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Wastewater infrastructure for the next century

Embracing collaboration to deliver a vital sewer upgrade, capable of withstanding earthquakes and extreme weather

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The Silicon Valley Clean Water Gravity Pipeline project is a 4.1m (13.5ft) internal diameter tunnel and pipeline that offers a valuable template to water authorities across the US and beyond, as they grapple with the twin threats of climate change and deteriorating 20th century infrastructure. The 5.3km (3.3 mile) tunnel, which is being delivered by a joint venture (JV) team including Arup as multidisciplinary designer, had to address numerous environmental and technical constraints. These included difficult ground conditions and the challenges of building large-scale infrastructure next to residential areas, an airport and a nature reserve. At the same time, innovative construction techniques were needed to ensure a 100-year design life, particularly in the face of climate-related extreme weather, the aggressive chemical environment predicted in the tunnel, and potential earthquakes – the San Andreas fault lies just four miles away.

The $253m tunnel was the first tunnelling project in North America to be delivered using the progressive-design-build (PDB) procurement method which utilises collaborative working between the owner, contractor and designer to maximise innovation and design efficiency while minimising construction schedule and whole life costs. As with conventional design-build, this involves the owner selecting a team at a very early stage of the project to develop the initial design. The difference is that the main construction contract price isn't fixed upfront but at the 60% level of design, before the final design and construction phase. Arup co-located its team with JV partners Barnard Construction and Bessac (BBJV) for two-and-a-half years. This interdependent working relationship was instrumental to fostering innovation and facilitating evaluation of project alternatives, such as the corrosion resistance of the installed pipeline. This led to the decision to use a large-diameter fibreglass-reinforced plastic mortar (FRPM) pipe within the tunnel – believed to be the largest such installation in North America. It also enabled the construction to start six months ahead of schedule.

Developing the concept design

The two-phase process of PDB took the project from 10% to 60% design in phase one, and then through to design completion and construction in phase two. Before that, however, the owner had to complete a concept design, approximately a 10% design level – which was a long and complex operation in itself. The project is part of the wider Regional Environmental Sewer Conveyance Upgrade (RESCU) programme run by the owner, Silicon Valley Clean Water (SVCW). The programme aims to effectively modernise their wastewater systems, building resilience and durable infrastructure for the local communities. This included replacing aged infrastructure, and upgrading pumping stations and sewage treatment works across the cities of Belmont, Redwood City and San Carlos, as well as the West Bay Sanitary District.

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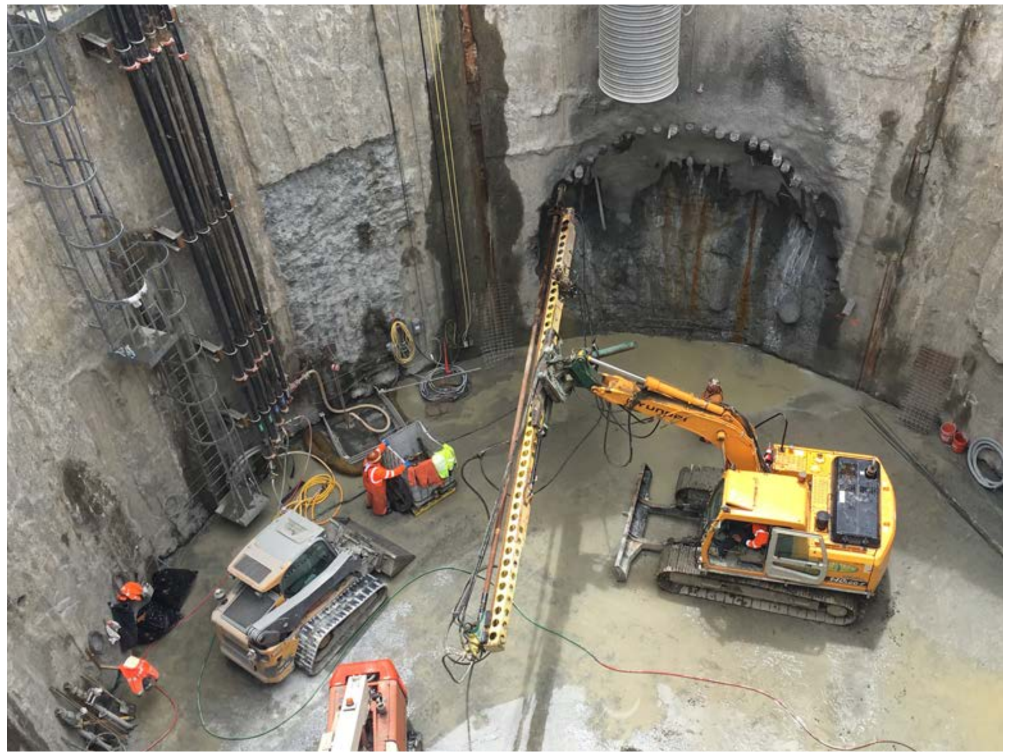
1: The project offers a template to water authorities in the US and beyond, as they grapple with the twin threats of climate change and deteriorating 20th century infrastructure

