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Using mature and proven technology for mechanized excavation of tunnels and shafts for hydropower schemes to provide sustainable clean energy

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ABSTRACT: As countries plan for their net zero targets, substantially more long-duration energy storage will be needed to support the integration of intermittent renewable energy sources such as wind or solar. Various storage technologies exist or are being developed, and of particular importance is pumped storage hydropower (PSH), a well-established technology that already provides around 90% of installed electricity storage globally. Hydropower and Pumped Storage Hydropower schemes have a network of tunnels, including pressure tunnels and pressure shafts. This paper focuses on the latest state of mechanized tunnelling technology used to advance the construction of these projects, thereby supporting the clean energy transition.

1 INTRODUCTION

The need for sustainable development and an actionable pathway towards net zero emission are two of the greatest challenges of our time. They are also interlinked; sustainable growth is only truly achievable if it is coupled with a massive upscaling of renewable energy development. As a mature technology, hydropower has played a vital role in enabling the industrial growth of the past, and its unique qualities are highly translatable to the pressing issues of today, such as the need to decarbonize industry and manage our water resources effectively.

Worldwide, there is enormous potential of making use of this technology, which requires the construction of new tunnels and shafts for renewing and upgrading the capacity of existing storage power plants. Environmentally compatible concepts and further development of excavation methods will be important for the economic success of such schemes, quite apart from the development of the worldwide energy market.

Hydropower schemes use the difference in height between the water source at the upper dam source and the turbine to generate electricity as the water flows down under gravity; the greater the height difference, the more power can be generated.

Pumped storage hydropower schemes generate electricity in the same way, but at times of low electrical demand, the excess power available in the grid is used to pump water up to the higher reservoir dam, thus storing power as potential energy. Then, at times of high demand, water can be released back to the lower reservoir through the turbine to generate electricity. Pumped storage hydropower schemes provide almost 90% of the world's energy storage.

Hydropower schemes and pumped storage power plants have a network of tunnels, such as water transfer tunnels, pressure tunnels, pressure shafts, and tailrace tunnels. Conveyance tunnels may be used to transfer additional water to the dams from other catchment areas. The water is then fed from the dam to the hydropower plant through pressure tunnels and pressure shafts. These pressure tunnels may be steeply inclined. After passing through the turbines, the water flows out through tailrace tunnels back to the river or into the lower storage reservoir of the PSH.

Mechanized tunnelling technology plays a vital role in hydropower construction. Tunnel boring machines are used to construct steep pressure tunnels and raise-bore technology supports the efficient production of vertical shafts. The design of vertical pressure shafts in the waterway systems of pumped storage systems is quite common. The paper highlights the state-of-the-art mechanized technology for tunnel and shaft construction. Applying reused or remanufactured mechanized tunnelling equipment and components can help to reduce the scheme's carbon footprint and improve sustainability performance.

2 MATURE AND PROVEN MECHANIZED TECHNOLOGY FOR TUNNEL AND SHAFT CONSTRUCTION

Hydropower or pumped storage plants are typically located in remote, mountainous, or environmentally sensitive areas.

The majority of the underground hydropower projects are built in rock formations that are suitable for nearly all kinds of mechanized rock excavation technologies. These remote locations present particularly challenging access to the construction sites for assembly and disassembly of TBM excavation equipment and the supply transport logistics.

Hydropower schemes require the excavation of diverse tunnel networks, including inclined tunnels or vertical shafts for access, water transfer and power cables. The latter are typically constructed using raise-bore technology for the efficient production of vertical pressure shafts. If the shaft can be set deeply enough in the rock, thus safeguarding it against hydraulic rock rupture, there is no need for a steel lining in the case of slightly permeable rock formations. This extremely economic concept has already been applied in many hydropower plants.

2.1 *Mechanized technology for tunnel construction*

In recent years, there has been an increased use of TBM technology for the construction of inclined pressure shafts with steep inclines of up to 90%. This paper will highlight some of these lighthouse projects.

