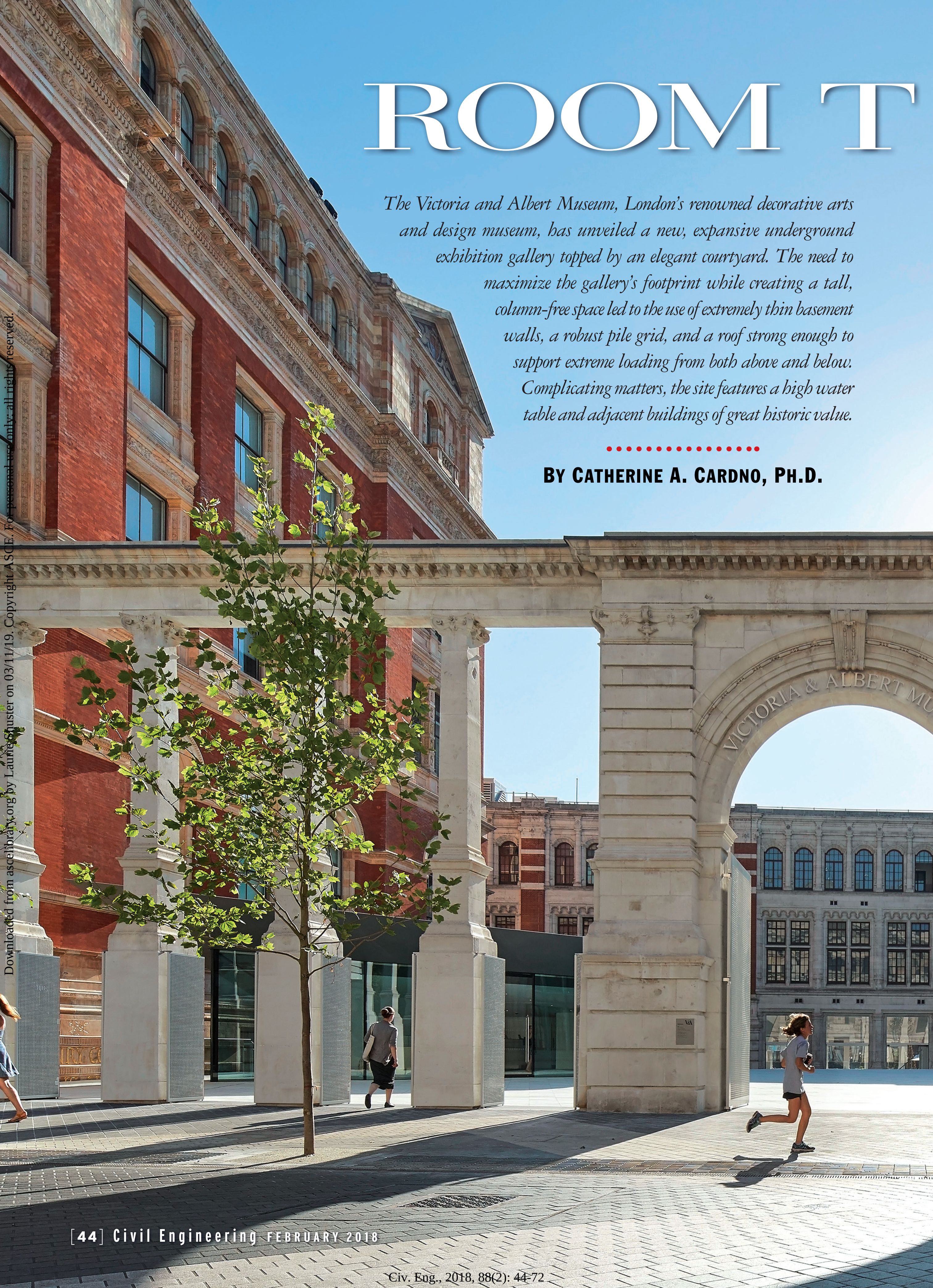
ROOM T

The Victoria and Albert Museum, London's renowned decorative arts and design museum, has unveiled a new, expansive underground exhibition gallery topped by an elegant courtyard. The need to maximize the gallery's footprint while creating a tall, column-free space led to the use of extremely thin basement walls, a robust pile grid, and a roof strong enough to support extreme loading from both above and below. Complicating matters, the site features a high water table and adjacent buildings of great historic value.

By Catherine A. Cardno, Ph.D.



