideration of high efficiency, energy conservation, and aesthetics, the National Speed Skating Oval adopted the saddle-shaped hyperbolic model. The curved curtain wall system on the facade is the main carrier of the concept of "Ice Ribbon". The unique design scheme, architectural requirements for Olympic competitions, frugal construction cost, and extremely tight schedule brought great challenges to the construction

Fig. 1 National Speed Skating Oval.

team. With the support of the Technological Winter Olympic Games Project — a national key R&D program, through theoretical research, simulation, experimental analysis, sample test, and system research and development, key technologies of green construction of the National Speed Skating Oval were systematically studied and comprehensively applied to the construction of the venues, so as to realize high-efficiency and high-precision construction.

2 Key technologies and innovation of the National Speed Skating Oval

The cable net structure of the National Speed Skating Oval is a typical flexible structure. The roof structure has a large span, which brings great technical challenges to the reasonable design, accurate simulation, safety and stability, and efficient construction of the cable net structure. Through studies such as theoretical analysis of cable net molding, digital simulation under multiple working conditions, 1:12 model test, pre-assembly of ring truss, and intelligent installation of ring truss and cable net, the high-performance structure system of large-span single-layer cable net + ring truss + curtain wall cable reticulated shell with different faces was designed in China for the first time, and the high-efficiency and high-precision construction technologies of low and high level track changing and sliding for the ring truss and ground weaving and overall lifting and tensioning for the cable net were developed. To provide guarantee for the excellent performance of athletes and realize the concept of holding "green" Olympic Games, the ice surface with an area of 12000 m^2 has been built as the fastest and the most environment-friendly one. To solve problems such as low accuracy of temperature control of super-large ice surface and hidden danger within the safety and environment protection of the refrigeration system, key technologies were systematically studied, including theories of the formation of the ice surface, structure of multi-function ice pool with super-large surface, and multi-function CO_2 ice making system, providing basic guarantee for the speed skating at 2022 Winter Olympic Games.

2.1 Construction technologies of the super large-span high-performance cable net structure

2.1.1 High-performance structure system of single-layer cable net + ring truss + curtain wall cable reticulated shell with different faces

The cable net structure is a typical nonlinear structure. Due to the huge roof structure of the National Speed Skating Oval, an applicable super large-span high-performance structure system has to be developed, and make sure that the structure design scheme is reasonable and reliable, the simulation analysis is accurate, the mechanical performance is good, the overall structure is solid, and construction and installation are convenient. Through the whole-process simulation analysis and model test, the super large-span high-performance structure system applicable to the National Speed Skating Oval was developed. Different from rack and truss commonly used in space structure, in the super large-span high-performance structure system, the elevation can be reduced by 8–10 m, which will greatly reduce the investment in

curtain wall and air conditioner, as well as construction cost and period; and the amount of steel used is only 1/4 of that used in traditional steel structure. Thus, a high-performance structure system with best mechanical properties, most savings in materials, convenient construction, low cost, and good durability can be realized (Fig. 2). To meet the demand for construction cost and time limit for the project, a major-diameter high-vanadium full-locked coil cable for construction was independently developed for the first time. The cable, Z-shaped steel wire, riding anchor, and other technical solutions were proposed, and the complete component processing and manufacturing process and production and quality assurance system were established, realizing the mass production of the major-diameter high-vanadium full-locked coil cable in China. Through the design adjustment and construction control, the domestic full-locked coil cable was applied to the national key construction project for the first time, which promoted its wide application in the construction field. The performance of the domestic full-locked coil cable has met the European standard, broking the monopoly of similar foreign products. As a result, the unit price of the cable decreased from 140000 to 35000 yuan/t and the supply period is shortened by nearly 1/2. In addition, the new shape-finding method of the super large-span cable net was developed. The influences of factors such as boundary shape, topological relation, prestress, roof weight distribution, etc., were considered, so that the maximum deviation distance of the initial configuration of the cable net from the theoretical paraboloid was no more than 5 mm, which basically matched with the hyperbolic paraboloid. Considering the shape control of the elastic boundary, through the pre-deformation of the ring truss and correction of the initial strain of the cable net, the shape of the cable net in the initial state of the main stress system was consistent with the results of fixed boundary. Thus, the shape control of the cable net under elastic boundary was realized, and the maximum deviation of the cable net relative to the target configuration decreased from 502 mm to no more than 5 mm.

