An enormous aerial park with the world’s largest public cantilever crowns the three towering hotel structures of Singapore’s Marina Bay Sands project. The 929,000 m² mixed-use resort complex also features one of the city’s first casinos, a lotus-shaped museum, and numerous other amenities that were constructed on reclaimed land on a site that posed formidable geotechnical challenges. • • • By Robert L. Reid

The Marina Bay Sands complex features an aerial park located 200 m above the city’s waterfront. The so-called SkyPark is elevated on columns atop the resort’s three hotel towers, overlooking both the lotus-shaped ArtScience Museum and an earlier project, the Helix Bridge.
The engineers designed a series of exceptionally large reinforced-concrete cofferdams that were constructed to depths of as much as 18 m below grade in key areas of the excavation.

To ensure that the project’s excavation work did not cause damage to the Benjamin Sheares Bridge, diaphragm walls T shaped in plan for additional stiffness were constructed at the base of the structure, new steel bearings were installed at the connections between the bridge deck and the piers, and monitoring equipment was used to carefully track potential movements of the bridge, which remained in operation throughout the construction phase, notes McNiven.

Because of the varying curvatures of the sections facing east, each of the three hotel towers has a unique geometry and must accommodate varying lateral loads, differential lateral movements, and overturning forces, McNiven says. These loads and forces are overcome via a series of reinforced-concrete shear walls spaced at roughly 6 m intervals along the north–south width of the towers. Each shear wall, McNiven explains, comprises a single vertical blade at the
The glazed atrium lobby is a continuous space that extends between the splayed legs of all three hotel structures. Beginning at roughly 20 stories in height, the atrium angles down to approximately 6 stories and features several commissioned works of art, including Drift by the British sculptor Antony Gormley. This three-dimensional stainless-steel polyhedral matrix weighs roughly 14 metric tons and is suspended in the air between levels 5 and 12 in Tower 1.

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Within the continuous atrium lobby, a series of hanging bridges at the upper levels of the glazed space provide connections between the eastern and western legs of each tower. The design of the towers also features a series of multi-story steel trusses that are located at the mechanical plant space starting at the 23rd level of each structure, the level just above where the eastern and western tower legs begin to splay. Referred to as linking trusses by the design team and constructed of large flat-plate steel elements that are embedded within the concrete walls, the trusses use shear studs and are approximately 9 m in depth. They also feature extended sections at their tops and bottoms, creating a Z shape in section. The trusses impart stability in the lateral direction by connecting the essentially vertical shear walls in the western tower sections with the leaning shear walls in the eastern sections. This arrangement creates what is essentially a giant moment-resisting A-frame system, says McNiven.

Because of the potential lateral movement of the towers and the changes that can be caused by the natural shrinkage of concrete over time, the design team faced an unusual challenge: it was difficult to find an elevator supplier that was willing to bid on a project in which the lift shaft might “have moved twenty or twenty-five millimeters this way and that way” over the first five years, notes McNiven. Of more than half a dozen potential firms, only two expressed interest. Ultimately, KONE, of Helsinki, Finland, was awarded the U.S.$43-million contract for elevators and escalators in the hotel towers.

Within the continuous atrium lobby, a series of hanging bridges at the upper levels of the glazed space provide connections between the eastern and western legs of each tower. Above the atrium, the gap between the sections forms the corridor between the rooms on either side of the structures. A series of lightweight posttensioned-concrete slabs with spans of up to 10 m forms the floor system of the towers and eliminates the need for internal columns.

The hotel structures feature two different facade systems. On the western facades, which face downtown Singapore and experience the greatest potential for heat gain, a customized facade was used to create a world-class city akin to New York City or Hong Kong in the way it relates to its waterfront.
The 1,396 m² swimming pool contains 1.4 million L of water and is the largest outdoor pool in the world at this height.

The SkyPark features a concrete deck supported on more than 7,000 metric tons of steel framing. Two tapering pre-stressed steel plate box girders, each 4 m wide and having a maximum depth of 10 m, create the dramatic cantilever, which begins at the northern edge of Tower 3. A third, shallower box girder is located directly above that tower and works with the two tapering box girders to form the roughly 50 m back-span support system for the cantilever, McNiven says. Six large steel trusses bridge the roughly 50 m distances between the towers. Three trusses are used in each span, and each truss is approximately 4.5 m deep and weighs 400 metric tons.

Lightweight steel framing was used to form the body of the SkyPark, which curves gently in plan and features a rounded bottom similar to a ship’s hull. Perhaps the most critical design decision involving the SkyPark and the three hotel towers involved the question of whether the structures should be rigidly connected—and therefore move together—or be articulated so that each could move independently, notes McNiven. After careful analysis, the design team selected the fully articulated solution because “the numbers in the fully fixed position showed that we would spend a lot of money and steel strengthening the SkyPark in order to force these huge hotel towers to all move in the same direction,” McNiven says. If the towers all moved together, the actual loads from, say, wind, would be “incredibly complicated” to determine, he adds, because the wind blowing on one of the towers would no longer be “a nice separate problem. Instead, it would be affected by the two other towers as well.”