For the construction of horizontal or slightly inclined or declined alignments with gradients up to 5% for water transfer, conveyance, headrace, or tailrace tunnels, standard, or close to standard Hard Rock TBMs, such as Gripper or Shielded TBMs, can be applied.

Alignment gradients between 5% and 15% demand adaptations to the TBM handling and supply systems, such as material handling, cranes, and mucking logistics. For declines, special requirements for dewatering must be taken into consideration.

Gradients in the range of 15% and 25% demand a specific TBM and back-up design based on the individual project conditions. These slopes affect not only the material handling and tunnel supply systems but also basic TBM excavation and primary mucking functions, cutter change procedures, maintenance work, the design of working platforms, walkways, segment handling, and process technology such as electrical equipment, hydraulics, lubrication, grout injection and dewatering, to just to name a few.

The steep gradient impacts diverse design aspects and requires a high development effort, both in the design and static calculation of the back-up steel structure and related towing connections.

With tunnel inclinations ≥ 25% the EN16191 demands a safety factor of three for towing connections and, also a redundant secondary towing system in case the back-up systems could move independently due to gravitational force in the event of failure of one towing connection. It also requires the monitoring of the loads carried by the towing connection between the TBM and back-up system.

2.2 *Mechanized technologies for vertical shaft construction*

Some Pumped Hydro Storage (PHS) projects are designed with vertical pressure shafts to carry the water from the dam to the hydropower plant. This involves different mechanized construction technologies for vertical shaft construction.

Typical pressure shafts can be of great depth, up to a couple of hundred meters. These shafts are typically constructed using either conventional drill & blast shaft sinking technology with shaft drilling jumbos or combined technologies using raise bore technology. The type of technology used depends on the project conditions or construction sequence. For example, using combined technologies, a vertical shaft is drilled using a raise bore rig, followed by a drilling jumbo to enlarge the raise bore shaft down from the top.

The following chapter will introduce lighthouse projects of pumped storage hydro schemes and applied mechanized construction technology that had to deal with challenges in remote areas and challenging geological conditions.

3 CASE HISTORIES OF INCLINED AND VERTICAL PRESSURE SHAFT CONSTRUCTION USING MECHANIZED TECHNOLOGY SOLUTIONS

This chapter briefly highlights the challenging hydropower projects in terms of their complexity and technical challenges.

3.1 *Pump storage plant Ritom, Switzerland – Tunnel construction under extreme conditions*

The Swiss Federal Railways (German: Schweizerische Bundesbahnen, SBB) SBB Ritom hydroelectric power station in Ticino, built in 1920, is being renovated and expanded to improve the electricity supply for the Gotthard railway line, with its performance being quadrupled. The project is unique due to the geological challenges, including local porous rock layers that are in parts water-bearing and steep gradients of up to 42°, corresponding to an extreme 90% gradient.

The focus in the PSP Ritom project is on the construction of the extremely steep section of the pressure shaft. The construction of the pressure shaft comprised three sections, of which two were constructed using Drill & Blast (D&B) technology. The D&B method was used for the 150m long upper section of the pressure shaft and the 650m long lower section, both being horizontal sections. The main section of the pressure shaft is 1,500m long with an extremely challenging 90% gradient. This inclined shaft was excavated using a specially designed 3.2m diameter Gripper TBM.

Preliminary ground investigations included the drilling of three boreholes along the proposed route of the pressure shaft. The information obtained from the ground investigation program indicated treacherous rock conditions along the lower tunnel section, with porous, permeable, and in parts water-bearing rock layers. The decision was taken to extend this D&B section until good rock conditions were reached so that the inclined shaft section to the upper lake could start in good rock conditions. The shaft had a diameter of 3.20 meters and was excavated by the contractor Marti using a Herrenknecht Shielded Gripper TBM that was specially adapted to the predicted and challenging project conditions with difficult rock and extreme gradient of 90%.