2.1.2 Intelligent construction technologies of low and high level track changing and sliding for the ring truss and ground weaving and overall lifting and tensioning for the cable net

The specific demands of the building function decide the complexity of the structure. The main structure of the National Speed Skating Oval includes the reinforced concrete structure, the ring truss with steel structure, and the cable net structure. In terms of stress relationship, the steel-reinforced concrete structure is the support of the steel structure, and the steel structure is the support of the cable net structure, namely, they are preconditions and post-conditions for each other. In terms of time, the construction of the steel structure is the link between the concrete structure and cable net structure. In terms of space, the steel structure is affected by the construction and installation of the structure in the lower part of the roof, and the cable net structure also affects the installation of the precast stand under the roof. To meet the requirements of safety, quality, time limit, site, and investment, scheme comparison and optimization of steel structures in the key processes have been made. Through the comparative analysis of various installation methods shown in Table 1, comprehensively considering the principles of technical advancement, economic rationality, and especially the prerequisites of guaranteeing the construction period, finally, the construction scheme of high-level sliding was selected for the installation of the ring truss of the roof of the National Speed Skating Oval. And combined with the actual conditions of the site in the implementation stage, the scheme was further optimized. Finally, the installation scheme of "sliding on the eastern and western sides + in-situ lifting on the southern and northern sides" was determined. In the process of sliding on the eastern and western sides, the computer-control based installation technology of low and high level track changing and sliding for the saddle-shaped ring truss with large drop was created for the first time, resulting in a deviation less than 10 mm of the ear plate of the cable, and saving 2800 tons of sliding falsework.

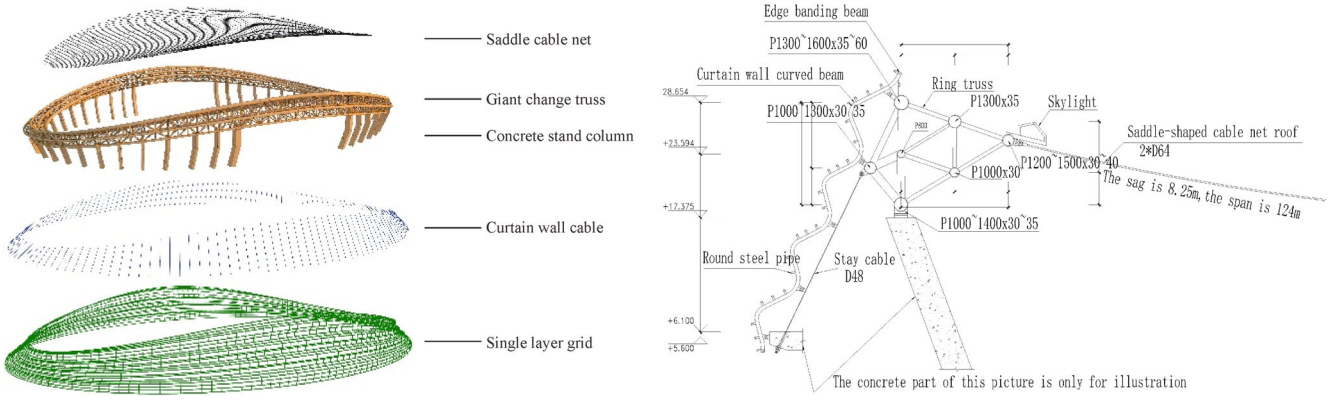

Fig. 2 Schematic diagram of the cable net structure system.

