Tunnelling into a Sustainable Future – Methods and Technologies

Edited by
Fredrik Johansson, Anders Ansell, Daniel Johansson, Johan Funehag and Jenny Norrman

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TUNNELLING INTO A SUSTAINABLE FUTURE – METHODS AND TECHNOLOGIES

Tunnelling into a Sustainable Future – Methods and Technologies contains the contributions presented at the ITA-AITES World Tunnel Congress 2025 (Stockholm, Sweden, 9-15 May 2025). The contributions cover a wide range of topics in the fields of tunnelling and underground engineering, including:

1. Innovating tunneling
2. Safety Underground
3. Use of underground space
4. Investigations and ground characterisation
5. Planning and design of underground space
6. Conventional tunnelling
7. Mechanised tunnelling
8. Complex geometries including shafts and ramps
9. Grouting and groundwater control
10. Instrumentation and monitoring
11. Operation, inspection and maintenance
12. Contractual aspects, financing and risk management
13. Impact from climate change

Tunnelling into a Sustainable Future – Methods and Technologies will serve as a valuable reference to all concerned with tunnelling and underground engineering, including students, researchers and engineers.

PROCEEDINGS OF THE ITA-AITES WORLD TUNNEL CONGRESS 2025 (WTC 2025), 9–15 MAY 2025, STOCKHOLM, SWEDEN

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Preface

Stockholm, May 2025

The World Tunnel Congress (WTC) 2025 and the 51st General Assembly of the International Tunnelling and Underground Spece Association (ITA), are held from the 9th to the 15th of May 2025 in Stockholm, Sweden.

The Swedish Rock Engineering Association is honoured and proud to host this outstanding event of the international tunnelling community. Thousands of experts, researchers, and industry leaders are gathering from around the world to discuss and advance the field of tunnelling and underground construction.

Stockholm, renowned for its engineering excellence and extensive underground infrastructure, provides an inspiring backdrop for WTC 2025. The city's rich history of underground development, from infrastructures such as metro systems, road tunnels, railway tunnels, and utility tunnels to rock caverns for everything from energy storage to our national library and urban tunnels, offers valuable insights into the future of tunnelling and underground space utilisation.

Under the theme "Tunnelling into a sustainable future – methods and technologies", this year's congress focuses on the critical role of underground infrastructure in addressing global challenges such as technological development, climate change, and resource efficiency. The event showcases cutting-edge research, state-of-the-art technologies, and best practices in tunnel and underground space design, construction, and maintenance, emphasising sustainability, safety, and resilience.

The proceedings encompass a diverse range of 13 different topics such as innovative tunnelling, utilisation of underground space, operation and maintenance, contractual aspects and risk management, impact from climate change, and case studies from around the world. Special attention is given to sustainable solutions that optimise the use of underground space while minimising environmental impact.

We are grateful for the impressive number of the almost 1000 abstracts we received and extend our gratitude to all authors and reviewers who have contributed to the congress. In these proceedings, we publish more than 600 papers from all over the world. We hope that the proceedings will serve as a valuable resource for researchers, engineers, and policymakers, inspiring continued advancements in tunnelling and underground construction. May the discussions and insights shared at WTC 2025 drive innovation and sustainability in our field for years to come.

Johan Brantmark
Chair of the WTC 2025 Organising Committee

Per Vedin
President of the Swedish Rock Engineering Association

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Innovative tunnelling

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Tunnelling in a landslide – technical challenges and monitoring

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ABSTRACT: The Riedberg tunnel, part of the A9 highway in Switzerland, traverses an active landslide slope with movement rates of several centimeters to decimeters per year. This paper discusses the investigations and construction measures implemented to manage the slope's behavior. Long-term monitoring revealed that movement rates vary along the tunnel, heavily influenced by water inflow, especially heavy rainfall. Based on these findings the tunnel's inner lining and design were optimized for flexibility and durability. Continuous monitoring of the slope and the tunnel during construction and the future operation tracks slope movements and tunnel stresses, guiding further measures to dewater the slope and enhance stability. Given the correlation between slope movements and water infiltration, further measures are also planned to dewater the slope, aiming to reduce movement rates and enhance the stability of the slope and tunnel.

1 OVERVIEW OF THE PROJECT

The Riedberg Tunnel is part of the new A9 highway in the canton of Wallis, Switzerland which runs between Brig and Martigny. The tunnel on the southern side of the valley close to the Rhone River connects the open stretches between Visp and Turtmann through the slope of the Riedberg. The clients are the canton of Wallis and the Swiss federal road department (ASTRA).

The Riedberg tunnel is a twin-tube road tunnel, with an average length around 550 m (Figure 1). The tunnel alignment consists of a circular arc with a radius of approximately 1000 meters and is constructed using the conventional method. The tubes are connected through a cross passage for pedestrians. At both portals, there are short cut-and-cover sections as well as technical rooms for the storage of electromechanical equipment. The tunnel has an outer and inner lining with a waterproofing sealing between them. Water from the surrounding soil is drained and led to the two portals.

Figure 1. Overview of the tunnel with the cross-passage (in red) and the portal areas with the technical rooms (in black).

Already in the early stages of the highway project the slopes of the Riedberg were investigated because of possible landslide activity. In 1989 an exploratory tunnel was excavated, and several monitoring targets were installed. Based on the results of this investigation the

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alignment through the landslide was confirmed as there were only minor movements in the range of 1 cm/year expected.

During the initial construction phase (2004-2005) significant movements could be measured (6 – 16 cm in the tunnel; average slope movement of ca. 20 cm/year), leading to the interruption of construction activities. A task force was established to investigate the causes of the slope movements and recommend appropriate measures. The task force's investigations concluded that the slope movements were primarily due to the geological conditions and the presence of groundwater. The task force recommended several measures, including the implementation of a stiff and stronger excavation support system, drainage systems, and reinforcement of the ground around the tunnel with radial jetting columns. These measures were aimed at stabilizing the slope and allowing construction to resume with an acceptable level of risk (H.M. & S.P. 2016).

The excavation of the tunnel was restarted in summer 2017. The excavation was done in short stages and with a subdivision of the tunnel face under the protection of a pipe umbrella. The excavation support included a layer of steel fiber reinforced shotcrete and a reinforced cast in place concrete lining with steel arches. Together with the inner lining, it represents the permanent support of the tunnel.

In parallel to the excavation of the tunnel, the design of the reinforced inner lining and interior design of the tunnel was adapted based on the new findings regarding the slope's behavior. The tunnel Riedberg is still under construction. The opening is scheduled for the end of 2026.

1.1 *Characteristics of the landslide*

The tunnel is located at the base of a sagging and sliding mass with a complex structural composition due to its multi-phase post-glacial formation history.

The area is characterized by postglacial rockslide material and debris with a lot of blocks. The slope above the tunnel has been destabilized and loosened due to glacial retreat, resulting in significant deep-seated sagging and landslide tendencies. The blocky material is primarily a densely packed, moderately to well-cemented silty gravel with occasional large blocks and stones. The lithological composition and grain size distribution within the slope are highly variable, with layers and lenses of finer-grained material also present. The analysis of geological investigations in earlier phases of the project and linking them to the monitoring data collected over the duration of the project as well as findings in the excavation of the tunnel led to a complex landslide model (Figure 2).

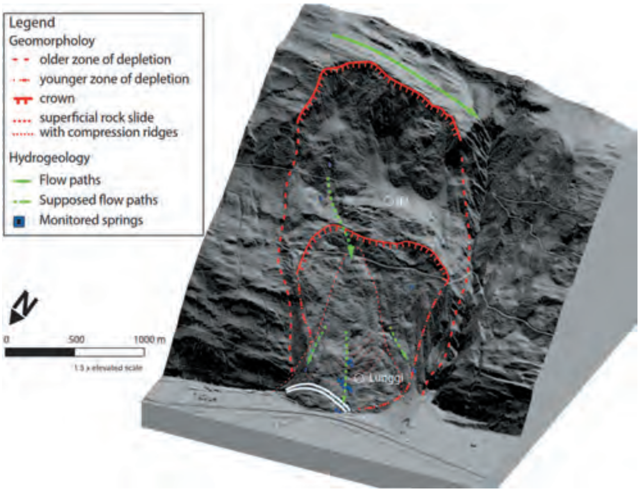

Figure 2. Geomorphological model of the slope.

The landslide consists of various mass movements of different ages and movement rates. In the area of the tunnel, in the middle of the slope, an active sliding mass was identified

(Figure 3). This active mass has higher movement rates and moves on a sliding surface that crosses the tunnel. This leads to three different sections of the tunnel: below, crossing and above the sliding surface. The result is that the movement rates of the slope vary along the tunnel, leading to differential deformation and translation of the tunnel.

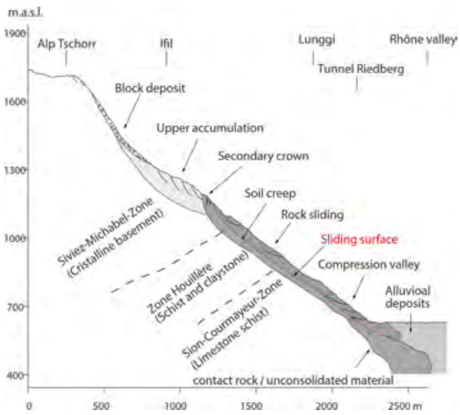

Figure 3. Geological profile of the slope.

A lot of investigation, instrumentation and drillings were carried out to examine the influence of water on the movement rates of the landslide. The hydrogeological conditions are complex with several small springs above the tunnel Riedberg and a very heterogeneous permeability of the slope from very low to medium. The infiltration of surface water into the slope, particularly during heavy or prolonged rainfall events, has been found to temporarily increase movement rates significantly. This water inflow can lead to increased pore water pressure, reducing the shear strength of the slope materials and triggering movements.

Heavy rainfall events, particularly in January and October 2018, led to significant increases in slope movement rates. The analysis of the various monitoring points on the slope has shown that the slope does not accelerate uniformly after a heavy rainfall, instead the time of the maximum displacement rate was earlier at the top of the slope than at the lower end.

2 MONITORING

The construction and subsequent operation of the Riedberg tunnel have required comprehensive investigations and monitoring to understand the behavior of the active landslide slope and to assess its impact on the tunnel.

2.1 *Monitoring during construction phase*

The first instrumentation of the slope and the surrounding infrastructure was related to the initial construction phase starting in 2004. The slope and the surrounding infrastructure were instrumented with geodetic monitoring points, inclinometers and pore water pressure monitoring. In addition, visual inspections were conducted.

Following heavy rainfall events in January and October 2018, the slope movements accelerated significantly. In response, the monitoring measures of the slope were intensified. This included the installation of new inclinometers, the increase in the frequency of measurements, and the addition of new geodetic monitoring points. In addition, a meteorological monitoring station was installed directly in the project area to record precipitation. It could be clearly shown that heavy rainfall has a significant impact on the movement rates of the slope. The rates can be well correlated to the cumulated rainfall over 28 days, showing that the movement rates increase with a certain time delay to the rainfall (Figure 4).

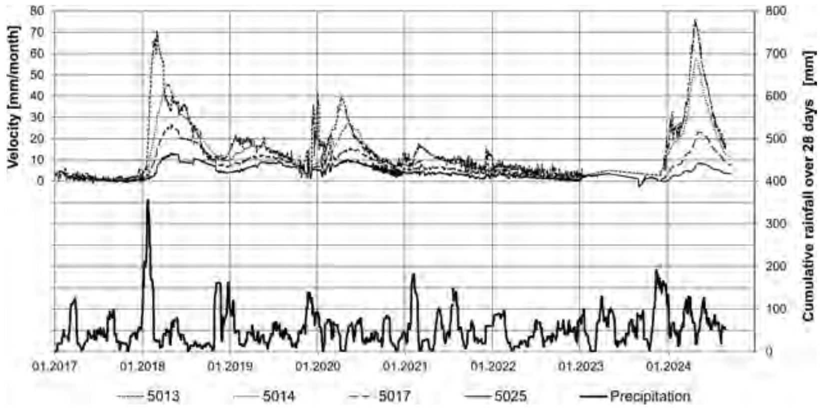

Figure 4. Correlation between precipitation and movement rates at different locations in the slope, where point 5013 is the highest and 5025 the lowest point in the slope.

Based on this monitoring the following conclusions could be made:

- Tunnel construction caused very small displacements of a few millimeters to centimeters in close vicinity of the tunnel only. However, it neither initiated slope activation nor caused harm to nearby infrastructure.
- The influence of rainfall on the slope's movements is by far greater than the influence of tunnelling on slope movements.
- High cumulative rainfall leads to a significant increase of the slope movement rates. They occur with a delay to the rainfall event, reaching the maximum velocity in the upper area of the slope first.
- After the heavy rainfall in January 2018 the slope got activated, leading to higher permanent movement rates. Presumably due to the higher saturation of the slope, less cumulated precipitation is subsequently needed to cause an increase in movement rates of the slope.

During the construction phase, the tunnel was geodetically monitored. The measurements showed that the tunnel was ovalized and shifted towards the valley due to the movement of the slope. The movement rates and observed phenomena varied considerably along the tunnel.

2.2 *Long-term monitoring concept*

Given the fact that the slope will continue to move and pose a risk to the tunnel it was decided to install a long-term monitoring system to monitor the slope and the tunnel in operation.

The monitoring measures of the slope are a continuation of the already installed instrumentation. The grids of the geodetic monitoring points, inclinometers and piezometers were tightened around the tunnel without neglecting the upper part of the slope. The geodetic surveys involve the installation of fixed points, measured either manually or automatically with tachymeters, and the use of GPS sensors. In addition, the slope is scanned with LiDar (Light Detection and Ranging) to get a comprehensive picture of the movements of the slope. The inclinometers are used to measure the displacement rates within the slope and to monitor existing slip surfaces. Porewater pressure monitoring is conducted using piezometers installed in boreholes to assess the hydrogeological conditions and the variation of porewater pressure due to precipitation or drainage of the slope.

In addition to extensive monitoring of the slope, the completed tunnel structure is also continuously and intensively measured during operation. In every block of the inner lining cross sections with 5 geodetic monitoring points will continuously and automatically measure the deformation and displacement of the tunnel. They allow also to calculate the differential movements between the blocks and enable to analyze the behavior along the tunnel. Strain gauges will be installed in different blocks along the two tubes. They are installed at four points around each block's circumference to monitor changes in strain and loading of the inner lining respectively. Additionally, annual laser scans of both tunnel tubes will be conducted.

Monitoring data is managed and presented in a GIS-compatible format, allowing for easy and automatic processing and including data in a BIM-model of the as-built tunnel.

3 CONSTRUCTION MEASURES

The tunnel is exposed to varying displacements rates in both the longitudinal and transverse directions, which leads to constraint-induced stress of the tunnel. Due to the size of the landslide slope, the slope displacements cannot be prevented with technically and economically feasible structural measures within the tunnel. Thus, the inner lining and interior design had to be designed flexible to handle these displacements, preferably without damage. The aim is to maintain the tunnel's load-bearing capacity and functionality for as long as possible, minimizing damage while considering practical and cost-effective maintenance, repair, and renovation strategies.

3.1 *Model conception*

The longitudinal behavior of the tunnel assumes that the slope acts like a continuous medium due to its geological structure, leading to mainly continuous (Figure 5 b) and subordinately discontinuous displacement (Figure 5 a) of the tunnel. Based on this assumption the expected differential deformation along the tunnel lead particularly to openings and closings of the joints between the blocks of the inner lining instead of offsets. This leads to a model of the tunnel that behaves like a linked chain with rigid chain elements.

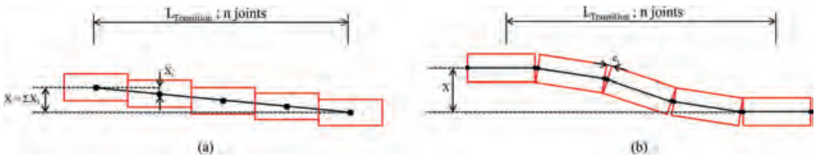

Figure 5. Models of behavior of the inner lining due to differential deformation along the tunnel. (a) Shifting of the blocks leading to offsets in the joints. (b) Bending of the blocks leading to opening and closing of the joints.

Depending on the design of the joints, joint openings/closures and offsets can lead to cracks and spalling, which can endanger road users. Various joint designs and arrangements of the joints in the longitudinal direction were examined and assessed in view of this hazard (Figure 6).

Since the slope movements lead to constrained displacements in the tunnel structure, it is not advisable to design stiff joints. Unlike compression joints (reinforced or unreinforced contact joints) dilatation joints allow for some movement before the inner lining in the joint area becomes excessively stressed and damage occurs. Therefore, the joints between concrete blocks of the inner lining are designed as deformable joints. Material is placed between the concrete blocks that allows the joint to close and open without damaging the concrete structure. The dilatation joints are designed with a width of 10 cm. The spacing of the dilatation joints is 6 meters, which corresponds to halving the originally planned block length. By shortening the block length, the differential constrained displacement is better distributed, the stress on the joints and blocks is reduced and this leads to a later occurring of damages.