2, 3: A FRPM lining was used for the tunnel to ensure long-term durability



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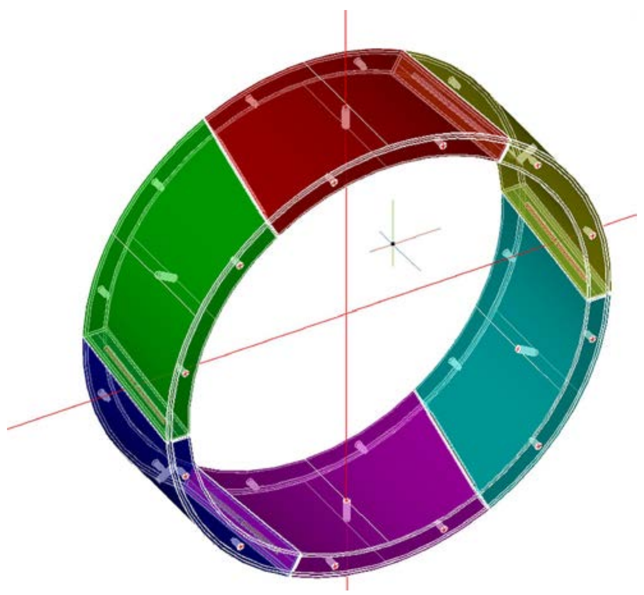
4: The large excavation for the TBM launch shaft was 18.3m in diameter and depth

5: The tunnel lining is constructed from 1.5m long precast concrete rings with an internal diameter of 4.1m



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The section leading to the main sewage treatment plant at Redwood Shores was one of the most urgent elements of the programme. Spills and leakages from the existing 1.4m (4.5ft) diameter forcemain were becoming commonplace, posing an environmental threat to the delicate ecology of the Bair Island Wildlife Refuge, as well as the local population. The concrete pipes, some of which were more than 80 years old, were deteriorating, and their capacity was proving inadequate. With SVCW identifying the need to manage increases in wastewater peak design flows of up to 390,000m^3 (103 million gallons) per day during wet weather, the risk of catastrophic failure was looming large.

SVCW considered 140 alternative schemes, evaluating capital and life cycle costs, reviewing risk and success factors, with five schemes evaluated in detail. Rather than a pressurised forcemain, which requires power to pump the effluent and carries the risk of both explosive leaks and expensive maintenance, the decision was made to design a tunnel system that would operate by gravity flow. This avoided an open-cut approach, either to repair or replace the existing shallow pipework from the surface level, which would have been disruptive to wildlife, transport, and local communities and businesses. The vertical alignment of the tunnel has a slight gradient to allow gravity flow conveyance of wastewater to the Redwood Shores plant.

The tunnel was sized to accept and equalise a broad range of flows from inlets connected to the existing network, as well as to store stormwater during peak wet weather events – this provided resilience to the system for both usage fluctuations and increased flows due to climate change. It also allows for flexibility of operation – saving costs by pumping wastewater during off-peak hours, for example, or pumping at a constant rate to prolong the lifespan of equipment. At concept stage, SVCW identified the notional diameter of the pipe to convey and store the flows as 3.4m (11ft). To install a pipe of this diameter at depth, a tunnel boring machine (TBM) had to be used to construct a tunnel large enough to allow pipe segments to be transported through it and connected.