Table 1 Comparison of different installation methods

Installation method	Crane type	Quantity of materials used/ton	Construction period of critical path/day	Advantages and disadvantages
Lifting outside the venue	750 t crawling crane	4000	90	Can be assembled 15 days in advance
Lifting in the venue	800 t crawling crane	3000	90	Can be assembled 15 days in advance, while post-construction is required for the concrete structure of the access way for the crane
High-level sliding	450 t crawling crane	2000	60	Can be assembled 60 days in advance, and the working platform for the on-site weaving of the cable net can be provided 30 days in advance, saving 3 months for the overall construction period

The first synchronous tensioning technology of super large-span single-layer orthogonal cable net with large-tonnage and large-area was developed in China. To be exact, 100% of the deviation of the stabilizing cable force is less than 10% and 96% of the deviation of the bearing cable force is less than 10%, which are both lower than the acceptance standard of less than 15% (Fig. 3). The health monitoring system for the whole life cycle of the project was established, realizing the synchronization of construction guidance and early warning. In the overall structural construction of the National Speed Skating Oval, based on technologies such as unified building information modeling (BIM) for the whole process, integrated collaboration of all participants, high-precision simulation of the whole construction process, high-quality high-precision components processing and installation, real-time high-precision measurement and control, real-time adjustment of construction deviation, and refined control based on big data and AI for people, machines, materials, resources, and environment, the high-efficiency and high-precision parallel construction technology system was created, realizing lean and efficient construction of the National Speed Skating Oval.

2.2 CO_2 Transcritical Direct-cooling Ice Making technology for super-large ice surface

2.2.1 CO_2 Transcritical Direct-cooling Ice Making System

For a long time, the design standards and specifications of ice-snow venues, as well as the corresponding core technologies of refrigeration and environmental control systems have been monopolized by the US, Europe, Japan, and other countries, especially the ice making technology and core equipment for large-scale sport events such as Winter Olympic Games and Winter Paralympic Games. Therefore, the theory of ice surface formation of the speed skating track of the National Speed Skating Oval, and key technologies such as the construction of ice pool with multi-function super-large ice surface, multi-function CO_2 Transcritical Ice Making System, fine control of the indoor environment, and automatic monitoring of ice surface and indoor environment were studied. To realize the concept of holding "green" Olympic Games, the multi-function full ice surface design scheme and the CO_2 Transcritical Direct-cooling Ice Making System were selected for the National Speed Skating Oval (Fig. 4). CO_2 is colorless,

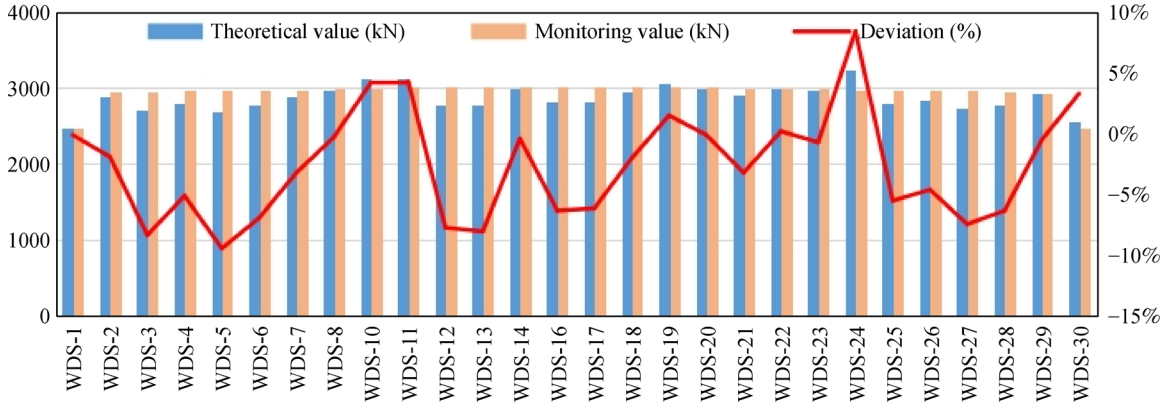

Fig. 3 Comparison of the cable force of the stabilizing cable.