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O GROW

THE VICTORIA AND ALBERT MUSEUM, founded in 1852 in London's Royal Borough of Kensington and Chelsea, not only holds design masterpieces, it is one. This past summer, the museum unveiled its newest gallery space: an expansive underground exhibition hall topped by a porcelain-tiled courtyard. Filled with natural light and accessible via two new five-flight staircases carefully inserted into and beneath an existing museum building, the 1,100 sq m column-free Sainsbury Gallery exhibition hall is a striking addition to the museum's collection of architecturally significant spaces.

The museum, typically referred to as the V&A, is reportedly the world's largest devoted to decorative arts and design. Its collection is housed in numerous buildings. Three of these are adjacent to the new 1,200 sq m Sackler Courtyard and are listed with Historic England, the public body responsible for protecting

The rebuilt Aston Webb Screen at the V&A welcomes visitors to a new courtyard and museum entrance.

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England's historic built environment. They are designated as either grade II* or grade I; grade II* structures are deemed by Historic England to be "particularly important buildings of more than special interest," while grade I buildings are deemed to be "of exceptional interest" (the highest rank). These include the Henry Cole building, a Grade II* structure located to the north of the new courtyard and dating to 1871; the Aston Webb building, a Grade I structure located to the south and dating to the 1890s; and the Western Range building, a Grade I structure located to the east and initially completed in 1863 and rebuilt in 1897.

The new courtyard is surrounded on three sides by existing historic buildings, and on the fourth by the semipedestrianized Exhibition Road. Aluminum gates can be closed to wall off the courtyard from the road.

"Balancing the V&A's need for extra exhibition space whilst protecting these important buildings was probably the most important task of the project team," notes Stuart Hardy, Ph.D., an associate director in the geotechnics group for the London office of Arup, who was responsible for all soil-structure interaction analyses and ground-movement predictions on the project.

The design team for the new £54.5 million (U.S. $72.78 million) project for the Trustees of the Victoria and Albert Museum was led by AL_A, an international design and architecture studio. The London office of Arup, a multinational firm, was responsible for the civil, structural, geotechnical, building services, and fire engineering as well as acoustics, security, logistics, sustainability, and daylighting. The London-based firm DHA Designs designed the lighting, and Giles Quarme & Associates, also of London, served as the historical adviser. The main contractor was Wates Construction Ltd., of Leatherhead, Surrey, United Kingdom.

The underground structure has been built in a 0.3 ha back-of-house space that connected all three museum buildings and was long known as the Boiler House Yard. This space, which in plan was shaped almost like a cleaver, or a dog's leg, contained unlisted, low-rise buildings that provided the building's services. (These functions have been taken over by a new building services system constructed as part of the project's upgrades and located in the narrow handle, or leg, portion of the site.) The small site's elevation varied considerably, and the ground floors of the historic museum buildings abutting the site on three sides differed in height from one another by up to 6 m.

Exhibition Road, a recently semipedestrianized street known for the access it provides to the museum district south of the city's famed Hyde Park, extends along the fourth side of the site. Because of its previous use for building services, the site was long hidden from the street behind a classical Portland stone structure known as the Aston Webb Screen. The 38 m long and 9.5 m high screen boasted twelve full-height decorative columns, connected by entablature at the

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top and supported by a 1 m wide, 4.5 m tall wall that had hidden the yard from the street since its construction in 1906. Appearing to be made of stone blocks, this wall contained a brick core clad with facing stones. As part of the project, the screen was carefully catalogued, dismantled, and stored for reassembly—minus the infill wall—after the completion of the new underground structure.

The underground exhibition hall project is the museum's largest architectural intervention in more than a century. "Obviously, we're working in this amazing context," says Matthew Wilkinson, an associate at AL_A and the project architect. "It was very important to us that it didn't feel separate from the museum and that it just felt like a continuation of the museum that has grown through the last 150 years." The gallery occupies the upper level of the underground structure beneath the courtyard with a lower level providing conservation, mechanical, and storage space.

The engineering required to weave the new structure seamlessly into the site and the existing buildings' accessways proved complex. The extremely tight site constraints, value of the surrounding historic buildings, and underground design created three highly significant engineering challenges for the project. First, a solution was needed to keep the 15 m deep underground structure in place despite the fact there was no heavy superstructure to balance the uplift created by ground heave and water pressures. Second, an interior corner of the Western Range building had to be delicately deconstructed and underpinned so that the stairways to the new underground exhibition gallery could be built within and underneath the building. Third, the entire project had to be designed, sequenced, and monitored to ensure that no more than 20 mm of settlement occurred in all three of the surrounding historic museum buildings, both during construction and in the following decades.