The TBM was launched from a cavern about 650 meters deep in the rock. The 100m long TBM was transported to the cavern on trucks in six sections as shown in the following figure.

Figure 1. Special transport of the TBM Ø3.2m by truck into the shaft base cavern.

The TBM was assembled in the 80m long cavern on a launch ramp having an initial gradient of 26°. During assembly, the TBM was pushed up the launch ramp, and tunnelling could start with a partial installation of the TBM. Temporary arrangements were necessary for muck removal and material supply for the first few meters of the tunnel until the entire TBM was assembled. The regular advance began when the entire TBM was in the rock. The excavated rock was transported to the starting cavern at the bottom of the inclined shaft by a material channel in the invert. The material slid independently down the inclined shaft with water added to assist the flow. After a 900m long climb at 23° and crossing beneath the River Foss, the TBM then continued its drive for the next 633m with an extreme inclination of 42° corresponding to a 90% gradient. The 100m long and 290-ton machine was reliably prevented from slipping back by the grippers and by means of a specially designed and proven toggle lever device in the safety recoil unit, guaranteeing that the TBM remained securely gripped against the rock at all times. It was decided that, for redundancy and additional safety reasons, a second gripper unit with mechanical clamping function should be implemented. This arrangement always guaranteed that during the excavation cycle, two grippers were braced and at least one gripper with a mechanical self-clamping function was braced.

TBM supply and personnel transport from the starting cavern was managed via a funicular. Supplies were taken to the TBM supply on a just-in-time basis due to the limited storage space available on the 3.2m diameter TBM.

During the construction of the inclined shaft, pipes for cooling water and compressed air were fixed on one side of the tunnel wall, and fresh air and power supply on the opposite tunnel wall. The cable of the funicular was also running on the same side.

The 3.2m diameter TBM was designed with fresh air supply pipes and the slide channels for transportation of the excavated material to the shaft bottom, which were installed underneath the machine. To protect the subsequent work, the tunnel crown was secured with rock bolts and steel mesh, with a specially adapted rock bolting unit directly installed between the front shield and the gripper shield.

The supporting structure and the stairs for the TBM crew were mounted above the muck transport channel in the invert. A material-carrying cableway was installed along all the back-up trailers, and the route had to be kept clear along the entire trailers. Back-up number 1 was located directly behind the safety recoil system and carried an 11KW drill rig and a dust lock for a shotcrete chamber that allowed manual shotcrete application. The air dedusting system and a shotcrete pump were arranged on back-up number 2. The operator's cabin and the hydraulic power pack with oil tanks were positioned on trailer 3. The other trailers carried transformers, control cabinets and electronics, hose reels for water and compressed air supply, water pumps, fresh air supply and the tunnel funicular station. Periodic track extensions for the funicular and the invert mucking channel were done through mounting holes on trailer 6.

The Ritom TBM was launched at the beginning of 2021 and finished its 1.5km long steep inclined section toward the end of February 2022, having successfully climbed 800 meters in altitude. The focus on safety was of utmost importance throughout the entire construction period and of its project layout.

3.2 *Limberg III pumped storage plant, Austria – Steep TBM challenge*

The Limberg III project is a 480MW pumped storage power project located in Salzburg, Austria. The project will contribute to Austria's goal of covering one hundred percent of its energy needs from renewable sources by 2030. The main challenge in this project was the excavation of the 770m long pressure shaft at a gradient of 42°. The 5.8m diameter Gripper TBM was designed specifically to work at the gradient of 42° with the highest safety standards during construction. The 770m long inclined tunnel is split into a section of 580m for the pressure shaft and a further 190m long section connecting to the surge tank.