The selected alignment for the tunnel was plotted along the estuary and generally followed the route of the existing forcemain. Starting at Inner Bair Island, the tunnel heads northwest towards San Carlos Airport, linking up with the Belmont and San Carlos pipelines before curving north-east to Redwood Shores. The depth was selected to ensure the tunnel would remain below a challenging geotechnical layer – the Young Bay Mud (YBM) – for the entirety of the alignment, eliminating the complexity of tunnel construction in a known difficult and sensitive ground condition. SVCW carried out an extensive geotechnical investigation for the whole route, conducting borings or cone penetrometer testing approximately every 75m (250ft). This identified the depth of the YBM and indicated a geological layer unit suitable for a TBM excavation along the tunnel alignment, through medium-stiff clays and sand, called the Upper Layered Sediments.

Building the team

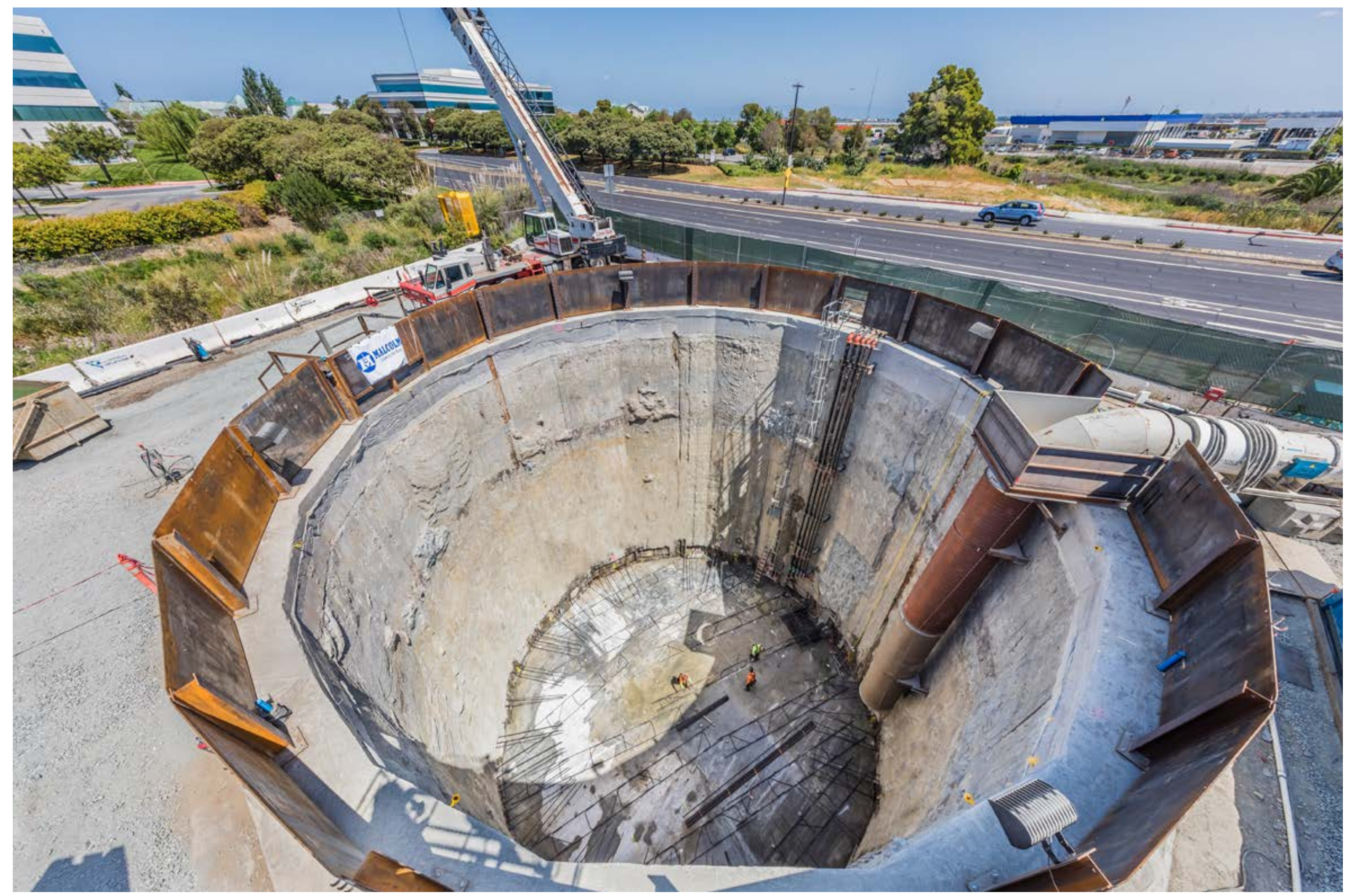
Once the concept design was completed and the project had achieved environmental clearance, SVCW invited bids for the PDB contract. As a knowledgeable owner with decades of sector experience, it made sense for SVCW to choose an approach that didn't involve a fixed budget and agreed requirements from the outset, but instead relied on flexibility, mutual trust and close collaboration with the builder and designer. An initial pool of six bidders was shortlisted to three teams. Over the course of three months, SVCW then conducted confidential meetings with each shortlisted team, evaluated their proposals and held interviews.