This concept with the dilatation joints differs from the normal design for an inner lining and represents a novel and innovative solution to deal with constrained, differential displacements along a tunnel.

The transversal differential deformation of the cross-section is addressed with a highly reinforced block design that allows a ductile behavior of the concrete lining combined with a high load-bearing capacity.

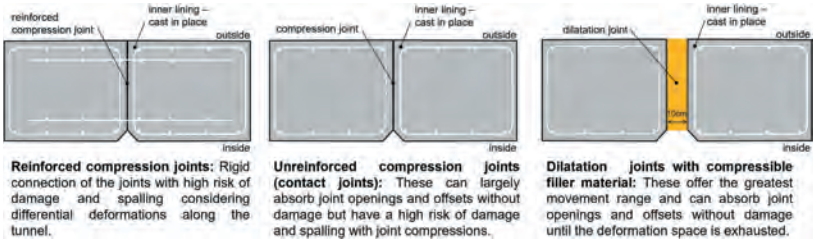

Figure 6. Comparison of different joint designs.

It is assumed that the deformation/ovalization of the tunnel cross-section is the result of a linearly increasing displacement distribution within the sliding slope, which leads to constraint-induced stress in the lining. The timing of when damage occurs, or failure happens depends on the movement of the slope.

Numerical calculations were carried out in which the tunnel (non-linear material behavior of the lining) was embedded in an elastic continuum (2D FEM). The slope displacements were simulated by continuously distorting the upper free edge of the FE model, which results in deformation and loading of the tunnel (Figure 7, left). This made it possible to estimate the states of the structure, ranging from initial damage to complete collapse of the tunnel (Figure 7, right). Subsequently, in combination with the predicted displacement rates, corresponding times could be estimated.

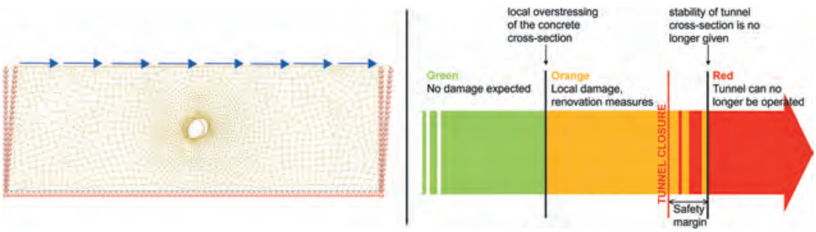

Figure 7. Left: 2D FE-model; Right: States of the structure.

3.2 *Resulting technical solutions*

3.2.1 *Inner lining*

The inner lining is divided into blocks of 5.9 m along the axis of the tunnel and divided by a dilatation joint of 10 cm leading to a division in 6 m instead of 12 m as originally planned. The requirements for the material in the dilatation joint are:

– Low compression during the concreting of the blocks (concreting pressure)
– As high compression capacity as possible before reaching the concrete compressive strength
– Fire behavior: non-flammable, no smoke and toxic gas development
– Durability (> 100 years)
– Flexibility for installation/workability

The evaluation of different materials led also under consideration of the costs to the choice of Foamglas®T3+, an insulation material made of very small, completely sealed glass cells (Pittsburgh Corning 2024). The production is in the form of plates and the material can also be easily cut to size on site. Below the driving space extruded rigid polystyrene foam is used because there is no risk of fire. The dilatation joints were created together with the concrete of the inner lining.

The reinforcement concept was revised to increase the load-bearing capacity and ductility of the inner lining. The transverse reinforcement was increased to Ø 26 every 15 cm, with stirrups Ø 16 every 17 cm.

3.2.2 *Waterproofing*

The risk of damages of the sealing is increased because of the constrained deformation and movement of the blocks. The PVC-P waterproofing membrane specified in the original design was therefore replaced with the FPO membrane SikaProof®-200 with greater elongation capacity (PVC: ca. 300%, FPO: ca. 700%). Another great benefit of this new membrane is a special hybrid bonding layer that forms a permanent bond with the fresh concrete, preventing water from flowing freely between the lining the membrane in case of damage to the membrane (Sika 2024). Water ingress into the tunnel is only possible if there is a crack in the concrete at the same location as the damage in the membrane. In such cases, the leak can be sealed by injecting the crack. In the joints between the blocks a protective film is installed to avoid damage on the waterproofing membrane due to the formwork for the inner lining (Figure 8).

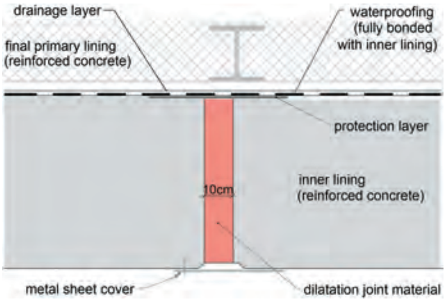

Figure 8. Detail of joint between blocks with concept of waterproofing.

3.2.3 *Interior design*

The interior design of the Riedberg tunnel includes the roadway and the side benches with slot drains or curbs. All utility protection pipes for the operational and safety equipment were originally routed in the benches. The wastewater is to be collected in the slot drain and is discharged into the underlying concrete-encased collection pipe through siphon shafts. Any seepage water was planned to be collected in a base drainage pipe.

The movements with opening/closing of the joints also affect the benches and the utilities. Therefore, the interior design was adapted, and a utility conduit was provided under the roadway to accommodate all pipes and cables (Figure 9). The cables are laid on cable trays with movement space, and the fire water and wastewater collection pipes are fixed in the conduit. Flexible couplings can be used in areas with significant slope movements to increase deformation capacity. The utility conduit simplifies maintenance and repairs in case of damage.

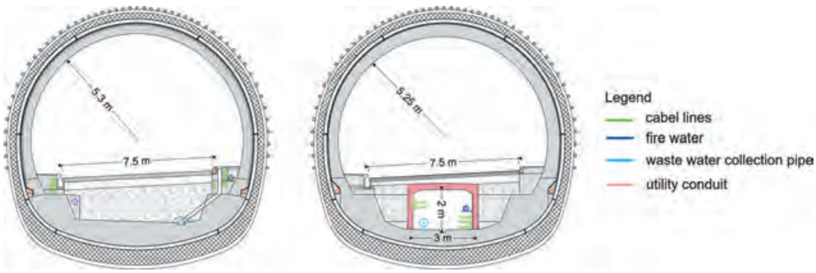

Figure 9. Interior design before (left) and after (right) adaption.

4 FUTURE MEASURES

To ensure the long-term stability of the Riedberg tunnel and the surrounding slope, future measures have been planned. These measures focus on enhancing the drainage and reducing the movement rates of the slope. Different options to drain the slope were investigated and compared like drilling campaigns from the surface or shafts from which the drilling could be carried out. As best solution a drainage tunnel was identified. The tunnel will be aligned in the rock mass below but close to the sliding slope allowing to drill into the sliding mass and drain the slope. Beside the drainage of the slope the boreholes provide additional information about the structure of the slope and help to understand its behavior more deeply.

Already in the first phase - the excavation of the tunnel exploratory and drainage boreholes are planned in a regularly spacing to gain information about the drainage capabilities as a basis for the decision of future drainage drilling. The second phase involves expanding the tunnel into a full drainage tunnel with deep drainage capabilities. This phase aims to create long and precise drainage boreholes into the hydrogeologically relevant layers to dewater them effectively. It is also possible to extend the tunnel further to expand the drainage measures into the upper slope area.

Continuous and intensive monitoring of the slope will be carried out during the construction of the drainage tunnel and the boreholes to track the effects of the drainage on the slopes movement rates. Any necessary adjustments to the drainage system will be made based on the monitoring results.

5 CONCLUSION

The comprehensive measures undertaken for the Riedberg tunnel project underscore a meticulous approach to ensuring long-term stability and safety in the face of an active landslide slope.

The project addresses the fundamental challenge of slope movement, employing innovative solutions such as deformable joints between the blocks of the inner lining and a new waterproofing sealing membrane to maximize the flexibility of the tunnel Riedberg. The design of the inner lining and the interior ensures both durability and ease of maintenance.

The planned drainage tunnel along with the strategic placement of exploration and drainage boreholes, provides additional insights into the hydrogeological landscape and allows for precise and effective dewatering of relevant layers to reduce the movement rates of the slope.

The monitoring throughout the construction phase of the tunnel provided valuable information about the slope and allowed to optimize the design of the tunnel. The long-term monitoring of the slope and the tunnel is crucial for the assessment of the condition of the tunnel and this data-driven approach also enables informed decisions on further drainage drilling and other stabilization measures.

Ultimately, the Riedberg tunnel project exemplifies a robust response to the complex demands posed by landslide-prone environments. The concerted efforts in monitoring, designing, and implementing the drainage tunnel as mitigating measure provide a resilient framework that enhances the tunnel Riedberg's operational lifespan and guarantees the safety of both the structure and its surroundings.

This project was successful due to teamwork and dedication from everyone involved. We sincerely thank the client for their vision and trust, the suppliers for their instrumental role in finding the perfect solution with their high-quality materials, the contractors for their expertise and commitment in tackling the Riedberg slope's challenges, and lastly, all stakeholders whose support and involvement was crucial to the project's success.

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Tunnelling into a Sustainable Future – Methods and Technologies – Johansson et al (Eds)

A special 11 m diameter SS TBM will bore at 47% slope the 1,6 km long inclined pressure shaft of the snowy 2.0 hydropower project in New South Wales (Australia)

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ABSTRACT: The Snowy 2.0 Hydropower Projects includes 29 km of tunnels to be excavated by three 11 m diameter TBMs.

One of these TBMs, TBM1 has started to excavate a 1,6 km long Inclined Pressure Tunnel (IPS) having a vertical alignment variable with continuity from zero to 47%.

To excavate at variable slope the TBM required a specific design so as to be able to progressively adapt to the increase in slope and finally be able to work at the maximum gradient of 47%.

The special design concerned both the TBM and the back-up system, with specific regard to muck transport, segment handling and installation, transport of materials, transit of personnel, workstations and some of the components. At the same time, innovative systems have been designed for the transports along the inclined shaft to serve the TBM, such as: MSV with rack & pinion traction for the transport of segments, a cascade sandwich belt system for the excavated material, a monorail hanging to the crown of the tunnel for transporting the personnel. The supply to the TBM of water, power and grout mix, required specific implementations. The large Single Shield installs a newly designed one pass precast lining system developed for this application and able to resist the internal pressures expected during the operation of the work. The article describes the design process that led to the innovations, the encountered difficulties, the tests carried out and the achieved results in the first period of excavation. The aspects linked to the design development and implementation of the one pass lining system will instead be the subject of separate presentations.

1 DESCRIPTION OF THE SNOWY 2.0 PROJECT

The construction of the Snowy Mountains Hydro-electric Scheme is part of Australian history and is widely regarded as one of the engineering wonders of the world. Construction did not start today, it has its roots in 1949 and the completion dates back to 1974, with the construction of 7 power plants, 16 dams, 80 km of aqueducts and 145 km of tunnels, which today can produce over 3.500 MW of renewable energy.

Snowy 2.0 is a pumped hydro-electric project, a major expansion of the existing Snowy Scheme and the largest committed renewable energy project in Australia. It is being built in the Australian Alps in southern New South Wales, within the Kosciuszko National Park. The project would provide 350.000 MWh of large-scale energy storage and additional 2.200 MW of quick-start electricity generation capacity to the grid at critical times of peak demand when energy supply is constrained. A series of new underground tunnels, including the largest high pressure hydraulic inclined shaft ever built with a TBM, will link the existing Tantangara and Talbingo reservoirs. A hydro-electric power station will be constructed within an underground cavern at 800 m depth.

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Future Generation Joint Venture (FGJV), constituted by Webuild, Clough and Lane Construction, is the main Contractor to build Snowy 2.0 on behalf of Snowy Hydro Limited (SHL).

1.1 *Description of the Inclined Pressure Shaft (IPS)*

One of the main works to be executed in the Snowy 2.0 Project is the construction of the Inclined Pressure Shaft (IPS) having a length of 1,6 km long and an internal final diameter of 9.9 m. The IPS will be excavated by a Herrenknecht Single Shield TBM at a progressively variable slope from declining at -9% to rising at +47% and with a maximum overburden of about 800 m. (Figure 1). The 11,07 m diameter SS TBM installs a special 420 mm thick precast segmental lining in a 9+0 configuration.

Once built this IPS will be the largest inclined pressure shaft ever built and one of the longest but, more importantly, this IPS will be the first one excavated by TBM along such a strongly variable vertical alignment. (Valiante et al 2022).

This solution was selected as an alternative to the vertical shaft option, with significant saving of cost and time for the project, with the additional benefits:

- Better hydraulic behavior of the hydropower plant
- Improved safety and working environment granted by the TBM excavation method.
- Capability of the TBM system to excavate long shafts with better productivity and overcome adverse geological conditions.

The concept design of TBM1 and of the transport systems along the Inclined Pressure Shaft was carried out by Webuild, which then followed the coordination of the TBM design with that of the other equipment (monorail, rack and pinions, MSV, conveyor belt, etc.). Webuild then actively cooperated with Herrenknecht during the TBM final design and its set up on site including the following aspects:

- Choice of the muck collection and extraction system from the excavation chamber has been designed to be the most suitable for the different slopes.
- The TBM conveyor belt to be replaced by a screw conveyor before tunnelling the inclined section to ensure safe transport of the material.
- The working platforms and containers are adjustable according to the inclination in a predefined pattern to enable safe working on the TBM.

In terms of hydraulic loads, the IPS of Snowy 2.0 is subject to maximum internal steady state pressure of 780 m and transient internal loads due to water hammer in the order of +29 and -27 bar. Thus, the tunnel lining must be designed considering both the hydraulic loads as well as the geomechanical loads.

In case the external pressure is higher than the internal one, the lining is subject to compressive stress while in the opposite case tensile stress would arise in the lining and a structural continuous ring capable to resist tensional forces is required.

To address the above challenging conditions, an innovative segmental lining system, referred to as Force-Activated Coupling System (FACS), was developed specifically for the IPS of Snowy 2.0 project.

2 GEOLOGY ALONG THE IPS

Geologically the IPS starts after the Long Plain Fault Zone (LPFZ) in the final part of the Ravine Bed East Fm. (RBE), After the change in slope it passes into the Boraig Fm., in which it remains nearly for its complete length, to change in its final part into the Ravine Bed West Fm. (RBW).

The IPS can be roughly subdivided into three Geomechanical sections comprising four stretches. From top towards the bottom of the IPS the Geomechanical properties are increasing as the distance to the LPFZ-System increases (Figure 1.).

- Upper part, Disturbed, bad to fair rock (RBE - siltstone, vulcanite)
- Middle part, Transition, fair rock (BRG - conglomerate, sandstone)
- Lower part, Undisturbed, good rock (RBW - siltstone, sandstone)

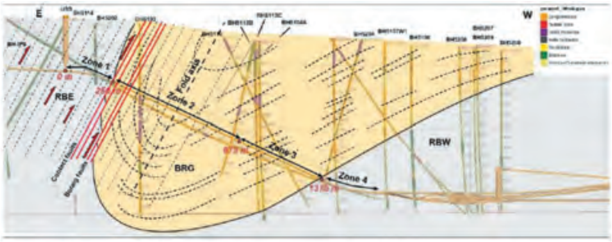

Figure 1. Geology of the Inclined Pressure Shaft (IPS).

3 TBM EXCAVATION OF THE IPS

3.1 *Single Shield TBM HK S-1220*

The SS TBM HK S-1220 - TBM#1 (Figure 2) utilized to excavate the IPS started boring excavating a sub-horizontal emergency tunnel (named as ECVT) for about 3.0 km with a descending gradient of -9%. At the end of the ECVT, the TBM was modified inside the tunnel and adapted for the uphill excavation of the inclined IPS.

Figure 2. Single Shield TBM HK S-1220 - TBM#1.

The muck collection and extraction system from the TBM excavation chamber has been designed to be adapted to the different slopes. The choice made was to use a standard tunnel conveyor belt for the -9% downhill section and substitute the belt with a screw conveyor for the variable slope uphill section to ensure safe transport of the muck also at the maximum slope. The design and procedures to substitute the belt conveyor with the screw conveyor at the bottom of the ECVT tunnel, before starting the IPS, was one of the critical challenges in the development of the TBM.