"We needed to keep the damage to category 1 or less according to the Burland classification system…[which] is defined as 'very slight' and comprises cracks up to 1 mm that can easily be treated during normal redecoration," Hardy says. "This project required a collaborative design and construction team completely committed to delivering a first-class exhibition center, constructing to the highest standards of workmanship to meet the exacting project requirements."

In addition to its elevation changes, the site varies geologically. "The levels of the soil strata are not completely consistent: there's 'made' ground [fill] on the top, and then under that there is terraced gravel deposits, which vary in thickness from about 2 m to 7 m thick," explains Alice Blair, CEng, a senior structural engineer with the London office of Arup. Blair was responsible for delivery of the basement structural design on the project. "The existing museum buildings were generally founded on [shallow] strip footings on the river terrace deposits, and then under the river terrace deposits, we have London clay…that extends to more than 50 m in depth," she says.

Structurally, the two-story underground space is composed of structural steel and reinforced concrete, according to Blair. Approximately 235 linear m of permanent, hard/firm secant bored pile walls, in which reinforced piles are interlocked with unreinforced concrete piles, form the perimeter of the underground structure. The tops of the piles are connected together at ground level with reinforced concrete capping beams. "Half of the piles are nominally 900 mm in diameter—that's around the courtyard space—and then in some of the more awkward and narrow areas we have 600 mm diameter piles so that we could use a smaller piling rig to fit in that space and because we needed the space internally for all of the things that needed to go into our building," Blair explains.

"The size of the gallery was directly related to how thick the perimeter wall was, including the pile wall thickness, and therefore, [the critical question was] how close you could get a piling rig up to these beautiful facades with lots of cornices," Blair says. "It was this balance between wanting to go as far as we could, without going too far," she notes. Ultimately, the design team determined that the piling rigs could safely work 1 m from the edge of the historic buildings, which meant they were within just 300 mm of high-level projecting cornices. This also resulted in secant piles placed just 150 mm from some of the

The underground structure's hybrid folded-plate, structural steel-truss roof contains one primary planar truss and 13 triangular secondary trusses that give the space a striking, geometric appearance.

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foundations, according to Dinesh Patel, a director in the geotechnics group in the London office of Arup. Patel, who was the geotechnical project director for the project, wrote in response to questions posed by *Civil Engineering*.

Temporary, instrumented, hollow-steel props held the top of the excavated pit firmly in place during construction, while a so-called "doughnut" slab enabled excavation of the lower portion of the pit.

The secant pile wall system was chosen to create very stable excavation walls and limit, as much as possible, the amount of groundwater that leaked into the site. Protecting the historic buildings from settling was linked to the behavior of the groundwater beneath them. The groundwater was 3.5 m above ordnance datum, which is about 6 m below the level of Exhibition Road and about the same level as the lowest basement of the existing buildings around the site, according to Blair. If that level was allowed to drop during construction—for example, by allowing water leakage into the excavation pit—there could be a loss of ground beneath the adjacent structures with potentially damaging consequences, Blair explains. "So [the groundwater level] was really important to control," she notes.

So the team had tighter tolerances for the secant pile walls than is usual and maintained the interlocks to greater depths than normal, according to Blair. "Normally you would maintain the secanting maybe one or two meters into the London clay, and we took it deeper to make sure that there was more of a barrier to the groundwater coming through the piles underneath the terrace gravels," she notes. In some locations, it was necessary to seal joints against seepage using grout-injected silicone.

The underground structure's base slab is a reinforced-concrete raft slab measuring 1,200 mm thick. An 8 m by 9 m grid of deep tension piles measuring 1.2 m in diameter extends 34 m under the basement base slab to control heave. "In the long term, because the ground has been unloaded [through excavation], it wants to swell upwards, and that applies quite a significant heave pressure on the underside of the basement," Hardy explains. The 12 heave piles located underneath the raft foundation "prevent the basement popping out of the ground like a champagne cork," he notes. "It was a case of finding an economic solution which protected the building and provided a resistance to that heave force and also water pressure." Because of the low permeability of the London clay, Hardy estimates that it will take between 10 and 20 years for the ground pore-water pressure to dissipate and reach equilibrium underneath the existing buildings and around the new underground structure.