The winning consortium, BBJV, comprised Montana-based heavy civil construction experts Barnard Construction, which had recently completed the San Francisco Central Subway tunnels; French tunnel boring specialist Bessac; and Arup, whose multidisciplinary design role included everything from hydraulic and tunnel design to additional geotechnical investigation and analysis, and all other aspects of civil, structural, mechanical, electrical and seismic engineering.

The first phase of the contract, up to the 60% design milestone, included all aspects of the permanent works, such as the tunnel and shaft design. The design of the temporary TBM launch shaft, which needed to be big enough to assemble, accommodate and disassemble an 815-tonne (900-ton) machine, was also undertaken.

The flexibility of PDB meant that key project elements could be advanced to a higher level of design in phase one,

6: The project was the first tunnelling project in North America to be delivered using the PDB procurement method



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allowing the construction work to progress quickly after final costs had been agreed. These elements included the enabling works for the TBM launch shaft, the 100% design of the precast-concrete tunnel lining, and the specification of the TBM, which relied on BBJV's expert knowledge of closed-face tunnelling in the local ground conditions.

Tunnel design

The TBM launch shaft was placed near the airport, about a third of the way along the route. This ensured that the sizeable launch construction activities were located away from the ecologically sensitive Bair Island at one end of the tunnel and the residential areas at the north end. From there, the TBM would drive two tunnels, each to the retrieval shafts on opposite ends of the alignment, where the TBM was extracted.

The $18.2m machine, 200m (650ft) in length with all support elements, was manufactured by Herrenknecht in Germany. It operates using earth pressure balance (EPB), a system that works well with cohesive soils such as clay. EPB involves turning excavated material into a paste and using it as a support medium behind the cutterhead, balancing the water and ground pressure and thereby controlling the stability of the tunnel face during excavation.

The tunnel has a diameter of 4.9m (16.2ft) and was bored at a 0.5% gradient, dropping from 6.1m to 10.7m (20ft to 30ft) below ground level on the first tunnel drive, and then to 18.3m (60ft) on its way to the new SVCW headworks facility. The lining is constructed from 1.5m (5ft) long precast concrete rings with an internal diameter of 4.1m (13.5ft), with each ring composed of six segments. Dowels provide connections from segment to segment and from ring to ring – bolts being deemed more likely to corrode, and requiring more manual work around the TBM.

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A high-density concrete mix was specified for the tunnel lining segments to minimise the risk of chloride-induced corrosion in the brackish ground conditions in the vicinity of the tidal estuary. Likewise, fibre reinforcement was preferred to traditional steel rebar. This had the added benefit of increasing the flexural strength of the tunnel and being less likely to crack – an important aspect of the seismic design. The segments were cast by Traylor Precast in Stockton, California to sub-millimetre tolerances using precision moulds made by CBE Group in France. Each of the six segments is slightly different in form, which gives the completed ring a tapered edge. This allows the tunnel to curve, simply by rotating the point of connection between one ring and the next.