Also, the backup system and its utilities had to be designed to adjust in steps to the progressively increasing slope. The conveyor belt, the precast segments handling systems (quick unloaders, segment crane and segment feeder), the lifting equipment, the walkways and work platforms, the operator cabin and other utilities were therefore designed and built to adapt in successive steps to the variable slope and to be able to work at the maximum slope. The backup structures and the connections between the carriages were sized to resist the greater gravitational forces on the maximum slope. (Figure 3).

All operational and maintenance procedures and functions were verified in compliance with European and Australian regulations, safety and environmental norms.

In the concept and detail design were also considered the challenging interfaces with the transit of the Multifunction Service Vehicles (MSV) transporting the segments and of the suspended monorail vehicles transporting the personnel.

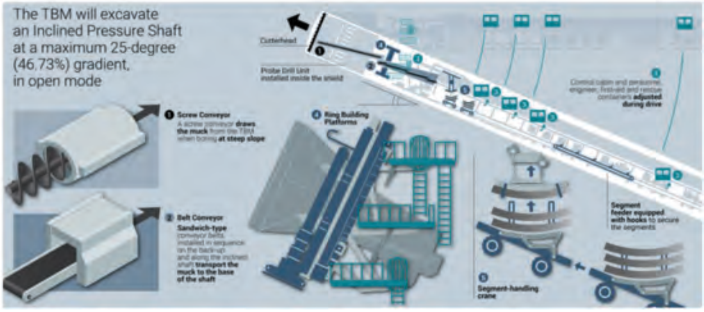

Figure 3. TBM Configuration for the Inclined Pressure Shaft (IPS).

Been 47% an excessive steep slope to rely only on traction capacity of the rubber wheels, the MSVs have been equipped with a special rack and pinion system ensuring about 50% of the necessary total traction force.

3.2 *TBM Reconfiguration before starting the IPS*

The TBM was modified inside the tunnel once it reached the bottom of the ECVT before starting the excavation of the IPS. The modification included the following main operations:

3.2.1 *Removal of the belt conveyor*

The first back-up conveyor and a number of components from back-up gantries 1 & 2 were removed to facilitate the transport and installation of the screw conveyor.

3.2.2 *Installation of the screw conveyor*

The installation of the screw conveyor required a complex lifting and transport crane system anchored to the segments.

The Screw conveyor was transported in 4 sections; the auger sections were welded in place while the outer case elements were bolted one to the other. The entire screw is over 25 m long and has a weight of about 56 tons. Hydraulic and electrical connections were completed prior to commissioning (Figure 4).

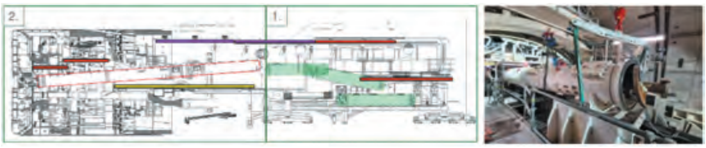

Figure 4. Screw conveyor and lifting system.

3.2.3 *Cutterhead modification*

New bucket tools contained additional grill bars were installed to reduce the maximum size of rock blocks entering the excavation chamber; by this modification the maximum size of block allowed to enter the cutterhead was reduced down to 270 mm in diameter (Figure 5).

3.2.4 *Tail Shield brushes modification*

New brushes were installed on the tail shield to suit the new thicker segment ring (420 mm) installed along the inclined section of the IPS.

3.2.5 *Segment feeder modification and quick unloading*

To accommodate the new segments, the feeder and the quick unloading were modified (Figure 6).

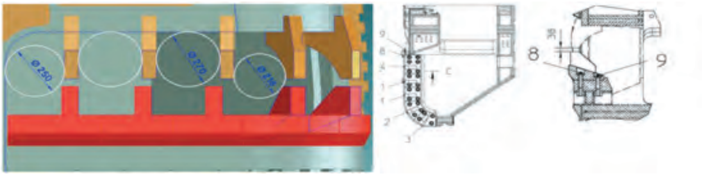

Figure 5. Cutterhead modification.

3.2.6 *Segment crane and erector plate modification*

New vacuum plates were installed on the segment crane and erector due to the increased weight of the segments and the decrease of the internal radius. (Figure 7).

3.2.7 *Ric BU installation*

The back-up belt conveyor was removed and substituted by a new sandwich type conveyor.

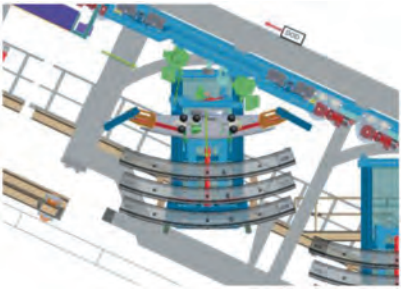

Figure 6. Quick unloading.

Figure 7. New segment crane pad and erector vacuum plate.

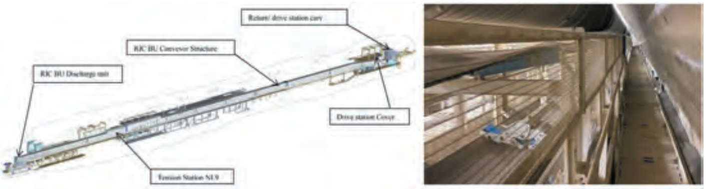

Figure 8. Ric BU installation.

3.3 *Modifications along the tunnel*

In addition to the modifications to the TBM configuration, for the excavation of the IPS it was necessary to develop new and innovative transport systems for the muck, the precast segments and the personnel that were compatible with the variable slopes of the shaft.

3.3.1 *IPS RIC tunnel conveyor system*

To transport the excavated muck along the IPS in a controlled manner, avoiding slippages and overflows, it was chosen a special sandwich belt conveyor system made of 480 m long sections connected in cascade one to the other and pulled by the back-up of the TBM. (Figure 9).

This special sandwich conveyor system, named RIC, designed and manufactured by the Swiss company Rowa, is connected at the base of the IPS to a standard tunnel conveyor system that receive the muck and transport it along the ECVT up to the tunnel portal. A Hi-ab crane and two installation platforms were added to the last gantry of the back to assist the installation of the support structures that support the RIC conveyors system.

Figure 9. Tunnel conveyor structure.

3.3.2 *Monorail system*

For the transportation of personnel along the IPS up to the TBM back-up special monorail transport system has been developed, suspended on chains anchored through brackets to the prefabricated segments. These brackets are bolted to the segments using steel inserts which cast into the segments (Figure 10 and 11).

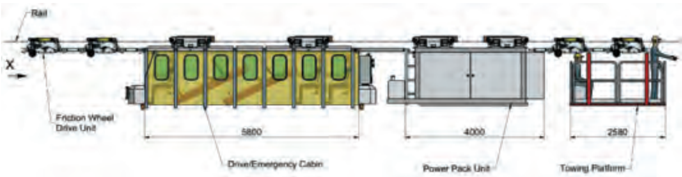

Figure 10. Monorail.

The monorail system, designed and built by the company Scharf, includes two stations, one located at the base of the ECVT and one arranged on the TBM back-up. Two vehicles run suspended to the monorail; one for the transport of the TBM crews having capacity for 20 persons and a smaller one for emergency evacuations which is normally stationed on the back-up. The design of the station on the back up of the TBM and the interface between the monorail vehicles and the back-up required deep studies specially to ensure the safety of the workers when entering and exiting the vehicles as well when they are waiting for the vehicle arrival.

3.3.3 *MSVs MultiTaction – Rack and pinion*

The transport of the precast segments along the IPS is entrusted to the same MSVs used for the transport along the ECVT, so that the same vehicle transports the segments from the tunnel portal to the TBM back-up without the need for transshipments. The MSVs were designed and manufactured by Metalliances and were tested at the factory in France on a inclined path simulating the slopes and working conditions along the IPS:

Their transport capacity on the maximum slope is 70 tons, sufficient for a full ring, 9 segments.

To allow this, the MSV has been equipped with a special additional system of the rack & pinion type TBM (Figure 12).

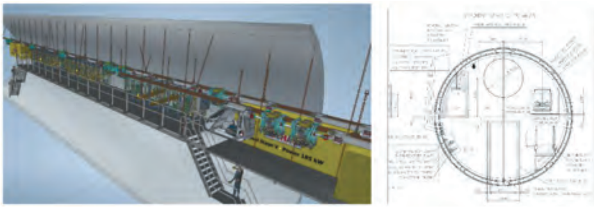

Figure 11. Monorail station at the base of the ECVT and at the backup.

The rack is fixed by special bolts directly in the middle of the invert segment. A system consisting of 4 pinions hydraulically driven are fixed under the MSV and engage directly on the rack. The combination of the rubber wheels and rack and pinions ensure the vehicle has the capacity to climb the maximum slope. The rack and pinion system is engaged when the MSV approaches the IPS while along the ECVT the traction is provided only by the rubber wheels.

A special rack and pinion system engagement station is located at the base of the IPS.

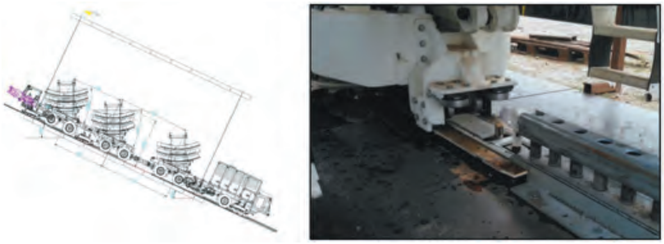

Figure 12. Rack and pinion.

4 FORCE-ACTIVATED COUPLING SYSTEM - FACS

4.1 *Innovative segmental lining*

The innovative segmental lining FACS was developed specifically for the IPS of Snowy 2.0 project and includes pin and socket steel couplers embedded along the longitudinal joints of the segments (Valiante et al, 2023). The coupling mechanism is achieved during erection of a segment by inserting its pins into the sockets of the adjacent and previously erected segment. The pin coupler, which is equipped with a cup-springs stack, is dimensioned to move outward while sliding inside the socket, imposing the cup-springs to deform and immediately activate pre-compression force on the segments joint (Figure 13). Additionally, the cup-springs stack allows smooth and secured coupling as it accommodates production tolerances (steel elements and concrete segments) without compensating full joint closure nor erection completion. The created connection provides the segmental lining with the pre-compression and tensile resistance needed to prevent risks such as joint dislocation and joint openings during normal operation conditions. This innovation presents a single-pass segmental lining which can cope with transient hydraulic pressures and hence can be used to construct high-pressure tunnels. The extreme operational dynamics loads acting on the lining over a period of 150-year makes fatigue design one of the most critical aspects in developing the FACS solution (Stucchi et al 2025). An additional important component of the lining was the backfill grout requiring very high performances to cope with the extra-ordinary cyclic loading conditions of the project (Di Giulio et al 2023, Elgarhi et al 2025).

4.2 *Large Scale Test*

In the final stretch of ECVT tunnel the modified TBM1 was used to excavate an additional section of the ECVT in which FACS segments (420 mm thick) were installed. Initially, eight consecutive FACS rings were planned for installation (from ring 1461 to 1468, then additional rings were installed up to ring 1473) in the context of Large-Scale Test (LST). The main purpose of the LST was to fine tune the constructions and control methods for the FACS segmental lining.

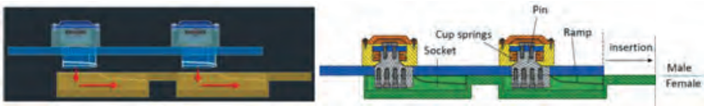

Figure 13. FACS Spring.

Based on the LST results it was possible to define the monitoring and measurements that are required during the construction of the IPS. Main objectives of the LST in ECVT were:

- Confirmation of adequate erection capability of FACS ring and optimization of ring erection operational procedures.
- Verification of admissible tolerances and relevant measurement control methods.
- Verification of execution methods for backfill grout and contact grouting.

During the execution of LST, multiple successful erection of FACS rings were completed and admissible tolerances of ovalization confirmed, with validation of reliable survey methodology based on laser scanning of the rings. On the other hand, challenges emerged during the grouting activities execution on rings from R1461 to R1473, e.g. discontinuous excavation, grout mixing issues and difficulties in coring the hardened grout.

In this context, was considered of extending the LST with 15 additional rings (up to ring 1490) and the backfill sampling method was further improved, successfully completing the LST and finally starting the construction of the IPS which is currently ongoing.

At the time of writing, about 100 FACS rings have been installed without major problems. The tunnel gradient is currently at about 30% of the planned 47%.

5 CONCLUSION

The IPS of the Snowy 2.0 project has some features that make it unique. By example, its large diameter, its length, the continuously variable vertical alignment from -9% to + 47% and then back to +5.2%, the internal operating pressures, the transients caused by water hammer, the high rock cover and the enormous hydrostatic load of the ground water table. These characteristics make both the construction and operation phases of the work quite critical. To address these criticalities, numerous innovations have been implemented in the technologies of execution and in the lining design. Each one of these innovations, which together contribute to making the undertaking possible, constitutes an important contribution to the innovation of the mechanized excavation technology.

The segment design and construction methodology were elaborated by the Designer in collaboration with Webuild and no-objected by the Client.

The fruitful collaboration between Webuild, SHL and the DJV Designers has allowed these challenging results to be achieved.

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Tunnelling into a Sustainable Future – Methods and Technologies – Johansson et al (Eds)
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Innovations in tunnelling technology by Bouygues Travaux Publics on the HS2 Chiltern tunnels

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ABSTRACT: The construction of the twin bore 16.1km Chiltern Tunnels for HS2 by Bouygues Travaux Publics (BYTP) enabled multiple advancements in innovative tunnelling. This paper examines the innovations implemented in their 10.2m diameter Variable Density Tunnel Boring Machine (TBM), which have significantly enhanced productivity, safety, and sustainability in the construction of the tunnels.

In partnership with Herrenknecht, multiple automation systems were incorporated on the TBM. These include: a robotic system, called Krokodyl, for removing wooden spacers between tunnel segments; ATLAS which enables semi-automatic and automatic ring building; a semi-automatic slurry system which makes it possible for the pilot to manage the 16km slurry circuit while remaining focused on mining parameters and the Centre of Thrust (CoT) which simplifies TBM steering. Krokodyl and ATLAS remove the hazard of people plant interface, manual handling, and working at height. The CoT allows for continuous mining by removing pairs of thrust cylinders to enable ring erection while still excavating.

Another key innovation is the integration of recycled water injection on the TBM reducing slurry feed flow and the size of the pumps and slurry pipes. This led to significant reduction in power and freshwater consumption with the associated benefit of carbon reduction and cost savings.

Development of an inert polymer in the Slurry Treatment Plant to process filter cakes is a first in the UK. This innovation enabled landscaping of 3 million cubic meters of spoil on site by removing the need for lime and acid treatment. This presented significant improvements in environmental sustainability, removed tens of thousands of lorry movements from local roads, and avoided the risks of operatives working with acid.

These innovations demonstrate BYTP's commitment to push the boundaries of tunnelling technologies and set new standards for projects worldwide, enhancing productivity, safety and environmental sustainability.

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1 INTRODUCTION

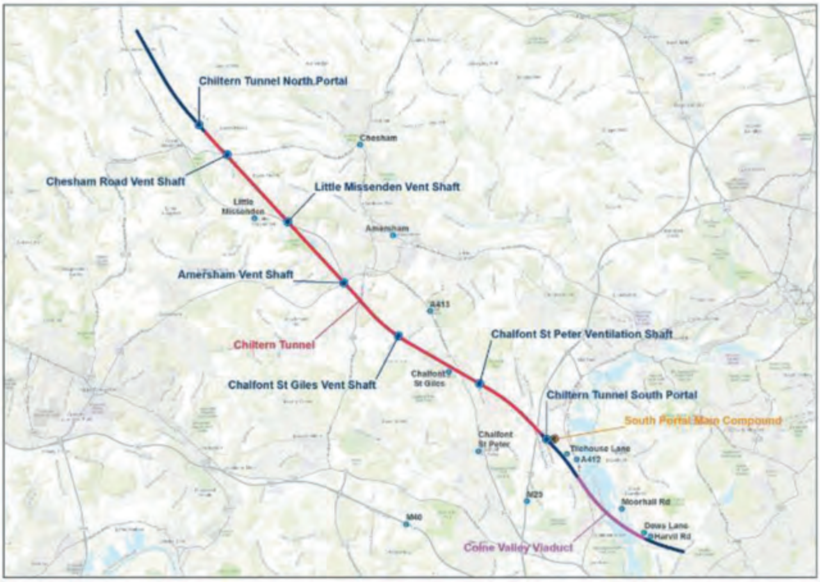

Figure 1. Tunnel alignment.

Bouygues Travaux Publics (BYTP) was selected as part of the Align Joint Venture to construct the 10.2m diameter twin bore 16km tunnels below the Chiltern Hills for HS2, the high speed rail link between London and Birmingham. Construction of the tunnels started in May 2021 and was completed in March 2024. The tunnels were bored primarily through chalk lithologies with varying flint content and weather grades, with a short section of superficial deposits at prior to breakout.