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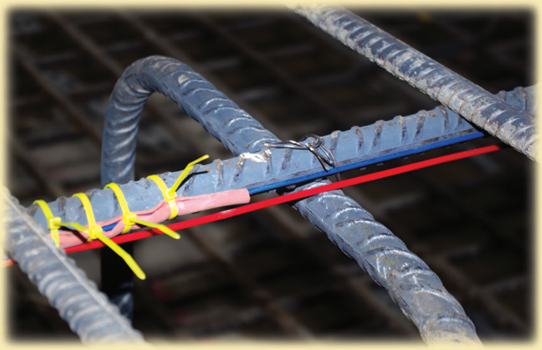
The gallery floor, one level up from the base slab, is a 300 mm thick reinforced-concrete slab. Above that, the roof spans 35 m at a height that ranges between 6.5 m and 10.5 m above the gallery floor. The roof had to be strong enough to support extreme loading from above (such as would be imposed by a temporary sculpture exhibition in the courtyard) and from underneath (such as would be created by the temporary hanging of exhibition objects), and it had to do so while remaining column-free and being perforated with skylights. "The big paradox of the project is that most of the project is buried in the ground, so there has always been this overriding ambition to make the invisible visible." Wilkinson says. "How do you make this new gallery underground and visible to the public in a palpable way, and in parallel with that, how do you make sure that those spaces, which are underground, don't feel at all like they're underground? How do they feel generous, and how do they have daylight? Those were key drivers for us."

The solution to creating a strong, yet perforated, roof that maximized the interior heights was a hybrid folded-plate, structural steel-truss roof that is topped with a composite metal deck slab to form the courtyard above, according to Blair. The folds are created by 13 triangular-shaped secondary trusses that accommodate a 2 m elevation difference between Exhibition Road and the new museum entrance in the Western Range building. "They ended up getting named Toblerone trusses after the chocolate bar, because that's the sort of shape they are," Blair notes. "We wanted to get a system that could mostly be

Permanent Sensors Turn Construction Project into Long-term Research Study

THE CENTRE FOR SMART Infrastructure and Construction (CSIC) at Cambridge University, in conjunction with Arup, has placed fiber-optic cables that will serve as permanent sensors on the underground structure built at London's Victoria and Albert Museum (V&A). By taking regular readings from the cables, the researchers will have a case study that will help validate the nonlinear elastoplastic finite element analysis that was used as a predictive tool on the project, according to Stuart Hardy, Ph.D., an associate director in the geotechnics group for the London office of Arup. The theory used in the analysis is applicable to short- and long-term heave movements in overconsolidated plastic clays, such as the London Clay that extends under the site, he explains. "Despite the novel use of heave-reducing piles in the main basement area [in the V&A underground structure], the prediction of heave pressures beneath rafts in stiff overconsolidated clays is not well understood and is often approximated by linear elastic methods that cannot capture the true behavior of the soil," Hardy says.



Fiber-optic cables attached to the rebar cages of the basement raft foundation and two of its tension piles will be accessed periodically over the coming decades to measure changes in strain and temperature.

ARUP

Fiber-optic cables were attached to the rebar cages of two of the tension piles underneath the basement raft foundation and in two directions in the raft itself to measure changes in strain and temperature. "By using fiber-optic [cables], we had this opportunity to monitor better how this heave will develop with time [and] investigate whether our current understanding, which is based on limited evidence, is adequate or if we have been overdesigning our basements," says Loizos Pelecanos, Ph.D., a lecturer in geotechnical engineering in the Department of Architecture and Civil Engineering at the University of Bath in the United Kingdom.

An access hatch has been built into the underground structure so that the team can set up its computers and take readings anytime. The analyzer—the machine that performs the readings—performs by shooting a light along the cable to detect strain and temperature every 5 cm along its entire length, up to a few kilometers, according to Kenichi Soga, Ph.D., the Chancellor's Professor in the Department of Civil and Environmental Engineering at the University of California, Berkeley. While an off-the-shelf analyzer was used for initial V&A monitoring, the team from CSIC and Berkeley is creating its own version to push the boundaries of the monitoring system so that it is more robust and can be used for long-term monitoring, according to Soga. Soga, who was formerly a professor of civil engineering at Cambridge University, and his team have spent the last ten years developing and refining the distributed fiber-optic sensing system that is being utilized to monitor the site.