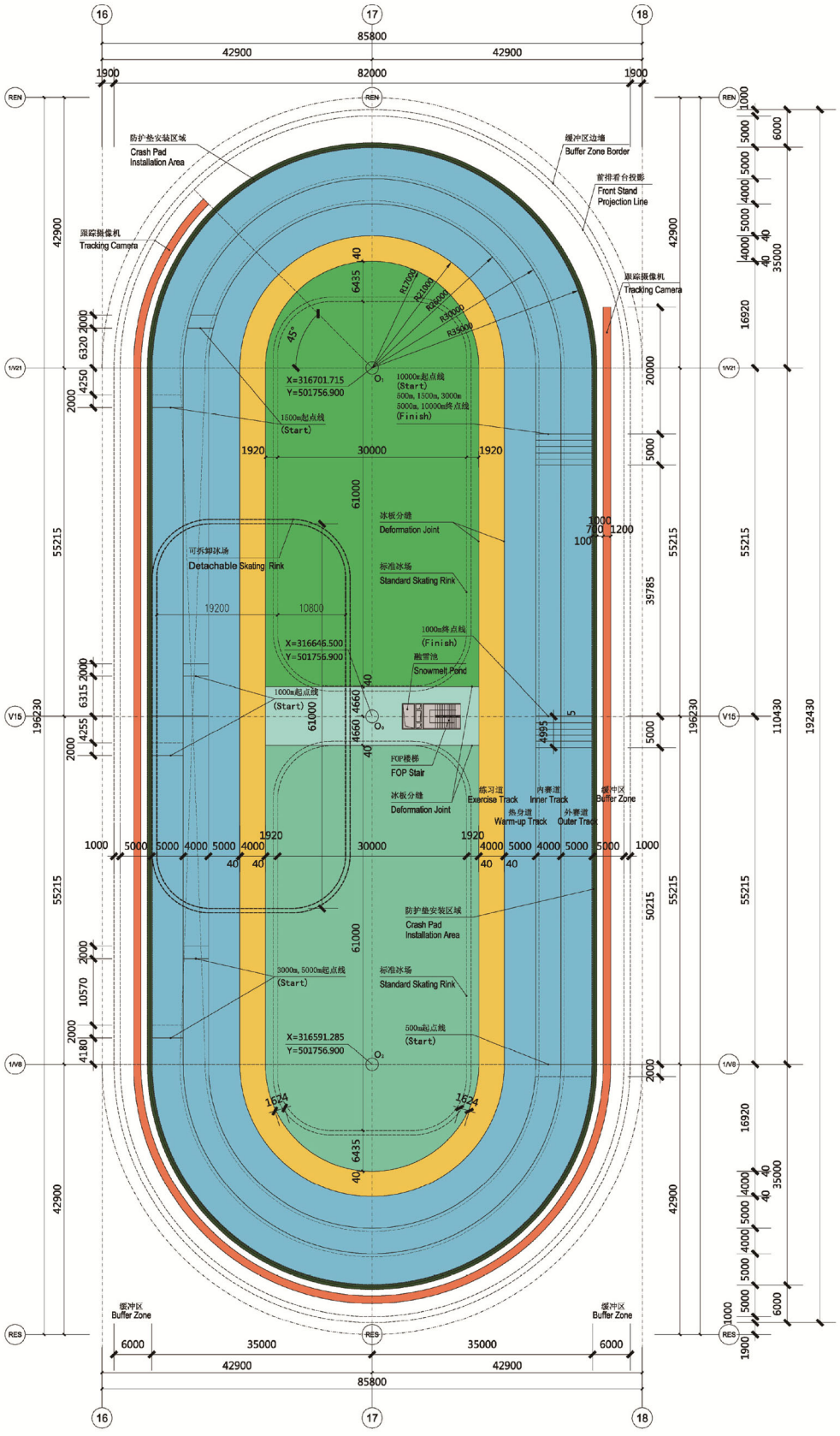

Fig. 4 Schematic diagram of the ice making system.

odorless, non-combustion-supporting, and non-flammable. Its ozone-destroying potential (ODP) is 0, and compared with traditional refrigerants, its global warming potential (GWP) has sharply decreased from 3985 to 1, while the energy efficiency has increased by more than 20%. Thus, CO_2 is one of the most environment-friendly and sustainable coolants. In the future, when the full ice surface of the "Ice Ribbon" is in operation, about 2 million kWh of electricity can be saved a year. At the same time, by establishing the dynamic three-dimensional heat transfer model of the freezing process, building test bench for the freezing process, analyzing the ice resurfacing thickness, initial water temperature, and other affecting factors in the dynamic heat transfer process, and summarizing related basic research data like hardness, thickness, temperature, and humidity, the theory of ice surface formation of the speed skating track of the National Speed Skating Oval was established. Consequently, the temperature difference of the full ice surface with an area of 12000 m^2 can be controlled within ± 0.5°C, which is far below the required temperature difference of ± 1.5°C for international speed skating competition venues. The National Speed Skating Oval has become the first Winter Olympic speed skating venue using CO_2 Transcritical Direct-cooling Ice Making technology in the world, which is highly praised by the IOC and the International Skating Union (ISU).