BYTP presented multiple innovation opportunities during the tender process, opportunities that the client was very willing to support, especially if they improved health and safety or reduced environmental impact. Once selected for the project BYTP worked very closely with the Tunnel Boring Machine (TBM) supplier, Herrenknecht (HK), to implement these innovations onto both TBMs. Some technology had been used previously on other BYTP projects around the world such as Mobydic however, some innovations were implemented for the first time ever such as the Krokodyl robot.

Throughout tunnelling operations BYTP worked to test and improve these innovations and address the inevitable teething problems encountered when using unproven technology. Alongside the commissioning, BYTP also trained and upskilled the TBM operatives in the use of this technology, something that proved difficult at first due to some skepticism from the operatives who were used to the traditional methods or working and had the mind set of 'if it isn't broken, don't fix it'. However, once the methodology and logic behind the innovation had been explained and demonstrated, the technology was largely adopted by the operatives, who provided feedback and worked closely with BYTP engineers to maintain and improve it.

2 KROKODYL

One of the common, and regularly accepted or overlook risks on the TBM is the unloading of segments from quick unloaders to the segment feeder. As the segments are separated in the stack by wooden spacers, the spacers traditionally need to be removed by hand between each segment movement. This often required working at height on top of the segment stack, manual handling of the wooden spacers, and working in proximity to moving plant. BYTP created the Krokodyl robot to remove these risks.

Figure 2. Krokodyl robot.

The Krokodyl robot was a world first on TBMs, it was based on a Kuka robot arm with a BYTP designed and manufactured effector head. It is a fully automated system requiring no input from the operator other than to activate it. To implement this robot on the TBM took a great deal of work as there is very limited space for movement of the robotic arm within the TBM, particularly when there is a stack of segments present on the quick unloaders. Once the TBM design had been finalized, and before its construction had begun, the BYTP team began with computerized models to map out the necessary swept path of the robotic arm within the TBM structure.

Due to the space constraints within the TBM, the size of robotic arm was limited, and as a result so was the lifting capacity. To enable the Krokodyl to work the effector head, or 'jaw', needed to be as light as possible, yet still able to lift the approximately 40kg of wooden spacers. This placed additional design constraints for the BYTP team to overcome. One solution to limit weight was to use a pneumatic system for the jaws rather than hydraulic, run off the TBM compressor rather than an onboard supply.

The Krokodyl was installed onto the TBM during the assembly process on the launch slab, and was commissioned in time to swing the bottle of Champagne to christen the TBM prior to launch. Once TBM production was underway the Krokodyl was soon put into service unloading the wooden spacers, firstly under the supervision of BYTP engineers, but quickly handed over to the operators and mechanics on shift.

To calculate the performance of the Krokodyl and identify opportunities for improvement, automatic data logging files were regularly reviewed by the BYTP engineers. A key indication was the performance ratio, as below.

$$Performance\ ratio = \frac{Number\ of\ full\ rings\ completed\ by\ Krokodyl}{Numer\ of\ rungs\ attempted\ by\ krokodyl} \tag{1}$$

Over a sample set of 20 weeks, the average performance ratio as per equation 1 was 87%, with a maximum of 98% and a minimum of 67%.

Due to the cycle time of the segment crane movement during unloading the of the segments, the Krokodyl fitted seamlessly into the ring unloading process. On picking up the first segment, the operator would active the robot, while they were lifting the segment onto the segment feeder, Krokodyl would pick up both spacers on the segment below and place them in the unloading area. By the time the operator had completed the first lifting operation, the Krokodyl cycle had finished and they could pick up the second segment. Krokodyl only needed activation once, after this it was fully automated based on feedback from the segment crane position.

3 ATLAS

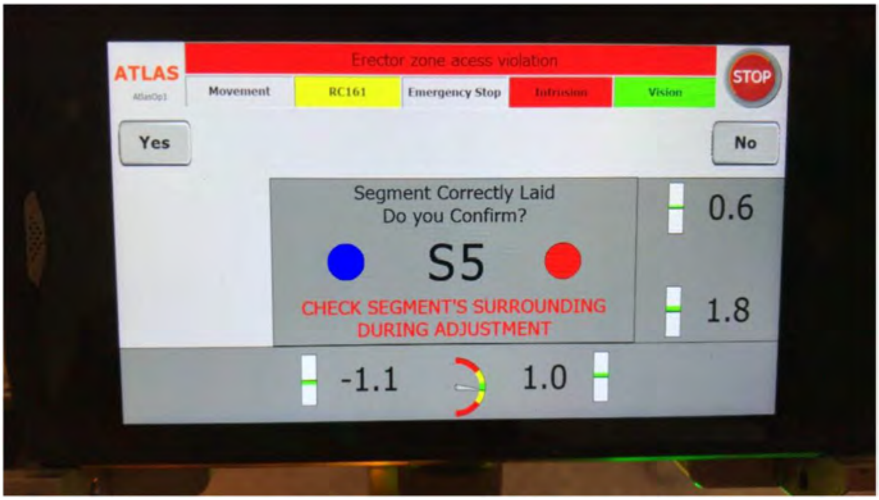

Figure 3. ATLAS automatic ring build.

Automatic Tunnel Lining Assembly System (ATLAS) and a subsidiary system called Marguerite were developed to automate all, or part of, the ring build process on the TBM. BYTP developed this with the preliminary goals of removing ring builders from the hazardous ring building area, assisting the erector operator with their task by reducing the amount of movement required between segments, and aiding them in reducing lips and steps in the rings. The secondary longer-term goal of the system is to fully automate the ring building process.

Marguerite is used to automate the collection of the segment from the segment feeder and the rotation of the segment to the correct position within the tailskin. Following this the system gives control back to the operator to finish placing the segment. ATLAS is able to collect the segment and place it into the partly built ring with millimeter accuracy, as well as operating the thrust cylinders to retract and extend to hold the segment in place.

The system is designed to fit onto any standard erector head and works with a frame work of 6 lasers and a 2D camera attached to the erector head which are able to detect pre-cast markers on the intrados of the concrete segment. During placement of the segment into the tailskin, a small tablet mounted on the erector control box shows the offset of the segment from the previous ring, and the segment adjacent to it in the current ring, with 0.1mm accuracy (Figure 3). This is used by the erector operator to ensure they build a ring with the smallest lips and steps as possible, as well as being able to correct ring roll if needed.

ATLAS and Marguerite were commissioned a few months after launch of the TBM and BYTP engineers trained the erector operators in the use of the equipment. It was found that after 2 to 3 rings of use the operators were confident in the use of the system, and after 10 rings were confident in the measurements provided by the tablet. Following site trials and improvements, ALTAS was able to build a ring within tolerance in approximately 30 minutes.

Marguerite was the preferred system of the erector operators as it enabled the ring builds to be completed in 20 minutes through a semi-automated workflow where the robotic system aided the operator rather than replaced them. This is a common thread found through many of the innovations of the project, where seamless integration of automatic or robotic systems with the human workflow improve safety and efficiency without impacting production. An additional advantage of the digital readout on the tablet was that the erector operators assistant was no longer needed for the ring build, this enabled them to focus on other tasks. Following future implementation, it may be possible to remove the requirement for the assistant entirely which is both a cost saving and safety improvement.

4 AUTOMATIC SLURRY PUMP CONTROL

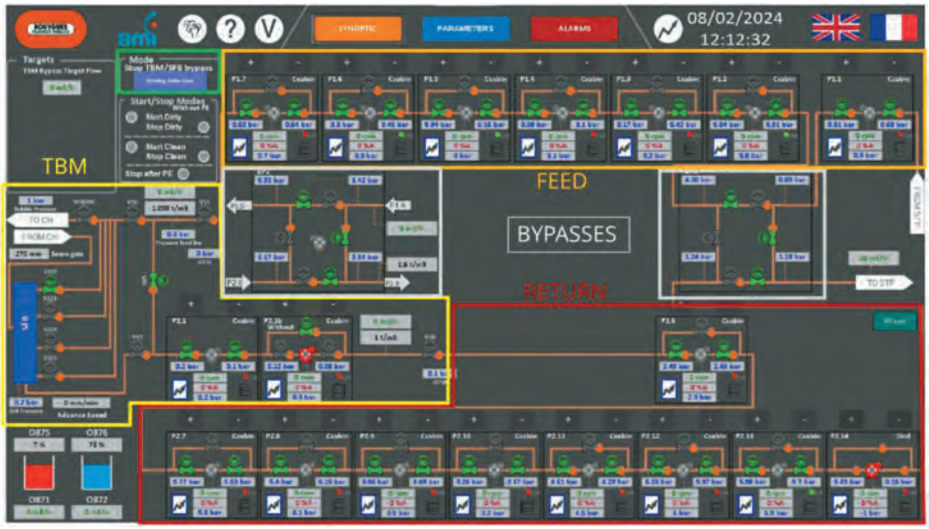

Figure 4. Automatic slurry control.

Due to the length of the tunnel 16km length of the tunnels, 16 slurry booster pumps were needed for each tunnel to provide the 1200m^3/hr flow required for material transportation. To add to this complication there was a significant 110m elevation gain between the launch and breakthrough sites, causing 11bar of static pressure in the slurry circuits towards the end of the project. BYTP knew that control of this slurry circuit would be a significant challenge, traditionally a second TBM operator would be required just to control the pumps, however BYTP opted to install an automated slurry pump control system instead.

The system was developed by BYTP prior to launch of the TBMs and then, as the system as not required immediately, it was adapted further following launch based on the actual mining parameters of the TBM.

At its core the system is fairly simple, it is told what flow is required, and it then controls pumps speeds to achieve this flow while remaining inside programmed pressure and RPM limits for each pump. In reality the system took a vast amount of development as slurry density, gravity flow, cavitation, ramp speeds, and valve operations all needed to be considered to ensure that the system was safe and would not lead to substantial pressure spikes or sedimentation within the pipes.

As each additional pump was added onto the system as the TBMs progressed the system became more complicated, as such a close working relationship was formed between the system designers and the onsite engineers to fine tune the system as required.

Despite these challenges, the automatic slurry system is arguably the most successful innovation implemented on the project. It was ubiquitously adopted by the TBM operators, with all saying it greatly reduced the pressure on them and allowed them to focus on other things knowing that the automatic system was reliable.

The system was integrated with the Herrenknecht slurry control system seamlessly, this enabled the use of 'shortcut' buttons implemented by HK to quickly go between standard and slurryfier box bypass, rather than needing to operate each valve individually.

Due to the length of the tunnel BYTP also integrated two bypass stations, one at surface, and one halfway through the tunnel. These were included in the automatic slurry system to allow circulation of dirty slurry between the STP and the bypass in the tunnel, while stopping the slurry circuit on the TBM to allow for pipe extensions. This meant that the slurry circuit could continue to be cleaned during pipe extensions and more importantly, the pumps could be kept running. To restart, the pumps between the TBM and the tunnel bypass were restarted, once the pressure between the two separate circuits was balanced the tunnel bypass could be opened and mining recommenced. This saved 20 minutes on start up as it could take up to 45 minutes for the circuit to stabilize after startup without the use of the bypass.

5 RECYCLED WATER

The recycled water system was proposed by the Slurry Treatment Plant (STP) supplier MS during the tender process in 2018. The feasibility of this system was studied by BYTP and following approval the system was implemented into the TBMs through collaboration with HK who also supplied all pumps required, including those needed at the STP. The recycled water is sourced from 'grey' water on site such as surface run off, and dewatering screens.

The purpose of the system is to reduce the flow of clean slurry required to effectively dilute the excavated material, reducing the size of the pumps required and thus also the power supply, and the processing rate required at the STP. The recycled water system does this by effectively splitting the feed flow into 2 parts, one 400mm diameter pipe for the clean slurry, and one 250mm diameter pipe for the recycled water.

The 400mm diameter feed pipe delivers 1250m^3/hr of clean slurry to the TBM, while the recycled water pipe delivers approximately 300m^3/hr of water to storage tanks on the TBM. Once the tanks on the TBM are full the recycled water feed valves close and the tunnel pumps stop. The water is then injected from the onboard tanks into the slurryfier box with onboard pumps on the TBM at a rate of 150m^3/hr.

This system reduced not only the amount of pumps required, but also the size, giving a cost and carbon saving on reduction of electricity usage. It also reduced pressure on the STP by reducing the flow required.

6 CENTER OF THRUST

The center of thrust (CoT) replaces the traditional method of steering a TBM using groups of thrust cylinders and potentiometers, with a touch screen control and computerization. With the CoT the TBM operator moves the blue dot on the touch screen, rather than changing the four individual potentiometers as shown in Figure 2.

On the Chiltern Tunnel TBMs, each thrust cylinder had it own hydraulic pumps to facilitate semi-continuous mining, a technology that will be detailed later in this paper, however the CoT also utilized this for the steering of the TBM. When the operator moves the CoT, the PLC system automatically adjusts the pressure on each cylinder individually to steer the

TBM. This allows for a much finer distribution of the thrust force around the ring as there is no longer a step in force between each thrust cylinder group.

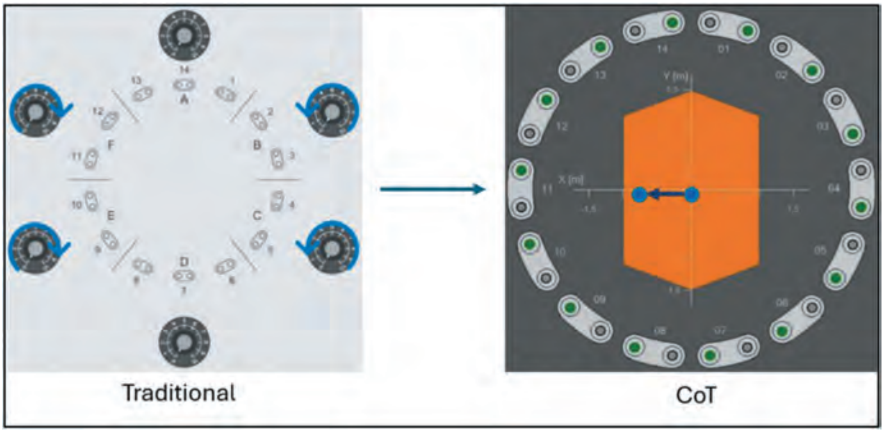

Figure 5. Traditional method vs Center of Thrust.

The PLC system is preprogrammed with the maximum allowable thrust force per cylinder, per segment, and per ring. These limits control the variation of the thrust force by the CoT to ensure that thrust limits are not exceeded. If the thrust force increases, the PLC decreases the size of the available steering window, shown in orange in Figure 2. This gives the operator a visual indication of how much steering is possible while remaining within the allowable limits, and will not allow them to steer outside of these limits.

This system removes a lot of the input and monitoring required with the traditional method of steering, all that is required from the operator with the CoT is one input of placing the blue dot where they want the thrust to be focused, the PLC handles the rest. This allows the operator to focus on other tasks and not continually adjust and balance thrust cylinder groups.

7 SEMI-CONTINUOUS MINING

Most TBMs encounter an unavoidable loss of time during production, stopping to build the segmental lining. BYTP aimed to remove the need to stop to build the ring and allow for continuous mining with segment installation occurring simultaneously. To enable this to take place each thrust cylinder was equipped with a standalone hydraulic pump to allow them to be controlled independently of each other by a dedicated PLC system.

The process starts once the trust cylinder extension exceeds 2000mm, at this point two of the thrust cylinders are removed to enable to the first segment to be installed. When these two cylinders are removed, the PLC system redistributes the thrust force between all other cylinders to maintain not only TBM advance, but also steering. It does this using the CoT technology detailed above. The thrust redistribution is shown in Figure 6 below.

In this example, the thrust distribution before ring building is shown by the green curve, the TBM is advancing and steering upwards by pushing harder on cylinders 7 and 8 in the bottom. The grey curve represents thrust distribution when cylinders 7 and 8 are removed to enable a segment to be installed in this location. The thrust on the adjacent cylinders increases proportionally to maintain TBM advance and steering input.

The estimated productivity gain prior to implementation was approximately 25% as shown in Figure 7 below.

Following implementation and trials on site, we found that the impact of machine roll translating through the trust cylinders onto a the first installed segment was too significant and caused the segment to move. We also found that during trials with higher thrust force, the first steel fibre reinforced segment installed could crack down the center as there was no support from adjacent segments.