"It's an interesting sensing technology [because] fiber optic itself becomes a sensor in a distributed way," Soga says. "Ground loads are not point loads; they are distributed loads, so our interest was trying to understand how the strain changes in the pile depth or across the slab." These loads change over time, as well, so the team plans to monitor the behavior of the piles and raft foundation for at least the next two decades as water pressures redistribute themselves through the site. "If you work on what we call clayey ground, within which water doesn't move very freely, initially when you take out the ground, you have what we call short-term [or undrained] behavior," Soga says. During this process, some suction in the pore water is generated, causing changing stresses in the soil. "And then what happens with time is that this water and soil interaction changes, and then greater heaving starts to generate in long-term [or drained behavior]."

—CAC

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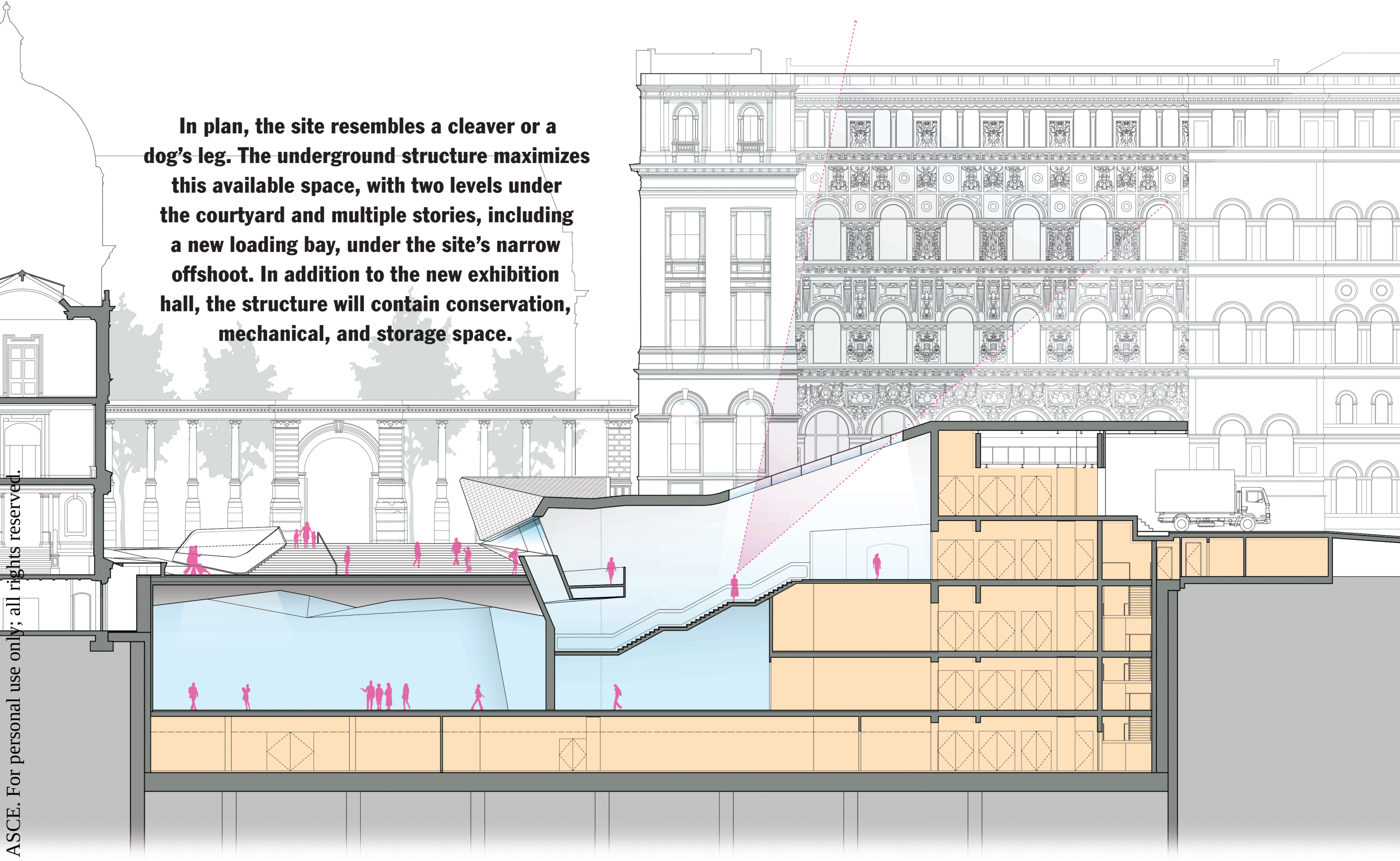

In plan, the site resembles a cleaver or a dog's leg. The underground structure maximizes this available space, with two levels under the courtyard and multiple stories, including a new loading bay, under the site's narrow offshoot. In addition to the new exhibition hall, the structure will contain conservation, mechanical, and storage space.