In the test in April 2020, of 30 temperature measuring points on the ice surface, the temperature difference of 29 points was no greater than 0.5°C and that of the other point was 0.7°C. Besides, the energy efficiency of the ice making system was more than 50% higher than that using traditional technology. The waste heat recycled from ice making has produced hot water of 70°C for ice resurfacing. In the global refrigeration industry, the feasibility of large-scale CO_2 Transcritical Refrigeration System was verified for the first time, which is an important technical direction for the promotion of sustainable development in the refrigeration industry.

2.2.2 High-precision detection of the morphology of the ice making pipe for super-large speed skating venue in complicated environment

At present, the reliance on traditional single-point mapping has some restrictions in complex scenes and the full coverage cannot be realized. The discrete measurement points are difficult to reflect the overall conditions of the installation of the ice making pipes, and the density of measurement points cannot provide enough data required by the acceptance standard of pipe laying. According to the Acceptance Standard of Construction Quality of CO_2 Direct-cooling Ice Making Project, the requirement for the acceptance precision of the laying of ice making pipes is high: In the same region, the allowable deviation of the elevation of each group of ice making pipes is ± 5 mm, the parallelism between each pipe is equal to or less than 1/1000, and the warping of the pipe plane is equal to or less than 3 mm. The quality inspection of the ice making pipes is spot check, in which the discrete sampling inspection can only be made on a few points and the sampling inspection quantity is 30%, which means 70% of ice making pipes cannot be checked. The quality inspection method is observation and inspection by measuring scales, which can be greatly affected by human factors (the inspection area needs to be stepped on) and the error cannot be accurately calculated. The high-precision installation of ice making pipes is the premise and foundation for guaranteeing the accurate control of indicators such as temperature, thickness, and stability of the ice surface. Therefore, to ensure the comprehensiveness and stability of testing results, the model-driven multipurpose new method of efficient measurement of the apparent form of the high-density netted pipes was proposed; and the high-precision test method based on three-dimensional laser measurement for the installation of the ice making pipes of super-large speed skating venue was invented, giving full play to the advantages of three-dimensional laser scanning such as high efficiency, flexibility, safety, reliability, high adaptability to the environment, and comprehensive functions, achieving the effective acquisition and super-high-precision positioning of the point cloud in complicated construction environment, and realizing the full-coverage detection of all the ice making pipes on site (Fig. 5). To effectively guide the installation and detection during construction and the acceptance check after completion for the ice making pipes, in the laying and installation process, fast data acquisition and processing are performed to accurately analyze the point cloud data, warpage, and horizontal shift of ice making pipes, thus the installation conditions of the pipes were obtained. Through multiple tests in different pipe installation stages, their spatial positions can be adjusted repeatedly to guide the on-site construction and quality acceptance. The detected precision of parallelism and warping has achieved ± 2 mm, which provides the basic guarantee for the effect of ice making and the realization of uniform refrigeration. The coordinates of the intersection point between the bracket and the pipe and other information can be extracted from the testing data to form the distribution diagram of pipes in the whole venue, which are the important data for finding the position, direction, and connection of the pipe in the venue, providing important basis for the sustainable operation and maintenance of the speed skating oval.