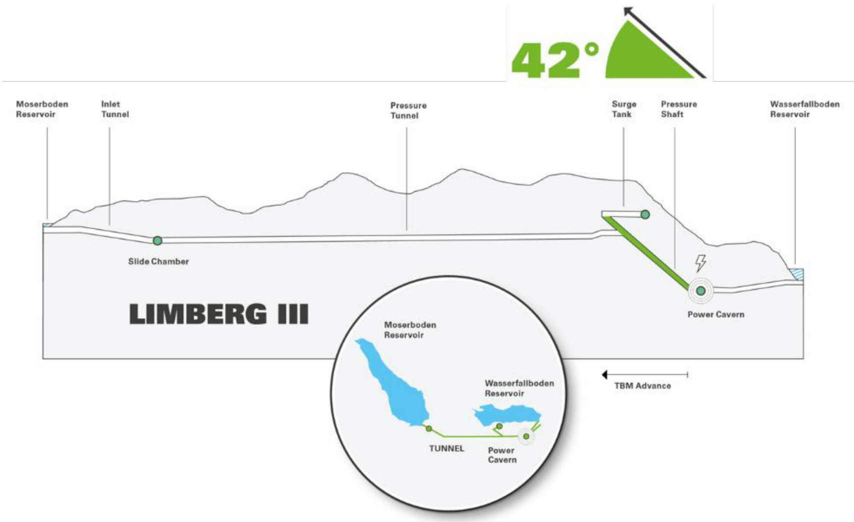

Figure 2. Overview of 770m-long TBM excavated pressure shaft (gradient 42°) at Limberg III.

Predominant rock types are calcareous slates with unconfined compressive rock strengths of 80 to 100MPa and quartz contents of 20 to 30%. The cutterhead was dressed with 17-inch back-loading disc cutters (25x single discs, 4x double discs). Due to the abrasive nature of the rock, the cutterhead was designed with wear protection composed of grillbars, protection wedges and Hardox plates in the face and gauge area of the cutterhead.

The TBM design included three clamping systems that ensured that the machine was always braced on two levels and in all operating conditions, preventing the Gripper TBM from slipping back on this 42° gradient. The first clamping level is the gripper bracing directly behind the cutterhead, followed by a double anti-reverse lock. The anti-reverse locks work mechanically on the principle of a self-locking toggle lever (automatic mechanical wedging), ensuring reliable bracing of the machine against the rock even in the event of a power failure or failure of hydraulic systems.

This double anti-reverse lock was located on the first back-up and had a full backup redundancy of the available bracing levels for the 1,000-ton TBM. It works in the way that while the first anti-reverse lock is rigidly connected to the back-up, the second anti-reverse lock moves along with the TBM advancement in an automated, hydraulic manner so that the back-up moves consistently with the TBM. This results in an operating cycle of TBM advancement, standstill, and re-gripping processes. In all these operating conditions, at least one anti-reverse lock is always securely clamped against the rock. Thus, at least two of three locking systems are independently and safely braced against the rock. This significantly increases the safety for personnel, the machine, and its structure in all operating stages.

For about 85% of the pressure shaft, the rock conditions required support consisting of three anchors at 3m ccs installed on the L1 area immediately behind the TBM and a 50mm shotcrete support in the L2 back-up area. The TBM was designed with two drill rigs that enabled the installation of rock anchors in the L1 area with a 3m anchor length (extendable to 4m) over the upper 180 degrees of the tunnel.

The excavated rock was collected by the cutterhead buckets and the rock chips were transported through an opening in the bottom of the cutterhead to a muck chute and channeled down to an intermediate storage in the starter cavern. The consumable supplies were transported to the TBM by an overhead monorail. The TBM back-up had intermediate storage locations for consumables, auxiliary, and operating materials.

The TBM was designed and manufactured by Herrenknecht AG in Germany. The assembly of the TBM on site in Kaprun was achieved within two months in a 45m long assembly cavern that was 14m wide and 11.5m high. The assembly started in a horizontal position and during assembly, the TBM was repeatedly moved forward through the starter cavern on steel beams by a pushing system. At the end of the horizontal section, a 40m ramp was built with a vertical radius of 50m through which the TBM was pushed into a profiled 22m long starting tunnel that had a diameter of 5.93m. Launching of the TBM took place with the grippers braced in the profiled starting tunnel and the anti-reverse locks still outside the starting tunnel. The gantries were then pushed into the starting position using the cylinders of the back-up displacement system and an external power pack.