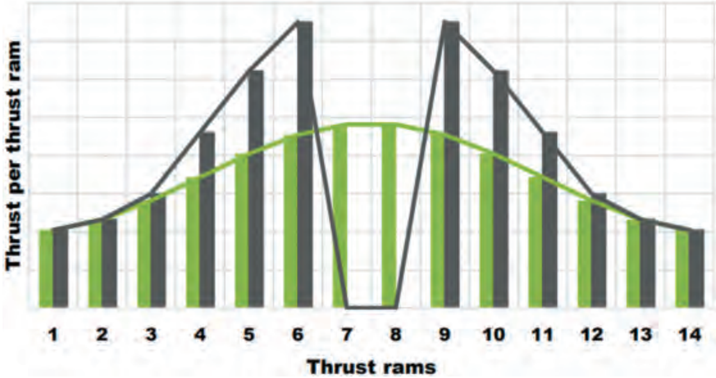

Figure 6. Thrust redistribution during continuous mining.

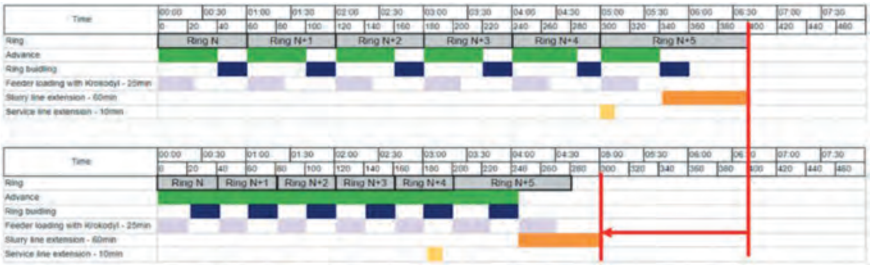

Figure 7. Estimated productivity gain from continuous mining.

To overcome these constraints we elected to stop mining to install the first two segments and then recommence mining. The stability that the two segments provided each other was sufficient to limit the impact of ring roll and prevent cracking in all but the highest thrust forces. Due to the requirement to stop for the first 2 segments, the real productivity gain was closer to 10%.

This technology would be more suitable for a TBM with longer ring build times, or with much slower advance rate where marginal gains are more beneficial.

8 INERT POLYMER FOR SPOIL TREATMENT

The Chiltern Tunnels pass through a chalk aquifer with multiple extraction wells along the alignment, these wells provide drinking water for the surrounding area and much of west London. As such the use of bentonite and chemicals for spoil treatment was prohibited to avoid contamination of the aquifer.

To enable the efficient treatment of the spoil arising from tunnel excavation BYTP gained approval from the Environment Agency to use an innovative inert polymer in the STP. This was the first industrial use of the polymer following trials by BYTP on another of the company's tunnel projects, T2A, in Hong Kong.

The polymer replaces the traditional treatment method of hydrated lime and sulphuric acid. Usually 5kg of lime and 1kg of acid is needed per ton of dry matter arisings, whereas only 0.075kg of polymer is needed per ton. This is a significant saving of 23,700 tons on raw materials, reduction of deliveries to the site on local roads, and a reduction in carbon emissions of 10,650 tCO_2e.

The use of the polymer meant that BYTP were able to directly landscape all processed material on site without the need for further treatment. This removed tens of thousands of lorry movements from the local road network reducing impact on the local community and eliminated the associated carbon emissions. It also enabled the creation of 127 hectares of calcareous chalk grassland within the site boundaries, this is a diminishing environment in the UK that is a key habitat for certain species of animals and plants. The creation of this grassland is a long-term legacy from the project that will benefit the local community through the inclusion of recreational areas, footpaths, and bridges.

9 CONCLUSION

The Chiltern Tunnels presented BYTP with an opportunity to innovate and improve the tunnelling industry by building on BYTP's previous experience, alongside the full support from the client and early engagement with suppliers.

The innovations were driven by a goal to reduce the impact of the project on the environment and local communities, improve the safety and efficiency of tunnelling operations, and leave a legacy of improvements and learning for future projects.

The implementation of the Variable Density Tunnel Boring Machine (TBM) with multiple automated systems such as Krokodyl, ATLAS, and the semi-automatic slurry system proved to be instrumental in reducing human risk factors and increasing operational efficiency. Krokodyl removed the hazards associated with the removal of segment spacers, while ATLAS and Marguerite optimized the ring build process, ensuring precise and safer segment installation.

The automatic slurry pump control system and recycled water injection not only managed the complex slurry circuit effectively but also contributed to substantial reductions in power and freshwater consumption, thereby lowering carbon emissions and operational costs. The deployment of an inert polymer for spoil treatment marked a groundbreaking shift from traditional methods, offering a more sustainable and environmentally friendly solution.

Overall, BYTP's innovative approaches contributed to raise standards for tunneling projects globally. The technological advancements balance the demands of modern infrastructure development with health, safety, and environmental sustainability. BYTP hope that lessons learnt from this project will be adapted by other contractors to aid in advancing the industry as a whole.

Tunnelling into a Sustainable Future – Methods and Technologies – Johansson et al (Eds)

Digitalization of a large tunnelling project through its design and construction

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ABSTRACT: Digitalization of large tunnelling projects during design and construction has progressed significantly in the past 10 years. The knowledge and know-how of tunnelling engineers have evolved to the point where digitalization involves not just digital drawings, but also building information modelling (BIM), complex common data environments (CDE) and digital reporting through online databases, combining them in a complex system which supports all project processes. In this article we provide an insight into the latest of such projects in Slovenia, the second railway track Divača-Koper, which was fully digitalized. Additionally, we present the goals of digitalization set up by the client, CDE implementation, and examples of digital processes during design and construction. These include usage of 360 photos, point clouds and 3D visualisations of design solutions, dynamic connections of BIM to bill of quantities and the process of digital daily reporting being used for As-Built BIM model generation.

1 INTRODUCTION

The focus of building information modelling (BIM) development has slowly expanded in recent years to include not just high-rise projects, but also infrastructural ones. As parametric modelling, implementation of programable APIs, highly flexible visual programming tools and design scripts were being implemented in modelling software, BIM was mainly used for bridges and only later expanded to cover other infrastructural projects including tunnels, although with varying success due to software limitations. One of the earliest examples of a well-known mega-project, which provided a working proof of BIM in tunnelling, was Crossrail in London, UK (Smith, 2014).

As companies embraced these new tools and started developing their own scripts and parametric components, BIM started to be implemented more frequently in tunnelling projects. Progress was hindered by the lack of BIM standards infrastructure, resulting in every project being handled in a different manner, learning from the mistakes of the previous project, and thus trying to improve the process. In Slovenia, this steady progress culminated in the biggest major public infrastructural tender for a tunnelling project, the second railway track Divača-Koper, where digitalization, with BIM at its center, was mandated and served as the cornerstone of the entire project.

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2 PROJECT OVERVIEW

2.1 *The second railway track Divača-Koper project*

A new, second railway track from the Slovenian port of Koper into the hinterland town of Divača (2TDK project) has been a long-awaited mega-project in Slovenia. The original single-track line was constructed in 1967, winding across 49 kilometres to bridge the 400-meter height difference. The track's alignment was far from perfect, cutting through some delicate natural habitats and first-level water protection zones, while posing a major fire hazard. Additionally, the port of Koper cargo traffic increased 5-fold in the past 50 years. After several studies and analyses, the construction of a new railway line was accepted as the best option in 1996. In 2012, all the necessary studies and spatial planning were finished, and the project moved from concepts to plans for attaining the building permit.

In 2019, a detailed design for project execution was commissioned by the client company 2TDK to a joint venture of three companies (Elea iC, IRGO, SŽ-PP) and their subcontractors to be finished in 9 months. Since classic design, scheduling and cost estimation solutions usually fail to perform well for larger tunnel complexes due to their sheer size and complexity (Isaksson, Stille, 2005), the client mandated the overall project digitalization during design. In addition to the usual 2D drawings, bills of quantities (BoQ), and reports, the detailed design had to include optimization of tunnel profiles and support systems, material usage and critical path definition, as well as the BIM modelling of the entire track and the dynamic connection of BIM models to BoQs.

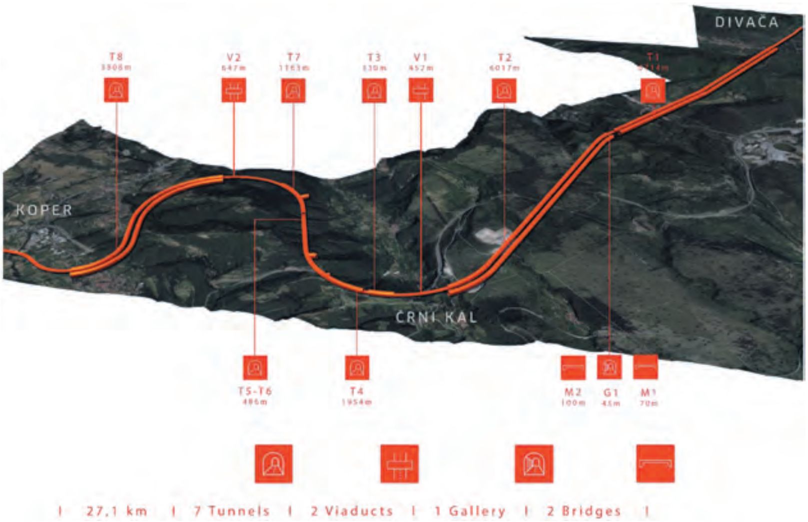

Figure 1. Final track solution presented with the surrounding terrain.

Table 1. Track's technical sheet.

Line length	27,200 m
Vertical difference	400 m
4 bridges and viaducts	1260 m (4.6 %)
8 tunnels	20,472 m (75.3 %)
All tunnel tubes (service and exit tubes included)	37,375 m
New access roads	20,013 m
Track type	slab track (80 %) sleeper track (20 %)
Maximum train speed	160 km/h
Maximum track slope	17 ‰

All tunnels were designed to be excavated conventionally using the New Austrian Tunnelling Method (NATM). Excavation profiles are comprised of the top heading and bench with invert with different profiles and support types as the existing geological and hydrogeological conditions vary along the railway alignment. For the first part (Divača to Črni Kal), karst conditions dominate with highly porous limestone with caves, caverns, and rapidly fluctuating groundwater levels. These conditions pose a major issue for the longest tunnels T1 and T2, which were designed with a circular cross-section where high water pressures were possible. The lower part of the track (Črni Kal to Koper) consists of 5 tunnels, driven through flysch rock passing numerous small valleys. Therefore, several short slope tunnels with low overburden and high portal pre-cuts with unstable natural slopes were foreseen (Jemec, Dvanajščak, Škerbec, 2019).

The longest tunnels, T1, T2 and T8, were designed as twin tubes with cross passages, while all other tunnels (T3 – T7) consist of a single tube with T4 and T7 featuring short emergency escape tunnels (see Figure 1).

In 2021, construction began on all tunnels as contracts between the client company 2TDK and main contractors Kolektor CPG, Yapi Merkezi and Özaltin were signed. In 2023, additional contracts were signed between SŽ - Železniško gradbeno podjetje Ljubljana and other smaller contractors to furnish the entire track and provide all installations (electrical, mechanical and telecommunication).

3 DIGITALIZATION GOALS

Digitalization was used in all aspects of the Divača-Koper railway design, beginning with digital logs of geological surveys. It continued with the CDE setup (see Chapter 4) and played a crucial role in design solution optimization, mainly for tunnel cross-sections and portal areas, where 3D models using FEA methods were used to simulate different ground and water pressures.

To integrate development of digitalization into all pores of such a large and time-restricted project the client demanded that organized digitalization achieves the following goals:

- documentation with version control and direct access by the client and supervisors;
- reduced communication errors and improved collaboration between designers;
- increased understanding of project design by contractors;
- improved data and information exchange between project stakeholders;
- improved insight into design solutions with 3D models for all project participants;
- confirmation of constructability using 3D models;
- use of BIM models to extract exact quantities for the bill of quantities;
- digital logging of performed works for better supervision and control.

4 COMMON DATA ENVIRONMENT

4.1 *Design phase*

Digitalization of such a large project would not be possible without a single source of truth in a form of a common data environment (CDE). The CDE chosen during the design phase was Thinkproject, as it allowed for rule naming conventions of drawings, models, reports and BoQs, which generated document meta-data for advanced filtering. Access to audit tracks of all submitted versions was available to all the project participants, while reviewers could comment on the latest design packages independently of each other (see Figure 2).

The design CDE handled more than 1000 reports and BoQs, 9000 drawings, and 700 building information models with all their previous versions. All in all, the final design submission amounted to 30 GB of data.

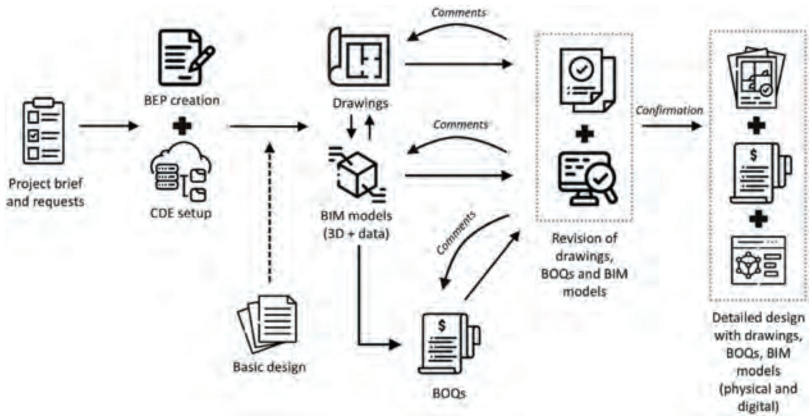

Figure 2. Digital workflow for design, coordination and revision.

4.2 *Construction phase*

Due to a decision made by the client, Thinkproject was phased out in favour of a new CDE platform, Dalux, for the entirety of the construction phase. The decision was made so that the CDE could also handle forms, tasks and integrated BIM models and would be more user-friendly, which is extremely important for large construction sites with multiple worksites and hundreds of people. Nevertheless, transferring the whole project from platform to platform unavoidably caused certain issues and should be avoided in other projects if possible.

In addition to all the documents and models, the naming conventions were also transferred and upgraded from the design phase. Connections between 2D drawings and 3D BIM models and new workflows with clear and strict rules were set up. Examples of such complex workflows are capturing underground data for excavation of all tunnels, tracking progress using 360-degree photos (see Figure 3) and document validation processes.

Figure 3. Geolocated 360-degree portal area photos at different times and point cloud with BIM model.

Drone aerial capture, terrestrial scanning methods, and photogrammetry are all used during construction to provide the contractor and the supervision with precise point clouds of underground and surface excavations and works. Since Dalux also allows importing of point clouds, it is easy to compare the theoretical planned 3D BIM models with actual measurements. This was done to a high degree of accuracy for tunnel excavation surfaces and primary lining surfaces, where point clouds derived from photogrammetry were compared to theoretical profiles for deviations (Urbančič, Česnik, 2024).

Tunnels T1 and T2 are excavated primarily in porous limestone, therefore a great deal of effort was put into protecting the water reservoirs and the newly discovered karst caves. All caves were scanned and transferred to BIM models, providing the basis on which solutions for remediations and spanning of caverns were defined, all visualized in 3D (see Figure 4).

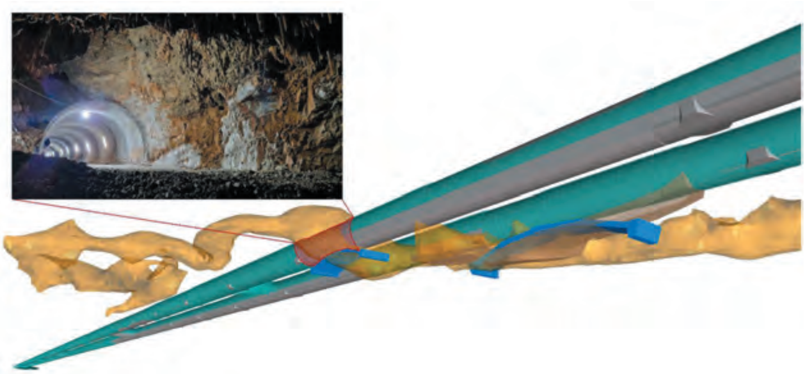

Figure 4. BIM model of a karst cave and underground arch bridges spanning over it.

5 BUILDING INFORMATION MODELLING DURING DESIGN

5.1 *BIM model setup*

Highly detailed BIM models of all the designed features and structures along the alignment were created and included everything from geological conditions, tunnels, railway tracks, earthworks and structures, to the equipment for all the structures, and the final landscaping (see Figure 5). Since BIM standards did not specifically target tunnels at the time of design, we relied on our previous experience from modelling infrastructural projects like the Karavanke tunnel (Žibert, Schubert, Lah, Saje, 2017) and the Pekel tunnel (Jovičić, Muhić, Pečovnik, 2019) to develop the entire framework in which all designers could work.