Specifying the pipe

The other critical consideration for the tunnel designers was the threat of microbially induced corrosion (MIC). Microorganisms thrive in the aerated zone of a sewer, feeding on the sulphur naturally present in the wastewater and excreting sulphuric acid, which then reacts with the calcium carbonate in the concrete. This can result in up to 100mm (four inches) of corrosion over a 100-year life.

The team explored a number of options to combat this, including using a high density polyethylene (HDPE) lining integrally cast with the concrete segments and changing the concrete mix design to resist MIC. With long-term reliability at the forefront of their thinking, the team opted for the most durable option: a 3.4m (11ft) diameter lining of FRPM. Full-scale testing of the FRPM was carried out to demonstrate the adequacy of the lining installation and performance in service.

7: The 815-tonne TBM was named 'Salus' for the Roman goddess of health and wellbeing

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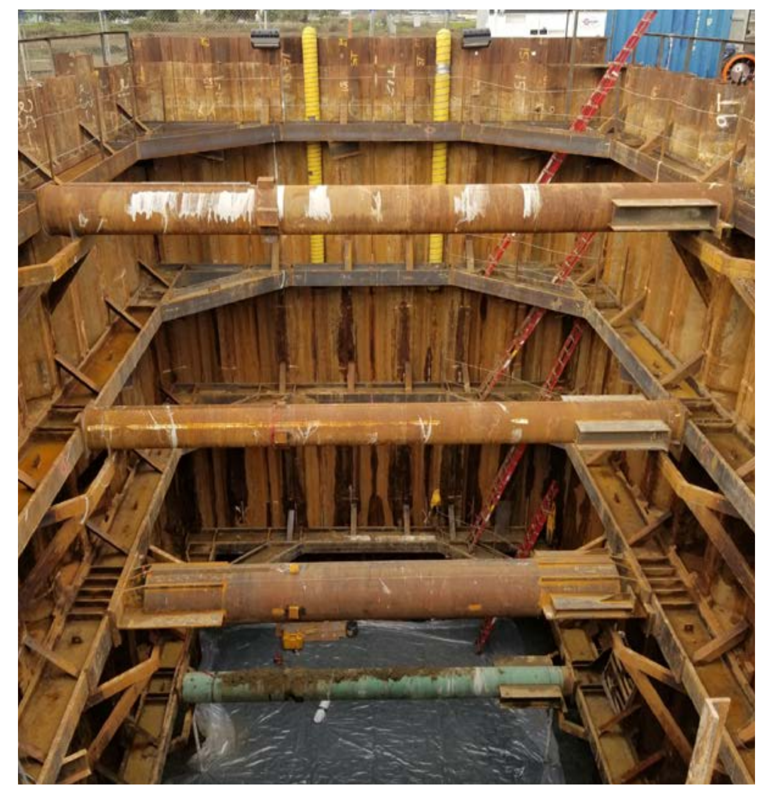
An additional challenge was that FRPM at this scale was uncommon for a pipeline in the US, and there were very limited options for facilities capable of fabricating such large-diameter sections. The best available option was to import it from Future Pipe Industries, who had a facility capable of producing the pipe in Jakarta, Indonesia. Here, the team came up with a design modification that essentially halved the transport costs and related carbon emissions. For the first tunnel drive, the pipe diameter was reduced to 3.05m (10ft) – hydraulic modelling indicated that this would not affect the flow equalisation. This meant that the 6.1m (20ft) long pipeline segments could be nested and transported with one pipe inside the other.

Launch and retrieval shafts

The TBM launch shaft, known as the Airport Access Shaft (AAS), was 18.3m (60ft) in diameter and depth, with 900mm (3ft) thick reinforced-concrete slurry walls. Starter tunnels for the TBM were excavated through these linings, using conventional mining techniques, 12.8m (42ft) in either direction. As the tunnelling involved removing more than 85,000m^3 (3 million ft^3) of soil, a separate 55m (180ft) long, 3m (10ft) diameter tunnel was designed and installed to convey this material from the shaft base to the surface.