COURTESY OF AL_A

fabricated off-site, so that we didn't need even more temporary works just to support the steel during construction." The secondary trusses are supported by a primary, planar truss.

"The steel structure was quite unusual in terms of its geometry and what we were trying to do with it," adds Carolina Bartram, CEng, MIStructE, an associate director at the London office of Arup and the civil and structural engineering leader for the project. "It's unusual to do a roof that is also going to have quite heavy loads like a courtyard, because it isn't really a roof, it's actually a floor, so I think the combination of those two was very interesting," she says. "There was a lot of exploration to see what worked best, not just for the structure but also for the architecture." Changing one thing in the design, such as how many folds the origami-like roof had or how far apart the folds were, had significant impacts on other elements that had to be fully understood, she explains. "This [process] required an intensely close working relationship between AL_A and Arup," adds Wilkinson.

The ceiling profile follows the geometry of the trusses, whose peaks give the hall a greater sense of height without the need to create such a high ceiling throughout the entire space, according to Wilkinson. These folded trusses also create a "powerful geometry" for the ceiling, Wilkinson notes, which fits with the V&A's tendency to display its buildings' structural elements. "The spaces in the museum are very didactic; there are a lot of cast-iron structures that are visible and decorative, and there are a lot of exposed arches and domes," Wilkinson says. "[The trustees of the museum] are interested that the way that the building is built is clear and accessible to the public as a form, so it was nice that we could play into this idea of didactic spaces."

The construction project was completed with only minor effects to the existing buildings, including two particularly fragile elements located adjacent to the site—sgraffito plaster facade frescos on the eastern exterior side of the Henry Cole building and an interior ceramic-tiled staircase in the Western Range building. This success was due in large part to the creation of a complicated three-dimensional finite element model of the underground structure that was developed with the geotechnical software LS-DYNA (produced by Livermore Software Technology Corp., of Livermore, California), which allowed all aspects of the geometry to be considered and predictions of building movement and potential damage to be made, according to Hardy. The model was so complex it took about 36 hours to run on a supercomputer, according to Hardy. "It was an incredibly complicated model, and it had every detail, every construction sequence, every structure modeled—it was incredible," Hardy says. "And we were using that as a design tool, not a final check tool, and we had to do it because we were pushing the boundaries so far on this project."

Blair notes, "We didn't think we were taking excessive risks, but if we'd gone for a conservative design everywhere, it would have looked quite different. We wouldn't have had the skylights. We would have had a much smaller gallery."

As part of the strategy to interweave the new exhibition hall with the existing museum buildings, an interior corner of the Western Range building was underpinned and disassembled above and below ground level so that the daylit staircases could be added to access the new underground exhibition hall. "That means that you move seamlessly from the new to the old," Wilkinson notes. "Whereas if we'd put a new staircase down to the gallery in the new courtyard, which would have

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been much cheaper, you in theory could move all the way down to the exhibition gallery and not connect with the rest of the museum."

"The scheme for underpinning the Western Range was developed collaboratively by Arup, Wates, and Toureen Mangan to ensure the proposed staircase could be built whilst protecting the facade of the Western Ranges and the adjacent ceramic staircase," Hardy explained. Toureen Mangan—part of Toureen Group, based just outside London—served as the civil and ground work subcontractor on the project.