Due to most BIM modelling tools being developed for high-rise buildings design and due to the complexity of the project, new tools and parametric workflows had to be created in existing BIM software, some even with direct support from software developers. These tools were used to create all the 3D models for most tunnel works (excavation, support, inner lining, linear equipment) and railway works, as modelling these by hand is practically impossible.

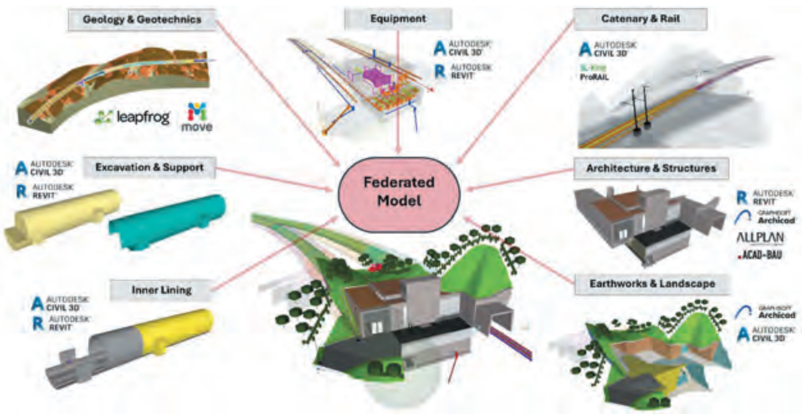

Figure 5. Partial BIM models for different disciplines and the federated BIM model.

Scripts and advanced tools were also used to append attributes to all the elements in BIM models and to make it possible to carry additional information which defines their purpose, semantically positions them in the project and connects them with specific quantities and properties. Since there was no standard for attributes in infrastructure in 2019, we had to define them specifically for this project based on our experience, project goals and overall workflows. These attributes were grouped and linked to different element types and then transferred into an attribute database, so all designers and modelers worked from the same source. All 432,000 elements were thus appended classification, location and description attributes which were needed to set up automatic checking rules, rules for clash detection, and dynamic links with BoQ.

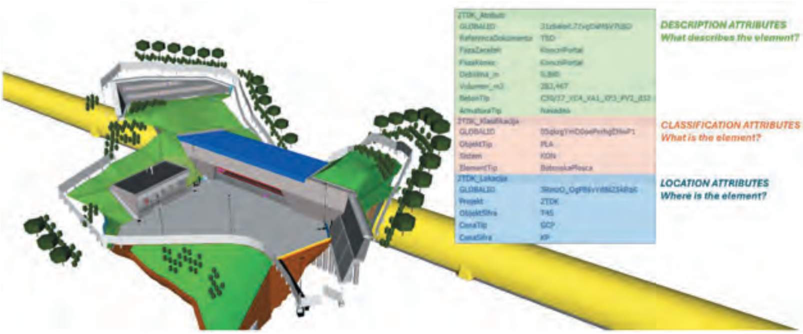

Figure 6. Example of a concrete slab element with all its attributes.

5.2 *Linking BIM models to BoQ*

While linking BIM models to schedules and cost estimation (5D modelling) for large infrastructural projects has been proposed before (Mayer, Frodl, Hegemann, 2016) and was also partly used in some pilot projects (e.g. Karavanke, Brüttener, Rufiji tunnels), it has never been used in such a short period of time on such a complex project. For the Divača-Koper railway project a standardized workflow was set in place with easy-to-follow instructions for all designers, modelers, quantity surveyors and checkers (see Figure 7).

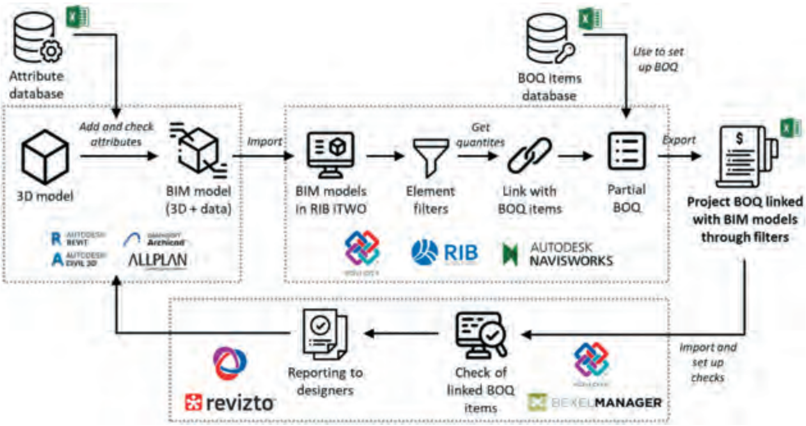

Figure 7. Workflow for BIM to BoQ connection and check inside the overarching BoQ creation process.

A database was set in place for all BoQ items used in the project for all designers to use the same descriptions (Slovene and English) and unit prices for the same kind of works on different parts of the project. This database, combined with a project-wide BoQ template, provided the client with a unified design and content for all 26,000 individual BoQ items. We also set up specific rules to create attribute-based element filters to dynamically connect BIM elements with specific BoQ items. This proved to be very advantageous as we could prepare the entire BoQ structure and all the filters in advance and, in case of model changes, simply import new models and run the quantity analysis again to update the BoQ. Using up-to-date models, we were able to get the exact quantities that could be verified by the BIM reviewer. As it is not realistic to model every detail (example: electric conduits) or represent nontangible works (example: site setup) some BoQ items cannot be connected to BIM models. Nevertheless, more than 10,500 individual BoQ items were linked to BIM element representing approximately 70 % of the project's value.

6 DIGITALIZATION DURING CONSTRUCTION

6.1 *Daily excavation reports digitalization*

Throughout the entire project the NATM method is used for excavation of all tunnel tubes regardless of profile size or shape. The NATM method allows work to be more flexible and adapt to the actual geological conditions, which also allowed for mixing of different drained or undrained profiles. It demands constant monitoring of geological conditions, deformation measurements and changes of support types. Due to the flexibility of the NATM method, it is crucial to record each excavation step in daily excavation and primary support report.

The traditional process involves manually filling out a paper form at the construction site and submitting it to supervision for approval. A logical upgrade would be to digitalize the input process by using Excel spreadsheets, but we improved this idea by taking advantage of online Dalux forms that can be filled out at the site with a smartphone. Centralization in a single database through a single online form required standardization (report form and possible values in fields must be agreed upon), consistency (user input should be limited by dropdown or other types of predefined menus and free input should be kept at a minimum), identification (each field has its own unique code), education (all involved must be properly trained), and validation (input must be validated by supervision for data correctness).

The main advantages of such an approach are direct, consistent input into a database, and immediate access to all the data of everyone involved. The contractor also saves a lot of time on each of the more than 10,000 daily reports, as it is faster and less prone to mistakes. Furthermore, designers and supervisors can now work faster with a structured database instead of searching through piles of individual paper reports. While general time savings benefit the project, the greatest benefit is having an organized, structured, and consistent database with all the data regarding excavation in one place.

6.2 *Generating excavation and primary support BIM models*

An excavation and support database makes it possible for everybody to query all the daily reports and export the data they need in a structured way. The designers could now acquire queried and structured data as Dalux provides an option to export all the gathered data into Excel spreadsheets which are then fed into custom-built modelling scripts. These scripts are used to generate excavation and support geometry based on report data (combined with project profile geometries and tunnel axes) while also appending attributes for support measures based on the project support type matrix. Due to such a large number of elements, the designers have opted for less geometry-heavy models, excluding all support measures such as bolts and steel pipe umbrellas except shotcrete, which has all the support data appended to its attributes.

The entire process (see Figure 8) is repeated monthly to update excavation and support BIM models. Time savings cannot be properly evaluated as manual BIM model creation is virtually impossible due to human errors in such an iterative process. Finally, exporting all tunnels into separate As-Built models in IFC format and then uploading them to Dalux allows the supervision to check the models and use them for further analyses, such as cost and quantity check and construction progress control. A similar approach was also set up for reporting progress on inner lining concrete works and installation of tunnel electrical and mechanical equipment.

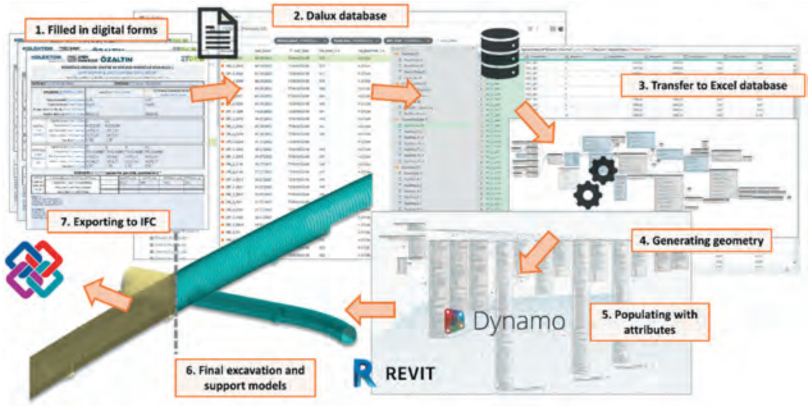

Figure 8. Workflow for reporting, processing and generating excavation and support BIM models.

7 CONCLUSION

This article discusses the Divača-Koper railway track project and how digital tools are being used to enhance large-scale infrastructure projects. Digitalization has improved the project by integrating BIM models with design documentation and BoQ, as well as enhancing transparency through the use of a CDE for all stakeholders. The design phase goals were fully achieved, and workflows, attribute definitions, and naming conventions developed during this phase were refined in the construction phase. Challenges, such as transitioning to a new CDE between design and construction, were encountered but led to the use of improved tools and methods for collecting reliable data. Data from the construction site was transferred through the CDE seamlessly and used to update BIM models monthly, integrating BIM into the construction phase, as shown by the generation of excavation models.

Large infrastructure projects particularly benefit from digital tools due to the complexity of managing vast amounts of data. However, successful implementation requires foresight, preparation, and strict adherence to protocols. Some challenges, like transferring all data to a facility management tool, remain unresolved, offering opportunities for future digital processes. This approach could be applied to similar tunnelling projects worldwide that have yet to embrace digitalization.

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Tunnelling into a Sustainable Future – Methods and Technologies – Johansson et al (Eds)

Transformative construction strategies for smart cavern

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ABSTRACT: The Relocation of Sha Tin Sewage Treatment Works to Caverns (STC) is a pioneering cavern project in Hong Kong, showcasing the use of rock caverns to unlock precious land in congested urban areas. The project faces challenges that must be overcome with positive thinking. STC is dedicated to developing and integrating various technologies to establish a model for a smart construction site. The objective of this paper is to outline our vision in establishing "STC Innovation Guidelines" for innovation development in the project to enhance productivity, efficiency and overall project success. This provides guidelines for site management staff to specify, manage, and assess innovative technologies for the project. The principle is that the design, implementation, management, and evaluation of innovative technologies require proactive engagement from the consultant, as they are uniquely positioned to discern the industry pain points that warrant transformation, along with the information technology professionals within technology companies.

1 INTRODUCTION

Hong Kong is equipped with rich experience in cavern development and there are various facilities accommodated inside caverns. However, cavern construction still faces some technical challenges (DEVB, 2023) The STC project represents a major advancement in urban development in Hong Kong, a city facing severe land constraints. By employing innovative cavern development techniques, it aims to unlock valuable land resources in congested areas to support sustainable urban planning. This initiative relocates sewage treatment works to underground caverns, freeing surface land for other uses and demonstrating how cavern development can alleviate land shortages. Large-scale projects like STC highlight the need for solutions that streamline operations and improve outcomes. Alkan and Basaga pointed out that the construction industry is a vital component of the global economy employing approximately 7% of the world's workforce, it is falling behind in terms of labour productivity (Alkan and Basaga, 2023). The importance of innovation is evident. By integrating advanced technologies such as real-time data analytics and automated inspection systems, the STC project directly addresses these challenges, fostering a more efficient construction process. This paper will explore the vision for the STC project, emphasizing the establishment of an "STC Innovation Guidelines" to guide the development and implementation of technologies that support the project's objectives and shape the future of urban development in Hong Kong.

2 PROJECT BACKGROUND

The existing Sewage Treatment Works is the largest secondary sewage treatment works in Hong Kong. It occupies significant area of land and serves a large segment of population in

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Hong Kong. Upon completion, not only will the land be released for other beneficial uses, the current issues relating to landscape, odour and aging facilities arising from the existing sewage treatment works will also be resolved. The future cavern complex for the relocated sewage treatment works will be the largest of its type ever built in Hong Kong and it needs to be implemented in stages. The overall dimension of the cavern is around 380m x 350m. The caverns consist of 7 and 4 numbers of parallel caverns aligned along its longitudinal and transverse axes respectively. The caverns have a generally consistent excavated span of around 28m to 32m, and the height of the caverns vary from 18m to 26m. Drill-and-Blast excavation method was adopted for the cavern construction. The general view of the project site is shown in Figure 1.

Figure 1. General view of the project site.

3 CHALLENGES IN UNDERGROUND CONSTRUCTION

The project team encounters significant challenges while navigating the complexities of a large-scale underground initiative. It is well known that cavern construction is considered the highest-risk endeavour due to factors such as confined spaces, round-the-clock operations involving against-gravity activities like shotcreting and rock bolt installation, and working at height, all taking place simultaneously. In addition to the on-site tasks, this project presents unique difficulties, particularly in managing its own Explosive Magazine Store (EMS) for the storage and delivery of explosives to the construction site. The team must implement an intricate system to oversee EMS operations. A primary challenge is the need for vigilant monitoring of explosive quantities to ensure that the EMS remains within its maximum storage limits, thereby reducing hazards and enhancing security. The administrative procedures for tracking the explosives quantities from blast design to explosives delivery is tedious as illustrated in Figure 2.

First the blast design must be finalized and endorsed at least two days prior to delivery according to the statutory requirement. The time allowed for checking the blast design is limited. Multiple blasts are often scheduled to occur on the same day for a large-scaled cavern excavation and the preliminary blast designs are typically completed only on the morning of the deadline day. In addition, it involves a considerable amount of work that requires meticulous attention to detail. Adjustment to the blast design due to cosmetic errors, sudden changes in geological features or unexpected irregularities in the as-built profile of the blast face are frequently happened. This can result in multiple versions that may become disorganized and lead to the use of outdated designs.

After that, the quantities of explosives specified in the design should be used to check against the EMS stock balance to ensure that the stored quantities are sufficient. If the stock is not enough, the blast may need to be rescheduled, or require replenishment of the EMS from the Mines Department. The interconnected nature of the information and documents challenges effective supervision.

The process is prone to human errors, particularly on one day prior to the delivery when the quantities of explosive listed on the explosive order form has to be input one by one manually into an electronic system for applying of permit for conveyance. The complexity is further heightened by the variety of explosives used, including cartridge explosives, detonating cords (5g/m and 40g/m), cast boosters, and detonators with a wide range of delay intervals. The presence of explosives from different brands adds another layer of complexity to the supervision process.

The project team endeavours to enhance workflow automation and improve data-sharing methods, ultimately streamlining operations and reinforcing safety measures in underground construction by adopting innovative technology.