The retrieval shafts were smaller, as the modular TBM could be disassembled before being hoisted to the surface. At the Inner Bair Island end of the line, the rectangular steel-lined shaft was 7.2m



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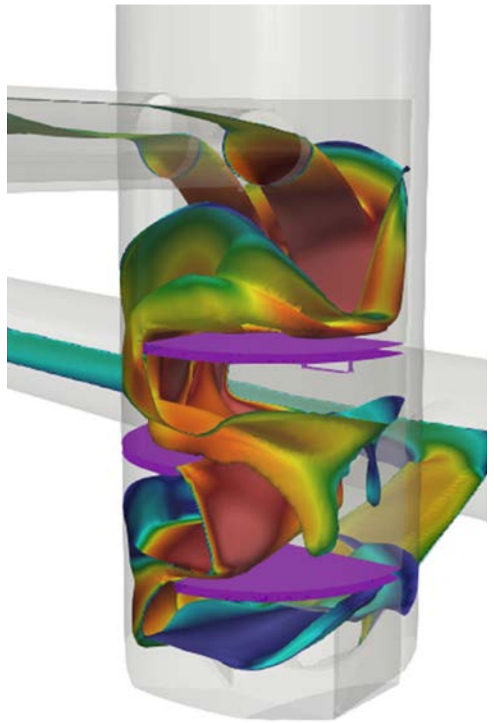
8: The FRPM liners, shown being shipped into the Bay Area, were designed with two differing diameters, so they could be transported with one pipe inside the other

9: A 7.2m by 18.3m steel-lined TBM retrieval shaft was constructed at Inner Bair Island



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by 18.3m (25ft by 60ft). At the other end, in front of the existing treatment plant, the retrieval shaft was 11m (36ft) in diameter, and also has a permanent use as a surge and flow splitter for a new headworks facility.

Drop shafts

Inflows of wastewater from the existing SVCW networks discharge into the tunnel at two locations. The flows are conveyed from the shallow inflow pipes to the deeper tunnel via two drop shafts. These structures were located at Inner Bair Island, at the eastern end of the pipeline where it connects to the Menlo Park forcemain, and at the existing San Carlos pump station, linking to the Belmont and San Carlos systems. To determine the flows, sediment travel and capacity, extensive hydraulic modelling was carried out. InfoWorks ICM was used to generate hourly and daily design flow scenarios based on average and peak rainfall derived from climate projections.

At Inner Bair Island, Arup designed a vortex drop shaft. As the influent drops from the pressurised pipe, the funnel-like shaft causes it to spiral, dissipating energy before reaching the base of the shaft and entering the gravity flow pipeline. Computational fluid dynamic (CFD) modelling was used to examine the influent and air flow, and ensure that there was no need for odour control facilities, which would have added operational and maintenance requirements to an otherwise sustainable, simple, low-energy system. The San Carlos shaft is slightly more complicated, as it connects to two separate inlets, each with different flow rates. Wastewater enters a hydraulic baffle drop structure, where it cascades down a series of ledges, before the combined flow is conveyed into the gravity pipeline via an adit, or connecting tunnel.

Arup worked closely with SVCW's and the JV's preferred suppliers to develop shop drawings for the unique drop shafts to accurately convey the design intent.