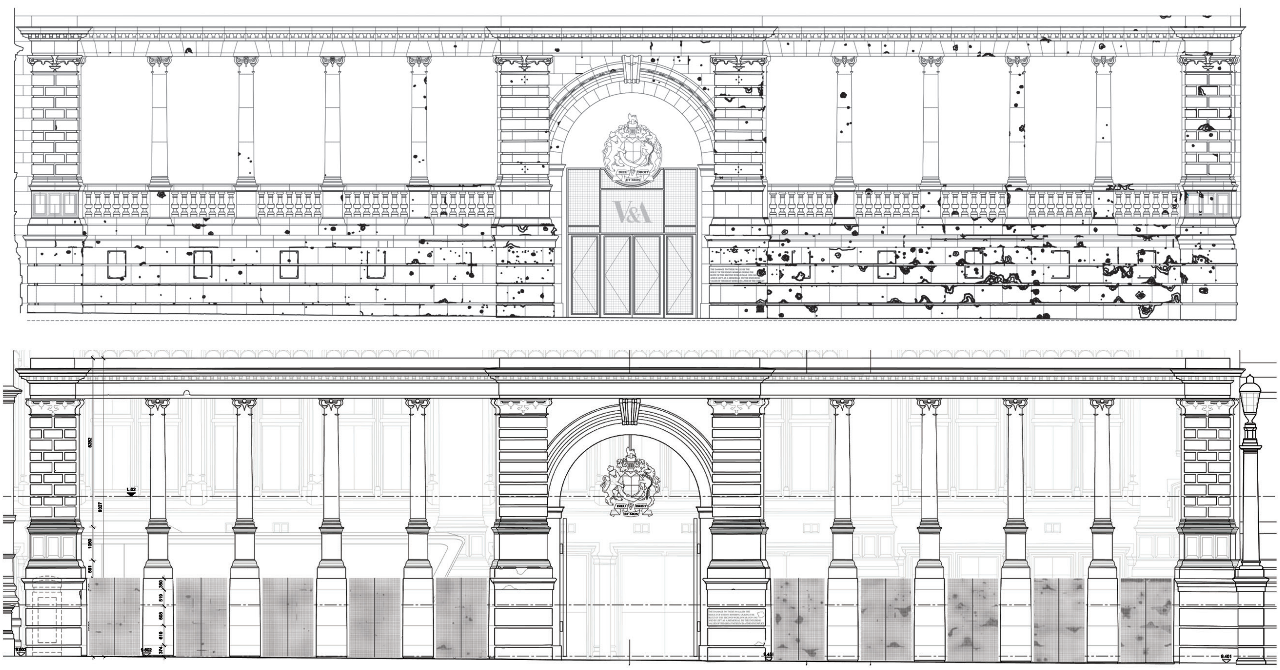
The work included significant underpinning of the building's shallow foundation, removal of part of its facade, and the use of a temporary hydraulic jack support system so that the stairs' new cross beams could be carefully threaded through the building's existing footings, according to Patel.

Installing the new staircase was one of the most complex aspects of the engineering, Bartram says. "We were opening up and taking out structural walls from an existing building and at the same time excavating underneath," she says. "It was [also] one of the most complex bits of sequencing."

To construct the main underground structure, a hybrid "bottom-up, top-down" construction sequence was developed. This system used two different types of props during the construction sequencing to hold the walls of the excavated pit solidly in place and control movements of the historic buildings. The props also had to work with the different elevations at which the surrounding buildings were located. "The key to the project was to excavate the basement as quickly as possible to minimize the effects of excessive ground movements, [which] this construction method allows," explained Patel.

The first level of props were temporary, instrumented hollow steel struts measuring up to 1 m in diameter that were placed high up on the excavated pit's walls and attached to the new secant wall concrete capping beams or temporary steel waling beams depending on their *(Continued on Page 72)*

To access the new underground gallery, an interior corner of the museum's Western Range building was carefully disassembled, and staircases flooded with natural light were added. The steel support system, painted a striking red orange, remains visible, *above.* The Aston Webb Screen was noticeably damaged by shrapnel during World War II. A laser scan of the original structure was created so that the screen's new gates bore the same historical scars, *below.*



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Room to Grow

(Continued from Page 51) location, according to Hardy. Vibrating wall strain gauges were placed within these props so that the data gathered could be used to calculate the force exerted by the wall to validate the movement prediction model that had been created by the engineers, according to Hardy.

The second type of prop was a permanent 300 mm thick "doughnut" slab with cross members for added stiffness that performed as a midheight prop during construction and the gallery floor slab afterward. This slab contained two cutouts through which the excavations beneath it were conducted. Twelve plunge columns support the sides of the slab and are founded on the heave piles below the base slab, according to Blair.

"Normally you have just temporary props or you have permanent props, so you do bottom-up or top-down construction, but we mixed the two together to provide a construction program benefit, plus cost savings…because you don't have to provide an extra level of temporary props [that] you just end up taking away," Hardy says.