2.2.3 Ultra-high-precision rapid measurement of continuous elevation surfaces of the concrete floor of the super-large ice surface

In the construction process of the National Speed Skating

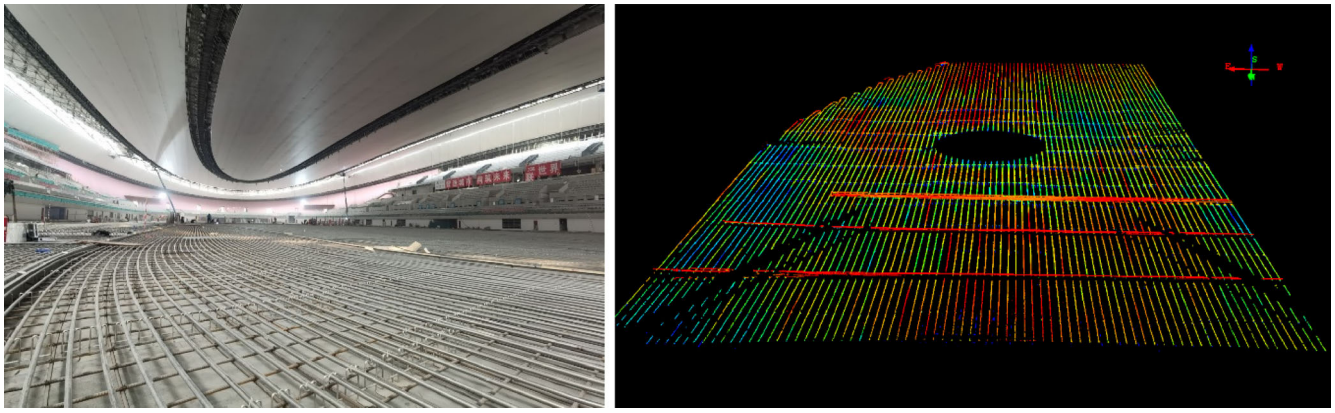

Fig. 5 Ice making pipes laying site (left) and related three-dimensional laser model (right) of National Speed Skating Oval.

Oval, the requirement for the flatness of the concrete base of the ice plate is extremely high, because the flatness of the base directly relates to the preparation of the ice layer and the quality of the ice surface, which not only affects the performance of athletes but also relates to the safety of all the people and equipment on the ice. The flatness should be obtained in real time in the casting process of the concrete floor, while traditional inertial navigation measurement method is limited by the fact that it cannot be implemented due to the weak indoor signal in the closed venue. As a result, a panel drag-and-drop inertia flatness measurement system was invented to integrate the plane coordinates and the inertial relative elevation of the high-precision total-station, so as to obtain the flatness of the concrete floor with continuous measuring lines, realizing rapid measurement of the flatness of concrete in the initial setting state, with the accuracy of ± 1 mm in the scope of 5 m, which helped the planishing of the concrete surface. Furthermore, a wheeled inertia flatness measurement system was also invented to integrate the high-precision speedometer and inertial navigation so as to realize the relative three-dimensional curve measurement of the floor. Through the measuring line grid with a certain density, the flatness of the floor can be comprehensively measured with an accuracy of ± 0.5 mm in the scope of 5 m. By applying the above measurement technologies, the flatness of the ice plate with an area of 12000 m^2 was ensured (equal to or less than 3 mm), which was much lower than the requirement of no more than 5 mm of the ISU, effectively guaranteeing the construction quality and efficiency of the concrete floor of the National Speed Skating Oval.

3 Summary

As the only city to host both summer and winter Olympic Games, Beijing has made full use of the legacies of 2008 Summer Olympic Games for 2022 Winter Olympic Games, realizing conservation and sustainable development, which is in line with the core idea of sustainable development of Olympic Games, providing Chinese experiences worldwide. As an iconic venue, the National Speed Skating Oval has made full use of greening, informatization, industrialization, and other modern technologies, and developed high-performance structure system, high-performance homemade materials, and high-efficiency and high-precision green construction technology, realizing carbon emission reduction in the whole process of design, construction, and operation and maintenance to the greatest extent. Further study will focus on the key technologies of low-carbon monitoring and carbon neutral adjustment and control, so as to realize the diverse collection and fusion and panoramic management and control of carbon emission data of the Winter Olympic Games. Meanwhile, the linkage and promotion effect of Winter Olympic Games on the economic and social development of Beijing–Tianjin–Hebei Region will be evaluated. Finally, the realization path and scheme of carbon neutralization in the Winter Olympic Games will be proposed.