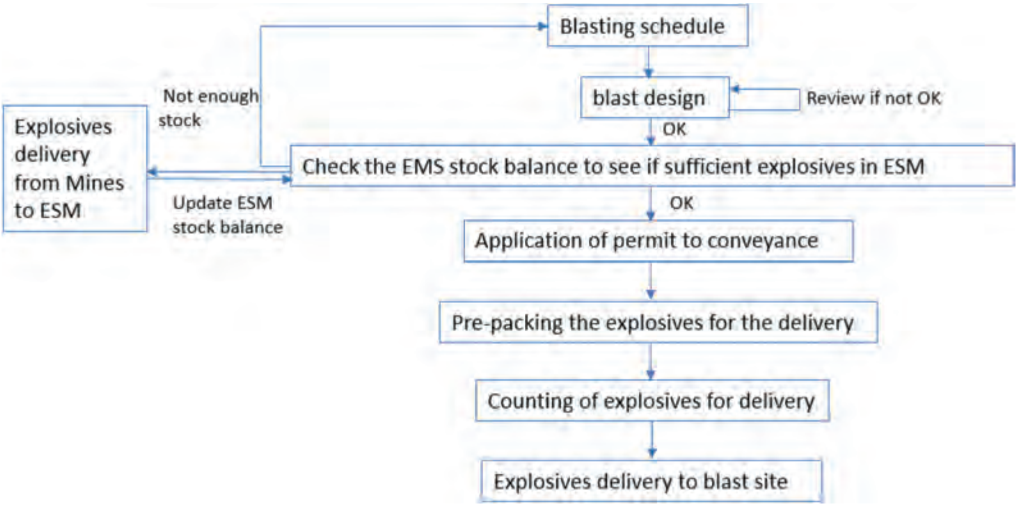


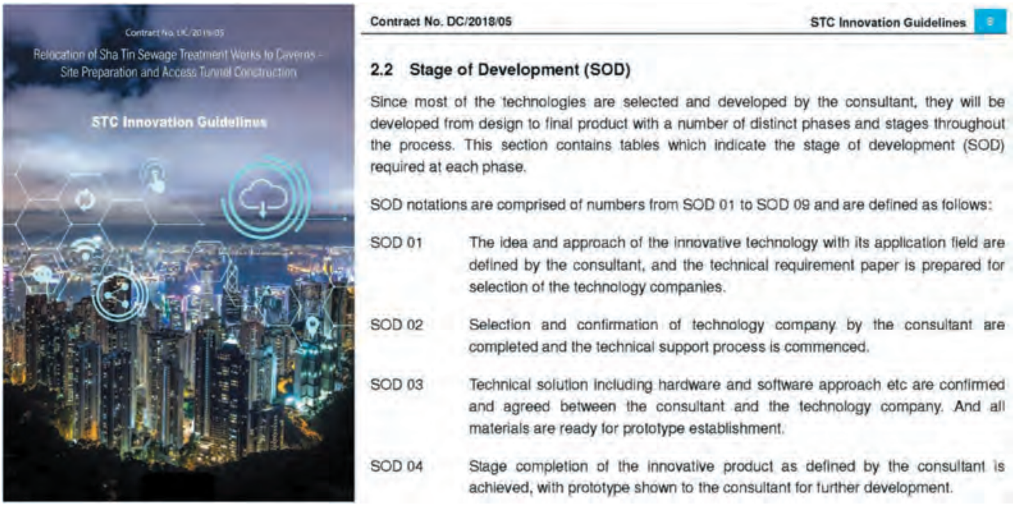
Figure 2. Administrative procedures for drill-and-blast operation at STC project.

4 INNOVATION GUIDELINES

The project team has established guidelines to assist site management staff, particularly consultants, in specifying, designing, implementing, managing, and assessing innovative technologies. These guidelines emphasize the critical role of consultant leadership, supported by technical expertise from technology companies and the active involvement of contractors and subcontractors. The Innovation Guidelines, as shown in Figure 3, serve as a comprehensive handbook, providing detailed advice on effectively integrating technologies into projects. They outline essential steps and considerations for adopting new solutions, ensuring that all site management personnel understand their roles and responsibilities. This framework aims to facilitate the successful incorporation of innovative practices, enhancing project outcomes and fostering collaboration among all stakeholders in the technology development process. The guiding principles emphasize that technologies should introduce new ideas or improve existing solutions, be original, have a positive impact, meet specific needs, and offer significant potential for future development.

5 STAGE OF DEVELOPMENT

“Rome was not built in a day” illustrates the complexity of technology development, where innovations progress through distinct phases, from concept to final product. This structured approach



Contract No. DC/2018/05 STC Innovation Guidelines

2.2 Stage of Development (SOD)

Since most of the technologies are selected and developed by the consultant, they will be developed from design to final product with a number of distinct phases and stages throughout the process. This section contains tables which indicate the stage of development (SOD) required at each phase.

SOD notations are comprised of numbers from SOD 01 to SOD 09 and are defined as follows:

SOD 01 The idea and approach of the innovative technology with its application field are defined by the consultant, and the technical requirement paper is prepared for selection of the technology companies.

SOD 02 Selection and confirmation of technology company by the consultant are completed and the technical support process is commenced.

SOD 03 Technical solution including hardware and software approach etc are confirmed and agreed between the consultant and the technology company. And all materials are ready for prototype establishment.

SOD 04 Stage completion of the innovative product as defined by the consultant is achieved, with prototype shown to the consultant for further development.

Figure 3. STC Innovation Guidelines.

facilitates thorough planning and iterative testing, gathering valuable feedback at each stage and enhancing collaboration among stakeholders to foster innovation and problem-solving. Initially, the consultant defines the innovative technology's idea and application, preparing a technical requirements document to select suitable technology companies. Once a company is chosen, the consultant collaborates on technical solutions for the prototype, which undergoes evaluation and refinement. The Minimum Viable Product (MVP) is developed, focusing on essential features for early adopters, and is tested through trials in both lab and on-site settings, with the consultant acting as an end user. This phase involves continuous feedback for ongoing enhancements. Once ready, the product is implemented on-site for regular use and data collection, allowing for the identification and correction of minor issues. Finally, the completed product undergoes testing and is aligned with all design requirements, while sustainable development, including a feasibility study for an upgraded version, ensures its long-term relevance and effectiveness.

6 OVERVIEW OF TECHNOLOGY INNOVATION IN THE PROJECT

6.1 *5G network and connectivity*

The idea of a site-specific 5G network was proposed by the consultant due to the critical need for reliable signal transfer. This transfer enables real-time progress reporting and updates, ensuring that all team members are informed of site developments. Effective signal transfer also facilitates immediate emergency contact and response, enhancing safety protocols in hazardous environments. In addition, robust signal transfer supports the integration of advanced technologies and remote monitoring systems, improving operational efficiency and oversight.

However, the development presents significant challenges. The site is located in an area where the commonly adopted 3.5GHz spectrum for 5G networks is reserved solely for aircraft satellite channels. Furthermore, dense rock formations create physical barriers that hinder wireless signal transfer between the inside and outside of the cavern. The complex layouts with narrow passages and varying elevations during excavation can further weaken signal transmission. It is crucial that base stations and antennas are installed in alignment with the excavation progress. If they are too far from the blast face, the signal may be insufficient, while being too close poses a risk of damage from blasting.

Consultants are uniquely positioned to estimate the data demands and understand the aforesaid specific challenges. Their expertise allows them to bridge the gap between cavern construction and technology. They engaged with various telecommunication companies to explore current capabilities and ultimately selected the most appropriate company. As a result, a unique 4.9GHz spectrum was established for a dedicated 5G network. By collaborating closely with telecommunication companies, the consultant team conducted trials and testing of the 5G network, providing feedback for stability tests and improvements before the network was ready for daily implementation. Their involvement extends beyond the implementation stage, as they will continue to work with the telecommunication company to enhance signal transmission.

5G network has high sustainability and provide large development space for many other technologies to be adopted inside caverns. One such innovation is the implementation of Measure-While-Drilling (MWD) technology. During blast hole drilling, errors can lead to deviations in burden, spacing, and alignment, especially for contour holes, resulting in excessive overbreak or underbreak and incurring significant costs. Leung and Ko (2022) suggested that current practices for quality supervision of blast hole drilling are not comprehensive enough and lack evolution with fast-developing tunnel technology in Hong Kong. Existing methods rely on brief visual inspections and manual depth measurements, limiting effective verification of blast holes. To address these limitations, the project team developed a systematic approach using MWD technology, which allows for real-time monitoring and analysis of the drilling process. Sensors on drilling jumbos, as shown in Figure 4, collect critical three-dimensional data on blast hole alignment, enabling immediate correction of deviations. MWD also provides insights into geological conditions ahead of the blast face, allowing for adjustments to the blast design for more efficient excavation. The success of MWD relies heavily on the support of a 5G network.

Figure 4. Drilling jumbos equipped with MWD sensors.

6.2 *Self-developed mobile apps*

The consultant has developed a suite of mobile applications designed to enhance the supervision of cavern excavation works. This integrated platform can be customized to meet unique project requirements and enables real-time data collection and analysis, facilitating informed decision-making on-site. Hypertext Preprocessor (PHP) and My Structured Query Language (MySQL) were adopted for the data input interface and database management, while Python was deployed for data analysis. These programming languages are recognized for their ease of use, making them accessible for engineers without extensive programming knowledge. By leveraging cloud technology, the applications ensure smooth data upload and retrieval, creating a common data environment for blasting operations. One of the applications, blasting cycle analysis, is illustrated in Figure 5.

The collection and analysis of data from these applications unlock tremendous potential for big data analytics. By utilizing advanced algorithms and machine learning techniques, this data can be harnessed to predict various engineering phenomena. Additionally, integrating this data lays the groundwork for developing digital twins, which are virtual replicas of real-world conditions and are anticipated in future phases. Ultimately, digital twins will enable engineers to simulate different scenarios and make informed decisions based on accurate and real-time insights.

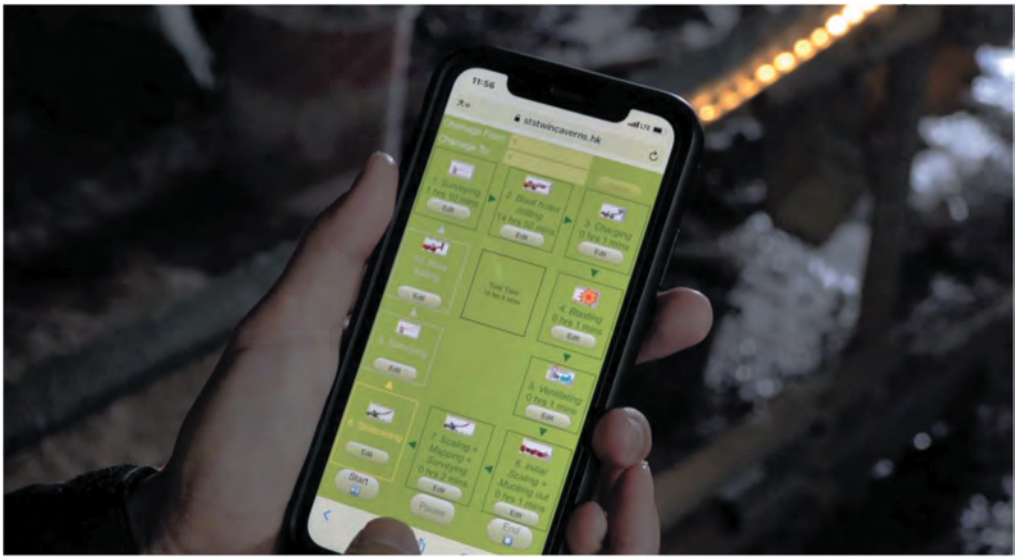


Figure 5. Self-developed mobile apps.

6.3 *Resident Site Robotics System (RSRS)*

The robotic monitoring system, as shown in Figure 6, was developed in-house by the project team and represents a pioneering solution for future cavern projects in Hong Kong (Huang 2021). The consultant began by identifying safety challenges in confined cavern environments, which are particularly pronounced after blasting operations. Registered shotfirers must inspect the blast face alone for any misfires, while the confined nature of caverns can trap toxic gases released during the blast. Additionally, explosions may damage rock formations, creating potential rockfalls. Insufficient lighting, combined with dust from the blast, further reduces visibility and increases the risk of falls. The presence of undetonated explosives also raises the possibility of accidental detonations, making the working environment highly risky.

To address these challenges, the team conducted market research and consulted with various technology companies to define specific features and specifications for a robotic solution. The RSRS is equipped with multiple air monitoring sensors for air quality assessment, minimizing the need for workers to enter hazardous areas immediately after blasting. It incorporates an unmanned navigation and mapping system (UNMS), allowing it to autonomously travel from the shelter to the blast face to perform its duties. Additionally, the RSRS can transmit and receive signals via a 5G network, enabling remote control from outside the cavern. It is designed to function effectively in low-visibility environments and on rapidly changing haul roads as excavation progresses, and it can operate on steep or uneven surfaces.

The consultant continued collaborating with the technology company to design the RSRS prototype. This prototype underwent rigorous evaluation to ensure it met operational standards. A series of controlled tests assessed its functionality under various conditions in the cavern, including low visibility and the presence of obstacles. The team focused on validating the effectiveness of the air monitoring sensors, ensuring they could accurately detect toxic gases and provide real-time data. The UNMS was also tested for its ability to navigate steep and uneven surfaces and respond to changing conditions within the cavern. The consultant's feedback during these tests was crucial, leading to further refinements of the RSRS. The team analysed data collected during testing to identify areas for improvement, making necessary adjustments to both hardware and software components. This iterative process ensured that the RSRS could operate safely and effectively in the challenging environment for which it was designed before full-scale implementation on site.

The development of the RSRS was not straightforward, even after its full-scale implementation on site. Several setbacks emerged that challenged the system's effectiveness. One major issue was the inconsistent network connectivity between the exterior and interior of the cavern, which hindered the performance of the UNMS. This inconsistency affected the RSRS's ability to receive commands and transmit data in real-time, compromising its operational reliability. Additionally, design flaws were identified in the mobilization system, which struggled to navigate steep and uneven muck piles. This limitation prevented the RSRS from effectively approaching the blast face, thereby reducing its operational scope. In response to these challenges, the project team embraced a philosophy of accepting failure as a norm. By fostering a no-blame culture, they encouraged everyone to contribute innovative ideas without the fear of negative feedback. This approach not only promoted creativity and collaboration but also enabled the team to learn from setbacks and continuously improve the RSRS, ensuring its long-term success in the field.

The RSRS comprises an unmanned robotic vehicle that serves as a multifunctional mobile platform to enhance site safety (HKIE 2022). In addition to remote air quality monitoring, several functionalities have been expanded to meet the growing demands of supervision as the project progresses. For instance, LiDAR cameras were integrated into the RSRS to capture point cloud data of rock faces, which can be used for mapping discontinuities and assessing rock wedge stability. An AI-powered camera system was also incorporated to recognize as-built permanent rock bolts, replacing the manual counting of bolts in dark, dusty, and high-risk environments. This integration significantly improves the efficiency of as-built record-keeping compared to manual methods.

Figure 6. RSRS for remote inspection under adverse working conditions.

7 CONCLUSION

Construction technology is reshaping the industry, with the STC project rapidly developing and implementing innovative solutions to streamline processes and boost productivity. However, many personnel remain in their comfort zones, relying on traditional design-build methods, leading to disjointed operations and stagnant productivity. Encouraging the project team to adopt innovative technologies is essential for fostering a culture of innovation. The Relocation of Sha Tin Sewage Treatment Works to Caverns (STC) project stands as a landmark initiative in Hong Kong's urban development, exemplifying how innovative construction strategies can address pressing land constraints in densely populated areas. By embracing advanced technologies and fostering a culture of collaboration and creativity, the project not only aims to enhance operational efficiency but also sets a precedent for future urban infrastructure projects. Through the establishment of the "STC Innovation Guidelines," the project team has laid down a framework that prioritizes the integration of cutting-edge technologies and innovative practices. This approach not only facilitates the effective management and implementation of these technologies but also ensures that they are tailored to meet the specific demands of the project. Leadership is crucial in this transformation, setting the tone for a no-blame culture that promotes idea sharing and collaboration. A well-defined innovation strategy clarifies expectations and encourages proactive contributions, while normalizing failure creates a safe space for experimentation. Management should actively support this willingness to experiment, providing resources and fostering an environment where new ideas can be tested. Open communication about innovation goals enhances engagement, and recognizing staff achievements boosts motivation. Ultimately, ensuring staff well-being is vital, as a secure environment encourages creative processes. More importantly, this transformation extends beyond mere technology. It requires a shift of mindset, a re-evaluation of industry norms, a re-conceptualisation of governance framework. As we move forward, the lessons learned from the STC project will be invaluable for future endeavours in cavern development and urban construction. By continuing to prioritize innovation, collaboration, and a proactive approach to problem-solving, we can pave the way for smarter, more sustainable urban environments that effectively meet the needs of growing populations. The journey towards transforming construction practices has only begun, and the STC project is poised to lead the way in shaping the future of urban infrastructure in Hong Kong and beyond.

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Tunnelling into a Sustainable Future – Methods and Technologies – Johansson et al (Eds)

A review of AI applications in caisson construction

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ABSTRACT: In this study, the origins and development of caissons are briefly reviewed, CiteSpace bibliometric software is used to summarize the traditional research focuses of open caissons, and the rise of artificial intelligence in the field is identified. Therefore, this paper reviews representative papers employing AI algorithms in caissons, including 30 journal articles published since 2014. Many scholars have conducted data-driven intelligent analyses based on various machine learning methods using numerous measured data such as inclination, stress, strain, soil settlement, etc., or combining the results of refined finite element model calculations aiming to sense the caisson states, provide feedbacks on construction risks, and provide scientific decisions. However, there are research shortcomings in the existing literature, such as high dependence on data and weak interpretability of models, which need to be addressed in the future to achieve more accurate, fast and efficient analysis and prediction of caissons.