The buildings were manually monitored weekly using 3D prisms and leveling studs together with inclinometers in piles and extensometers in the ground to measure heave. Movements of the existing buildings were predicted to be about 10 to 20 mm. During the installation of the pile wall, slightly more movement than expected occurred at the southeast corner of the Henry Cole building, so an additional prop was placed to limit the building's movements during the excavation of the lower level.

In addition to the temporary construction sensors, the site will also undergo long-term monitoring of heave [see "Permanent Sensors Turn Construction Project into Long-term Research Study" on page 61]. The Centre for Smart Infrastructure and Construction at Cambridge University, in conjunction with Arup, installed fiber-optic cables in the basement raft foundation and two of its tension piles. These cables will be utilized for short- and long-term monitoring of the forces affecting the structure.

To protect the exhibition hall itself and the artwork that will be displayed within it from groundwater, a layered wall system was installed on the site's perimeter. In this system, a reinforced concrete lining wall was cast against the perimeter piles, and then lined with a cavity wall drainage system. The drainage system captures any percolating water that might seep through the pile and lining wall and drains it to a cavity drain atop the base slab floor. This water is then filtered and pumped into the existing local combined sewer and stormwater system. The top of the hall offers layered waterproofing as protection against rainwater intrusion. The plaza's ceramic tiles are placed atop a system that includes rigid structural insulation, screed, a double membrane, and a concrete slab, according to Bartram. Channels around the perimeter of the plaza and at the base of the stairs that descend to the museum's new entrance doors collect water for drainage to the local sewer system as well.

The detailed attention paid to the project also extended to its finishes, including the plaza's handcrafted porcelain tiles, which have been created in 15 different patterns by ceramics company Koninklijke Tichelaar, of Makkum, the Netherlands. "There's this amazing history of ceramics at the V&A, and so that was a huge inspiration for us," Wilkinson says. Rather than creating a gray granite, civic-feeling courtyard, the team wanted to introduce color and pattern and bring the idea of ceramics to the new outdoor space, Wilkinson explains. To balance form and function, the tiles that the team created are grooved and off-white. A translucent, pale blue-gray glaze has been placed in the grooves to prevent pedestrians from slipping. "Because the grooves that we've put in the tile are semicircular, you get deeper glaze in the middle and shallower at the edges, so you read a deeper color in the middle, where there is more glaze and there is a lighter color at the edge," Wilkinson says. "So there's a lot of subtlety in them, which is beautiful." The tiles have been finished with a proprietary ingredient to ensure that as they wear, they do not polish through use and become slippery.

Once major construction of the underground structure and courtyard was complete, the Aston Webb Screen was rebuilt as a grand colonnade entrance to the new courtyard and the museum. The removal of the screen's infill wall creates a "powerful visual and physical permeability [to the screen], allowing visitors to drift into the museum from the street," Wilkinson says. The columns and entablature were reinstalled exactly as they had been originally built but founded on new reinforced-concrete bases that supported the columns in lieu of the former wall. "Where the wall was removed, new folding aluminum gates perforated in a pattern that responds to original World War II shrapnel damage [to the wall and which] can be closed at night to secure the museum [were added]," Wilkinson says. A new, lightweight, double-height cafe and shop has also been constructed along the northern edge of the courtyard, to maximize sunlight.

"It was really important to bring the city into the museum and take the museum out into the city," Wilkinson says. "The idea was that the courtyard would act as a mediator," he says. "In contrast to the main big entrance on Cromwell Road, which is grand and magnificent but also slightly imposing to some people, we wanted something that was much more informal, much more relaxed, that would allow you to drift in off the street, and that would speak of the V&A before you were in the V&A properly." **CE**


Cardno

Catherine A. Cardno, Ph.D., is the senior editor of Civil Engineering.

PROJECT CREDITS **Client** Trustees of the Victoria and Albert Museum **Architect** AL_A, London **Structural and geotechnical engineer and mechanical, electrical, and plumbing consultant** Arup, London office **Primary contractor** Wates Construction Ltd., Leatherhead, Surrey, United Kingdom **Piling subcontractor** Keller, London **Civil engineer and ground work subcontractor** Toureen Mangan, a division of Toureen Group, Harrow, Middlesex, United Kingdom **Instrumentation and monitoring subcontractor** ITM Monitoring, Uckfield, East Sussex, United Kingdom **Steelwork subcontractor** Bourne Group, Poole, Dorset, United Kingdom **Lighting design** DHA Designs, London **Historical adviser** Giles Quarme & Associates, London

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