Figure 3. 5.8m diameter Gripper TBM assembled in horizontal position shortly before 50m vertical curve radius.

The Gripper TBM successfully excavated the pressure shaft between May 2022 and October 2022 to help support an essential power bank for a safe, clean, and affordable supply of electricity in Austria.

3.3 *Búrfell Extension hydropower plant in Iceland – Shaft construction using raise boring technology*

The existing Búrfell hydropower plant (270 MW) has an installed capacity of 2,300 GWh per year. The project is located in the south of Iceland, about 130km east of Reykjavik, and has been operating continuously since 1969. A new unit, the Búrfell Extension project, was built to increase the total capacity of the combined Búrfell hydropower stations by 300 GWh per year. This new HPP Búrfell Extension project is located about 2km away from the HPP Búrfell at the foot of the Sámsstaðaklif depression and is one of the main power suppliers for Reykjavik. The nearest port is located some 100km from the site, and the roads leading to the site are part of a well-constructed road network. The area surrounding the site is uninhabited except for the operational personnel at the existing Búrfell Station.

The main structures of this expansion project comprised the construction of a cavern for the powerhouse with an excavation volume of 35,000m^3, various hydro and access tunnels and two vertical shafts with diameters of 4.5m and 6.2m that were constructed using a Herrenknecht VF 400 raise bore rig.

Figure 4. Pressure shaft (steel lined) at Búrfell III excavated by raise bore technology.


Figure 5. Herrenknecht VF 400 raise bore rig in use for the Búrfell II shafts.

All underground structures were constructed using drill & blast, except for the 4.5m diameter cable shaft and the 6.2m diameter pressure shafts that were excavated by raise boring technology.

Marti Tunnel AG executed the access and tailrace tunnels and powerhouse construction and also the raise boring and shaft construction works for the 108.5m deep cable shaft and 96.5m deep pressure shaft in 2017. The main geological structures in the project area consist of basalt with intersections of sedimentary layers. The 96.5m deep vertical pressure shaft was lined with a 5.2m diameter embedded steel liner. It connects the power intake with the turbine unit located in the underground powerhouse cavern. The Medium Voltage (MV) cables are installed in a vertical cable shaft leading to the Transformer building located on the top of the Sámsstaðaklif depression.

The VF 400 raise bore rig, which excavated the 4.5m diameter cable shaft, operated at rates of up to 21.2m per day for the pilot drill between September 3 and 9, 2016.

Figure 6. Herrenknecht VF 400 raise bore rig reamer head used for the cable shaft.

Shaft reaming was completed between October 6 and 18, 2016 at reaming rates of up to 15.9m per day.

The 6.2m diameter pressure shaft pilot was drilled between November 1 and 3, 2016 at rates of up to 44.7m per day and reaming was completed between November 7 and 22, 2016 at rates of up to 10.3m per day. The boreability of the rock was easier than expected and wear and tear was also kept to a minimum.

The raise bores used the Rotary Vertical Drilling System (RVDS) to support reliability and accuracy in drilling.

4 CONCLUSION

The selected hydropower projects are all resilient projects where mechanized tunnelling technology using TBMs and raise bore technology were applied. The highlighted tunnelling technology contributed to renewing and upgrading the capacity of existing storage power plants and thus supporting the supply of sustainable energy generation and storage with a reduced carbon footprint. Financing institutions are already seeking to address climate-related risk by ensuring that projects are planned and operated to be resilient to climate change. The aim is to construct projects safely and reliably to ensure grid stability so that that they can incentivize policy and investment.

5 REFERENCES

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