The articulated solution featured the installation at the tops of the towers of a series of small aluminum and stainless steel plates with multidirectional bearings that can swivel and move as the towers sway. The four large movement joints in the SkyPark structure can accommodate potential building sway that could reach as much as 200 mm under wind forces and nearly 500 mm under seismic conditions, McNiven says. These movement joints, however, posed a challenge for the SkyPark’s pool (with its “infinity edge”), which is composed of three interconnected 50 m long stainless steel sections that cross two of the joints. The waterproofing solution involved the use of a roughly C-shaped capping system and seals located over the movement joints. It was developed by Safdie Architects; Howard Fields Associates International, of Sarasota, California; Natera Corporation, of Indianapolis; and Singapore-based Innovetz. Most of the pool is about 1.2 m deep, explains McNiven, but over the joints the depth is just 200 or 300 mm. The weight of the water presses down on the caps, which can move back and forth, allowing the different sections of the pool to move away from or toward each other as necessary, McNiven says. Any water leakage is captured and reused via a gutter system, he adds. A full-scale mock-up of the pool system was created to test the design under potential movement conditions, Safdie wrote.

The completed pool system also features steel jacks to ensure that the infinity edge remains at its horizontal level even as the towers settle over time.

McNiven notes, because the frequencies that result from such activities are different from those induced by wind and are not as easy to accommodate by means of a tuned mass damper. However, the resulting movement could make visitors feel uncomfortable. The wind forces were accommodated by installing a 5 metric ton tuned mass damper at the tip of the cantilever. The damper is suspended from transverse girders within the body of the structure. The design included space within the cantilever for a second tuned mass damper, but an analysis of the structure’s performance showed that an additional damper would not be required, says McNiven.

The potential movement of the cantilever–observation deck, which includes one of the SkyPark’s restaurants, also posed challenges for the design team. Two issues in particular raised concerns: wind forces and such synchronized crowd activities as dancing. These factors are not likely to damage the cantilever because, McNiven notes, a thousand people could be jumping up and down at one time and still not damage the structure. However, the resulting movement could make visitors feel uncomfortable.

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Full-scale testing atop the unfinished cantilever, which involved more than 100 people jumping up and down in sync with a giant metronome, was conducted to confirm the design changes.

design changes, he adds. (During one such test, Moshe Safdie was present and was being interviewed by Martha Stewart; according to a report on Stewart’s blog, some of her staff members actually joined in the jumping exercise.)

The SkyPark was prefabricated in 14 main steel sections, the largest being 90 m long and weighing 1,100 metric tons. The sections were erected using hydraulic strand jacking, a process more commonly associated with bridge building, in lifts and installations that took as long as 16 hours to complete, wrote Safdie.

The other main buildings at the Marina Bay Sands complex are mostly steel-framed structures. Perhaps the most distinctive of these is the ArtScience Museum, the design of which was inspired by the lotus flower, noted Safdie in a written description of the project. Ten cantilevering petal-shaped sections of varying lengths, the longest reaching a height of 60 m above grade, form parts of the gallery and science museum shaped like the petals of a giant metal flower.

ammunities of the Marina Bay Sands complex: clusters at the northern end, a multilevel casino in the middle, and convention and exposition spaces at the southern end. Within the casino, the expansive ceiling features a giant crystal chandelier formed from a tension cable net system 6.4 m tall suspended 40 m above the gaming floor by a ring beam and cross bracing in the roof structure. Crowning these podium facilities is a series of stepped, curving roof forms that span lengths of up to 120 m and somewhat resemble the carapace of an armadillo, notes McNiven.

As was the case with many of the Marina Bay Sands structures, the complex steel shapes of the podium roofs were designed and documented using a combination of different three-dimensional computer-aided software systems. “There was no such thing as a straight line on this job,” recalls McNiven, adding that the project “took our three-dimensional analysis and documentation capabilities and pushed them to levels we’ve never done before.”

We actually issued three-[dimensional] models to the contractors, and the contractors used the models as the first stage of their shop-drawing process.” The approach definitely saved time and money, adds McNiven, who points out that steelwork projects typically involve at least a month of “answering questions on the geometry where things haven’t been quite well defined enough—but this way, everything was in the model and done very quickly.”

Towering in its scope as well as its challenges, the Marina Bay Sands complex “is really more than a building project—it is a microcosm of a city rooted in Singapore’s culture, climate, and contemporary life,” Safdie explained in an architecture and design statement. “Our challenge was to create a vital public place at the district-urban scale; in other words, to address the issue of megascale and invent an urban landscape that would work at the human scale.” As Safdie concluded in his paper in the CEBUJ Journal, “The success of the project lies in the fact that the inventiveness of the design... was matched by equally inventive and novel approaches developed by the engineering and construction team.”

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PROJECT CREDITS Owner: Marina Bay Sands Pte. Ltd., a subsidiary of Nevada-based Las Vegas Sands Corporation; Design architect: Safdie Architects, Boston; Executive architect: Aradis Pte. Ltd., Singapore; Structural, civil, geotechnical, fire safety, risk and security, traffic, facade, and acoustical engineer and three-dimensional modeling: Arup Singapore Pte. Ltd.; Landscape architect: Peter Walker & Partners, Berkeley, California, and Peridian International, Inc., Newport Beach, California; Contractors: SsangYong Engineering and Construction Co. Ltd., Seoul, South Korea (hotel); and JFE Engineering Corporation/Yong Nam Joint Venture, Singapore (SkyPark); Strand jacking consultant: VSL, Singapore; Mechanical, electrical, and plumbing engineer: Vanderweil Engineers, Boston, and Parsons Brinckerhoff Pte. Ltd., Singapore; Hotel elevator and escalator consultant: KONE, Helsinki, Finland; SkyPark pool consultants: Howard Fields Associates International, Sunalito, California; Nature Corporation, Indianapolis; and Innovertze, Singapore

Located near the giant observation wheel known as the Singapore Flyer, the Marina Bay Sands complex features a series of entertainment, cultural, retail, and commercial attractions, including a 721,000 m² convention and exhibition center, a pair of theaters, a 15,000 m² casino, numerous shops, and an art and science museum shaped like the petals of a giant metal flower.