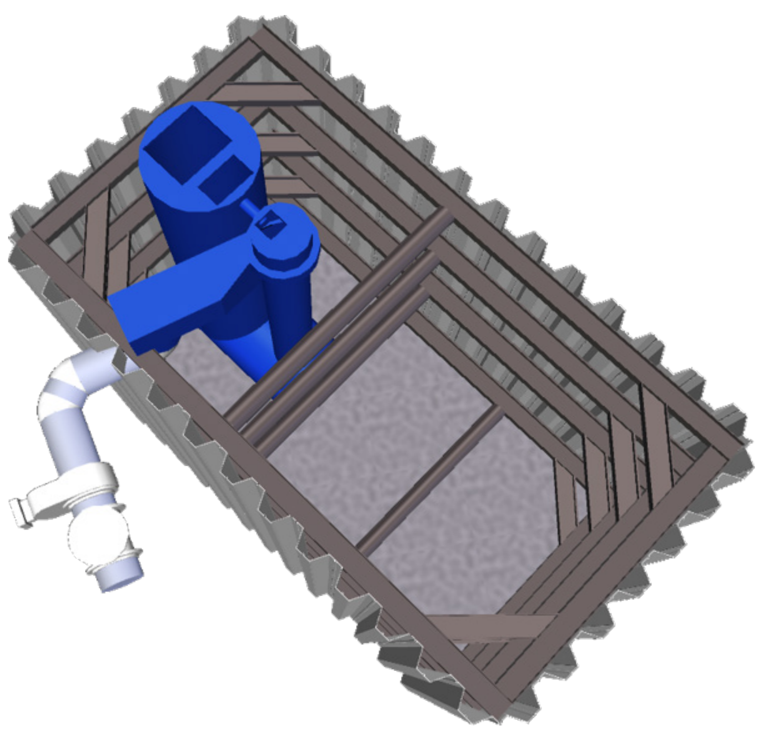
Construction

Work on the first tunnel drive began in July 2019, with the TBM (named 'Salus' for the Roman goddess of health and wellbeing) boring approximately a mile upstream from the AAS to Inner Bair Island. As much of the process as possible was automated. As the TBM progressed at the tunnel face, rails were laid behind it to deliver the precast tunnel segments and remove the excavated soil. The tunnel segments were transported on the tail section of the TBM and positioned using an erector, controlled remotely by the TBM operator. Once each ring was completed, it became the support for the TBM's thrust cylinders, pushing the cutterhead forwards into the tunnel face. The average excavation rate was approximately 30.5m (100ft) a day.

The first tunnel bore successfully reached the AAS in March 2020, at which point the main parts of the TBM were hoisted out of the shaft and transported back to the AAS to begin the second drive. Smaller components were taken back through the tunnel. The second drive, 4km (2.5 miles) to the headworks facility in Redwood Shores, began in June 2020.

As the second drive was under way, work began on installing the FRPM pipe in the first tunnel. This used a robotic pipe carrier, designed specifically for the project. The carrier could place the pipe precisely, rotating it and pushing it into the previous section, where it would be connected. The second drive reached the retrieval shaft on schedule in June 2021. The pipe carrier, which had been adapted for the larger 3.4m (11ft) diameter section, could then complete the lining of the pipeline. After the pipeline was installed into each tunnel drive, the space between the concrete tunnel and the FRPM liner pipe was filled with cellular grout to fix the pipeline in place.

SVCW and the JV partners are now working with the other RESCU project teams to coordinate the commissioning and start-up activities for the entire SVCW system. These activities are set to be complete by the end of 2023.



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10: CFD modelling was used to examine the influent and air flow of the pipeline

11: At Inner Bair Island, Arup designed a vortex drop shaft

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12: As the TBM progressed at the tunnel face, rails were laid behind it to deliver precast tunnel segments and remove excavated soil

Authors

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Project credits

Owner Silicon Valley Clean Water
Contractor Barnard-Bessac Joint Venture
Advanced technology and research, assets and operations, civil, electrical, geotechnical, mechanical, seismic and structural engineering, hydrogeology, infrastructure and tunnel design
Arup: Brian Albin, Eden Almog-Goldreich, Bernard Bodin, Jodi Borghesi, Stephen Burges, Kevin Clinch, Michan Condra, Tom Doyle, Steven Downie, John Eddy, Kirk Ellison, Chihurumanya Felly-Njoku, Nuno Ferreira, Audrey Fremier, Abraham Gebrezgiabhier, Mark Gilman, Alexej Goehring, Sheba Hafiz, Yuli Huang, Jon Hurt, David Knight, Guneet Kohli, Christopher Krechowiecki-Shaw, Pawan Kumar, Christopher Lim, Qiyu Liu, Dee Dee Maggi, James McCay, Mark Milkis, Angeliki Mitsika, Guillermo Munoz-Cobo Cique, Ryan Nordvik, Andrew Page, Luis Piek, Rubina Ramponi, Gayla Reeves, Sarah Sausville, Eric Sekulski, Keith Seymour, Surur Sheikh, Nik Sokol, Darren Sri-Tharan, Kevin Stanton, Emily Steinkamp, Eron Sudhausen, Anusan Sugumaar, Aihua Tang, Laura Thring, Alessandra Vecchiarelli, Julia Villanueva, Frederik Vind Jensen, Martin Walker, Pete Wilkie, Lazarus Zambezi.

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1, 4, 5, 9-12: Arup
2, 3, 6, 7: Barnard Construction
8: Infrastructure Solutions Australia