Keywords: artificial intelligence, open caissons, suction caissons

1 INTRODUCTION

A caisson is a structure constructed at ground and then sunk to a predetermined elevation by removing soil from its interior, overcoming the frictional force of the wall to the soil and the resistance of subsoil. This process utilizes gravity and related sinking techniques. A caisson typically includes components such as the well wall, cutting edge, inner partition wall, well hole, recess, bottom plate, and top cover. Historically, caissons were first used in bridge engineering, with Swiss engineer Charles Labely perfecting the concept during the Thames Bridge Project in 1738. In the 19th century, caissons application expanded significantly, featuring in projects like the Eiffel Tower in France (1885), the main tower of the Tower Bridge in London (1890), and the Luanhe Bridge in Tianjin, China (1894). Because of the advantages of caissons, such as high structural strength and stiffness, high impermeability, good durability, minimal construction area, and large internal space (Esteban Lefler and Rey Romero, 2009), caissons have led to their widespread use. They serve as foundations of bridges, offshore wind power and other structures, or built into underground garages, pumping stations, or as working shafts in pipe jacking and shield tunneling projects.

However, as the volume of caissons grow and the construction environment becomes more complex, often leading to dangerous situations such as tilting, stalling, sudden sinking, and sand turning, these challenges really pose significant risks. Traditional calculation methods based on empirical formulas or simple soil models struggle to rapidly and accurately reflect the state of caissons. In contrast, artificial intelligence aids in quick analysis and intuitive prediction. Therefore, this study aims to summarize the research focuses on caissons and their digital intelligence advancements through a comprehensive literature review, providing a reference for future design and construction. Section 2 highlights caisson research using bibliometric analysis software. Section 3 summarizes the research focuses of caissons. Section 4 examines the application of artificial intelligence in two types of caissons. Finally, Section 5 reviews research progress and future trends in caissons, establishing a foundation for further study.

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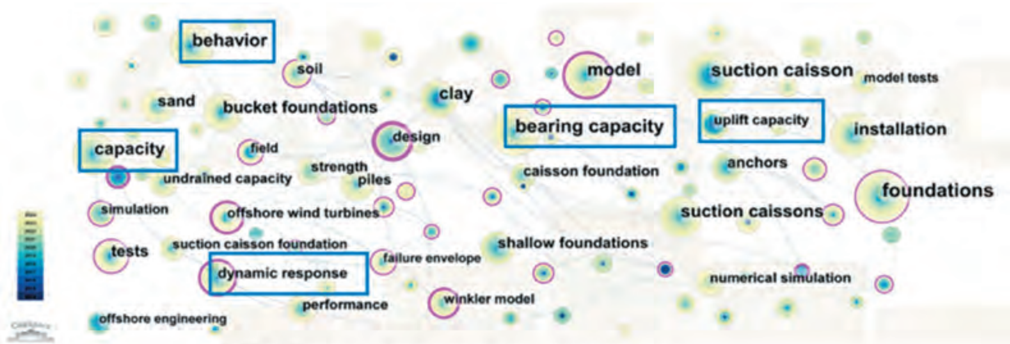
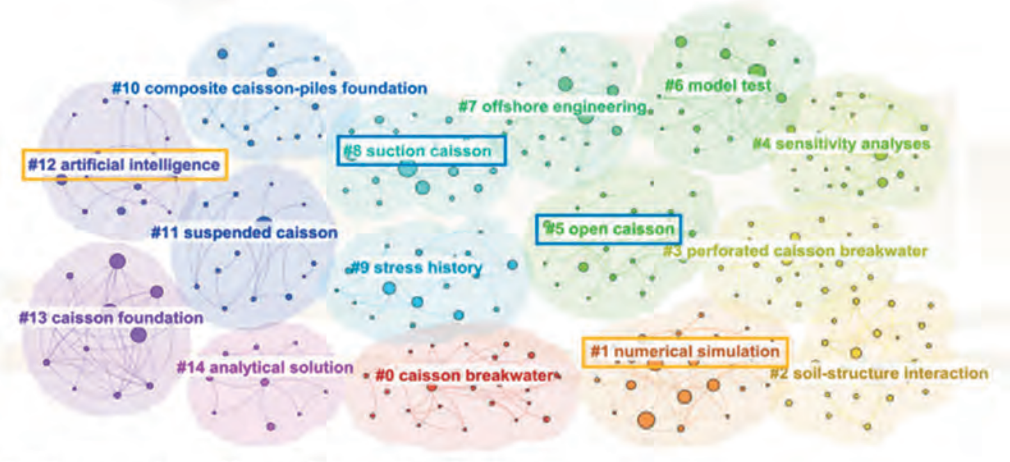
2 BIBLIOMETRIC ANALYSIS

In this section, a bibliographic analysis of papers on caissons was conducted using CiteSpace. The Web of Science Core Collection was selected as the database for this review.

To identify relevant studies, the search string "ti=(caisson)" was used, limiting the document type to articles and the time frame to 2014-2024, resulting in 484 publications. The visualization of the document keywords is shown in Figure 1. In Figure 1(a), the terms "behavior," "capacity," and "response" appear frequently, with "bearing capacity" mentioned 69 times, indicating that the focus of caisson research is on the response and subsidence of the surrounding soil. Figure 1(b) shows keyword clustering with two major types of caissons: "#5 open caisson" and "#8 suction caisson." The cluster "#12 artificial intelligence" also appears, highlighting the need to summarize findings and experiences regarding the use of artificial intelligence in caisson research to provide valuable insights.



(a) Co-occurrence analysis of keywords in articles related to caissons.



(b) Clusters analysis of keywords in articles related to caissons.

Figure 1. Keywords analysis of articles on caissons.

3 RESEARCH HOTSPOTS FOR CAISSONS

In this section, we briefly outline the primary research points concerning open caissons. Focusing on soil response around caissons, the research highlights the ultimate bearing capacity of soil and the soil's extrusion, damage, and deformation. Especially for vertically loaded small caissons, traditional bearing capacity formulas such as Terzaghi's formula (Terzaghi, 1943), Skempton's formula (Skempton, 1951), Meyerhof's formula (Meyerhof, 1951), and various normative formulas can be directly applied. There are also many scholars investigate soil damage modes during the sinking penetration of the edge footing and diaphragm wall of caissons. Some (Royston et al., 2016; Chavda et al., 2020) uses experiments to explore the effects of varying edge footing angles, external loads, and sinking depths on soil penetration response and flow mechanisms. Some (Lai et al., 2020) apply the Coupled Eulerian-Lagrangian method, which considers the coupling of penetration and excavation, to simulate the actual caisson sinking process.

From the perspective of caisson structure, studies on open caissons examines both the forces involved in caisson sinking and its sinking state. The forces affecting caisson sinking include self-weight (G), construction load (F_c), and sinking resistance includes water buoyancy (F_W), edge foot resistance (F_R), sidewall friction (F_S), and horizontal earth pressure on the walls (F_N) (Allenby et al., 2009), and scholars have mostly focused on the mechanism of the latter three. The sinking state of a caisson includes the sinking attitude and sinking capacity, determining whether it can overcome resistance to continue sinking. The control parameters of its attitude typically include the height difference of four corners, center deviation, plane torsion, deflection of the bottom surface, and deviation between the top and bottom surfaces. Caisson sinking speed visually represents sinking capacity. Abnormal sinking behavior, such as sudden or stalled sinking, can be used to assess the sinking coefficient (K), which reflects the relationship between caisson sinking force and resistance.

In conclusion, the construction of caissons is fraught with challenges due to the nonlinearity, heterogeneity, and uncertainty of the underlying soil layer, which complicates the prediction of soil bearing capacity and friction force. Additionally, the difficulty in controlling the sinking attitude and velocity hinders the smooth descent of caissons (Wang et al., 2022). Numerous scholars have conducted in-depth explorations of these pivotal issues through various approaches including theoretical calculations, on-site monitoring, laboratory experiments, and numerical simulations. However, as the construction of caissons evolves towards larger sizes, greater depths, reduced costs, and enhanced reliability, the demands for precise construction control have intensified. Consequently, it is important to accurately and timely predict the structural performance of the caissons and the reactions of the surrounding soil. Therefore, there is a pressing need for more efficient, rapid, and precise methodologies to facilitate the fine-tuning and optimization of caisson construction processes.

4 RESEARCH PROGRESS OF INTELLIGENT METHODS IN CAISSONS

4.1 *Research progress of intelligent methods in open caissons*

The application of artificial intelligence (AI) in open caisson construction primarily addresses the sinking state and structural response of caissons. This includes controlling the sinking attitude and assessing sinking capacity. Utilizing the structural stress and attitude monitoring data from the Changtai Yangtze River Bridge Project, (Dong et al., 2023a) evaluated 12 different machine learning algorithms. These encompass conventional methods such as Linear Regression (LR) and Elastic Net Regression (ENR), as well as ensemble learning techniques like Random Forest (RF) and Light Gradient Boosting Machine (LightGBM). For predicting caisson inclination, the most effective models were those based on Extremely Randomized Trees (ERT) and k-Nearest Neighbors (KNN). The sinking capacity can be simply understood as the sinking rate, while abnormal sinking rate, such as stagnation or sudden drops, can lead to risks like tilting, sand overturning, and structural damage. Therefore, Dong et al. employed various AI methods to forecast the sinking rate of open caissons using data from the same project, thereby mitigating potential construction hazards. (Dong et al., 2022a) used a Convolutional Neural Network (CNN) to predict the earth excavation subsidence index (SEI) time series. This approach offered a data-driven, active control method for caisson subsidence, ensuring caisson stability and construction safety by considering the relationship between subsidence rate and earth excavation volume. Furthermore, (Dong et al., 2022b) utilized a 3D-CNN model to predict the sinking rate by extracting the spatio-temporal features of the multi-structural stress data, and also analyzed the prediction accuracy with different step length. (Dong et al., 2023b) proposed a caisson sinking velocity prediction model based on the Gradient Boosting Decision Tree (GBDT). This model extracts features from structural stress monitoring data on the diaphragm wall and edge footing, successfully predicting caisson sinking speed and providing guidance for earth excavation planning.

Not many studies have been conducted on the mechanical response of open caisson structures. (Huang et al., 2022) utilized caisson subsidence and earth pressure data for the time periods of July 29, 2020 at 10:00 and August 7, 2020 at 23:00 and compared the predictive efficacy of four models, namely, the Improved Classified Regression Tree (CART), Multilayer Perceptron (MLP), Long-Short-Term Memory (LSTM), and Linear Regression, for forecasting footing earth pressure. (Dong et al., 2023c) successfully identified the optimal sensor layout by focusing on the variation in information gain across different sinking states and structural stress sensor locations. (Bolourani et al., 2021) used Principal Component Analysis (PCA) and Support Vector Machine (SVM) to reduce dimension and classify the damage-sensitive features associated with caisson structures. Based on these analyses, a Structural Health Monitoring (SHM) system was developed to effectively detect damages in harbor caissons.

In addition to research closely related to caisson structures itself, other scholars have directed their attention to the settlement of the surrounding ground and the optimization of excavation schemes. (Song et al., 2024) concentrated on predicting the shapes and sizes of both surface and subsurface caissons, discovering that the Empiricism-Constrained Neural Network (ECNN) has higher prediction accuracy compared with traditional empirical formulas. (Tian et al., 2024) aimed to develop a predictive model for caisson excavation commands. Through a comparative analysis of various methods, such as Multilayer Perceptron, Classifier Chain, and Multi-Labeled K-Nearest Neighbor (MLKNN), it was found that the improved MLKNN model demonstrated greater predictive accuracy. The successful application of this model could compensate for the existing monitoring system's data-mining deficiencies and mitigate construction risks.

In the domain of open caisson construction, the deployment of AI technology is notably broad, covering research challenges related to caisson sinking attitude, sinking capacity, soil response, excavation planning and other complex aspects, but still not deep enough. Table 1 exemplifies some of the AI-based studies in this field, highlighting the utilization of diverse models. It is evident that the structural geometry of the caisson, soil material parameters, state variables such as sinking rate and depth, and stress data in key areas like the foot of caisson and the diaphragm wall are essential input parameters for the majority of open caisson prediction models. The primary output parameters include footing soil pressure, open caisson subsidence rate, and soil settlement. A literature review indicates that many studies still rely on large samples to develop machine learning models.

4.2 *Research progress of intelligent methods in suction caissons*

However, statistical analysis reveals a higher concentration of AI technology applications in the domain of suction caissons, or suction anchor, a structure used for subsea anchoring. In offshore platforms, suction caissons are integral to the foundation system, and their failure may lead to catastrophic system failure. Thus, predicting the uplift capacity of the suction caissons accurately is critical for platform stability (Fattahi and Zandy Ilghani, 2023). Earlier, (Rahman et al., 2001) compiled a comprehensive database of experiments, comprising 60 individual tests from 12 independent published studies, training ANNs to predict the uplift capacity of suction caissons in clay. Based on the database summarized by Rahman, numerous scholars have employed different models and a number of controllable parameters to develop the optimal prediction model for the uplift capacity of caissons, as detailed in Table 2. (Luan et al., 2024) developed a sophisticated deep learning model for forecasting uplift capacity of suction caisson, using an extensive database from 65 published papers (comprising up to 1813 data items). This neural network model accounts for key factors such as soil properties, suction caisson parameters and loading conditions on the uplift capacity to accurately interpret the effective unit weight (γ'), shear strength (s_u), permeability coefficient (k), aspect ratio (L/d), caisson-soil interface friction coefficient (α), angle of internal friction (φ), and loading angle

Table 1. A recent 5-year literature review of the papers on artificial intelligence in the field of open caissons.

Study	Data source	Best models	Input variables	Output variables
(Bolourani et al., 2021)	A harbor caisson set in a stilling basin	Non-linear SVM algorithm with gaussian function	Natural frequency; mode shapes; modal assurance criterion; AR coefficients	The damage-sensitive features in both frequency and time domains
(Huang et al., 2022)	The Changtai Yangtze River Bridge Project	An improved classification and regression tree (CART)	Sinking amount data	Foot blades soil pressure values
(Dong et al., 2022b)	The Changtai Yangtze River Bridge Project	3D-CNN	Structural stress increment	Sinking speed
(Dong et al., 2023b)	The Changtai Yangtze River Bridge Project	Gradient boosting decision tree (GBDT)	23 structural stress monitoring values at a certain moment	Sinking speed of the open caisson at the next moment
(Song et al., 2024)	Physical modelling of caisson	Empiricism-constrained neural network (ECNN)	Soil depths along the caisson (z/H); caisson depths (H/D); radial distance (r)	Settlements
(Tian et al., 2024)	The Changtai Yangtze River Bridge Project	Improved multilabel K-nearest neighbor model (MLKNN)	Stress data from the foot blade soil pressure	The scheme for caisson excavation

(θ), among other parameters. Additionally, there are also studies likes (Lai et al., 2023) that commonly use their own numerical simulation calculations as the data source, employing artificial neural networks as a data-driven technique.

In addition to the investigation of uplift bearing capacity, researchers have also concentrated on other nonlinear load responses of caissons. (Lai et al., 2024) used an Artificial Neural Network (ANN) model to develop a prediction model for seismic bearing capacity. They analyzed the influence of various parameters on the potential failure mechanism by examining the relationship between the adhesion factor (α), anisotropic strength ratio (r_e), horizontal seismic coefficient (k_h), and other parameters with the seismic load carrying capacity coefficient. (Yin et al., 2023) concentrated on suction caisson foundations installed in clay seabed, aiming to predicte the mechanical response of suction caissons in clay. To this end, the authors evaluated three typical Deep Neural Networks (DNNs), namely Fully-Connected (FC) Neural Network, Convolutional Neural Network (CNN) and Long Short-Term Memory (LSTM). Ultimately, the FC network emerged as the most suitable for their case study model. Furthermore, the structural characteristics of suction caissons are also a significant research focus. (Suryasentana et al., 2024) utilized a Multi-fidelity Data Fusion approach (MFDF) to rapidly approximate the Finite Element Analysis (FEA) results. They assessed two Gaussian Process-based MFDF models, LARGP and NARGP, and concluded that LARGP more accurately estimates the layered static stiffness of suction caisson foundations under various soil conditions.

While the majority of literature pertains to AI algorithms addressing the mechanical response of caisson structures, there has been an notable increase in recent studies concerning the soil around caissons. (Wu et al., 2022) employed a Genetic Algorithm Backpropagation (GA-BP) neural network to forcast the mechanical behavior of the soil around a caisson, considering the nonlinear interactions between settlement, penetration pressure, effective stress, and required suction during construction. (Farahani and Barari, 2023) focused on developing a predictive model for suction caisson foundations for offshore wind turbine (OWT). They utilized the Group Method of Data Handling (GMDH) approach to estimate liquefaction-induced caisson settlement and examined the interaction between foundation soil, caisson structure and seismic loads. Similarly, (Moghaddam et al., 2023) also applied GMDH to estimate the settlement of suction caissons, with a focus on the impact of wave cyclic loading on seabed liquefaction and settlement. It is noteworthy that a few scholars have also focused on the inversion of soil mechanical parameters. (Li et al., 2023) utilized a Back-Propagating Artificial Neural Network (BP