A Clean Solution for Renewable Energy: Small Diameter Hydro Tunneling

S. Log[1]
[1]*Product Manager - Cutters, Robbins, Trondheim, Norway*
E-mail: logsindre@robbinstbm.com

ABSTRACT: Small hydroelectric power projects, with installed capacity up to 10 MW, are a relatively untapped but potentially game-changing source of renewable energy worldwide. In Norway, hydro projects are pioneering the use of small diameter TBMs in hard rock. Compared with drill and blast, TBMs offer increased production rates and reduction in cross section, as well as lowered rock support requirements and reduced project schedules.

The uniquely designed machines are engineered to take on steep gradients, up to a 45-degree angle in some cases. Both shielded and open-type TBM designs have been developed that utilize safety grippers and customized mucking systems to operate at steep grades. This paper will discuss the specialized TBMs and their performance at several projects in Norway, as well as the potential to use this technology throughout Europe and internationally.

KEYWORDS: Tunnelling, Hydropower, Small Diameter Tunnel Boring Machines (TBMs)

1. INTRODUCTION

Small hydroelectric projects, with installed capacity up to 10 MW, are a potentially game-changing source of renewable energy across Europe. In Norway specifically, hydro projects are pioneering the use of small diameter Tunnel Boring Machines (TBMs) in hard rock. Compared with drill and blast (D&B), TBMs offer increased production rates and reduction in cross section, among other benefits. The uniquely designed machines are engineered to take on steep gradients, up to a 45-degree angle in some cases. This paper will discuss the specialized TBMs at several projects in Norway, and the potential to use this technology throughout Europe.

2. BACKGROUND

Norway's history of hydropower is a long one. Most power plants in Norway were built before 1990 and more than 200 km of associated tunnels were excavated by TBMs from the late 1960s to the early 1990s, in what was Norway's biggest hydropower era. With a yearly production of 135 terawatt hours (TWh), distributed across more than 1,600 hydroelectric power plants, the production capacity covers more than 94% of the total electricity usage in the country.

When many Norwegian rivers, streams and waterfalls were 'tamed' for hydropower, public resistance grew against hydropower projects. In the mid-1990s, then Norwegian Prime Minister Jens Stoltenberg declared that the era of big hydropower construction was over.

Nevertheless, Norwegian topography and water resources still gave major potential for hydropower, especially if a solution with less impact on the environment could be found. One of these solutions included small hydropower projects, defined as hydropower plants with an installed capacity of less than 10 MW.

This paper addresses why small hydropower projects are an effective way of generating electrical energy and why mechanized tunneling is an ideal solution to build those projects.

2.1 Small Hydropower Projects & Why They Matter

There are currently more than 1,300 small hydropower plants operating in Norway with an installed yearly production of 11 TWh. The small hydro share of the total power production is currently around 11 percent (see Figure 1).

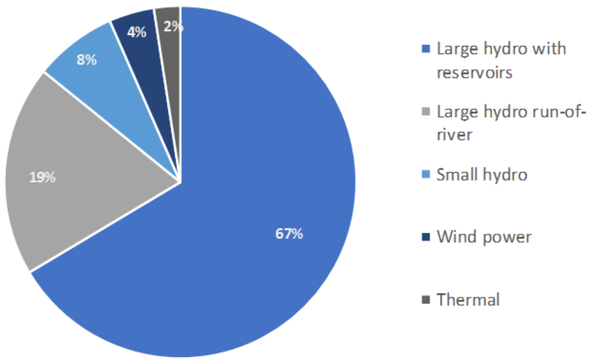

Figure 1. Power production by percentage in Norway (Normal year, OED, 2019)

The local impact on the environment for these small projects is generally lower than on larger hydropower projects: construction is cost-efficient and faster, and the initial investment required is lower. The widespread availability of locations where these projects can be built also offers plenty of opportunities for value generation across all parts of the country (Smakraftforeninga, 2016).

2.2 Construction of Small Hydropower Projects

A significant amount of the existing Small Hydroelectric Power Projects (SHEPPs) have been constructed either with pipes on the surface or by trenching. In recent years, it has been a general trend that larger parts of these SHEPPs are built in tunnels, either due to the topography or in an effort to reduce the environmental impact.

In small hydroelectric projects that require an underground waterway, the tunnel is usually built by one of the following methods:

- Trenching
- D&B tunneling
- Raise drilling
- Directional drilling
- TBM boring

As a rule, trenching is the most cost-effective solution for such projects; however, the topography and nature of the projects do not always allow for trenching. If a tunnel is needed, the other options have historically been between D&B tunneling, raise drilling or directional drilling, or a combination of those methods.

The SHEPPs that consist of a tunnel more often than not have some physical constraints that limit the construction method:

1. There is naturally a big elevation difference between the tunnel portals.
2. There is generally as much overburden as practically possible towards the downstream portal to avoid challenging geology, hydraulic fracking, and hydraulic jacking, and to lower costs.

These limitations mean that the vertical profile of a SHEPP tunnel is frequently similar to the illustration below (see Figure 2), with limited inclination in the downstream portal and high inclination towards the upstream portal.

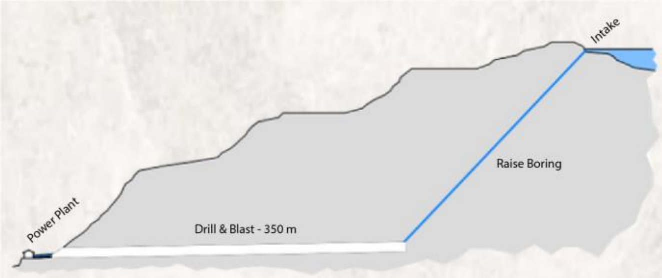

Figure 2. Typical small hydro layout (Norhard.no)

The traditional way of constructing such projects has been to drill and blast the flat part and raise bore the incline. A concrete plug is installed where hydraulic jacking forces are lower than the minor principle stress in the surrounding rock, and further through a pipe in the tunnel towards the powerhouse. The most common blasted cross section is between 16m^2 and 25 m^2, due to limitations in the available equipment as well as the challenges of excavating efficiently with D&B at diameters smaller than 16m^2. If the tunnel was to be excavated with other methods, a profile like Figure 3 would be typical.

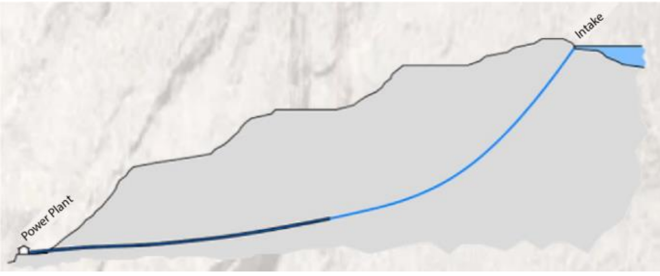

Figure 3. Typical small hydro layout (Norhard.no)

The alternative to the conventional method has been directional drilling performed with a heavily customized directional drilling rig such as that devised by Norwegian company Norhard AS. The Norhard drilling rig consists of a pilot tri-con bit for drilling with carbide raise drill cutters to ream up the diameter of about 0.7 m. The hole can then be reamed up with several drillings up to a diameter of 1.5 m. The drill string is powered by a non-rotational drill string from the outside (see Figure 4).

Figure 4. Norhard breakthrough with pilot hole on Grytendal project (NGK, 2019)

As the SHEPPs have become increasingly complex in recent years, TBMs have been introduced on several projects in Norway. The use of TBMs for excavation has proven to have its own unique advantages.

2.3 Benefits of Mechanized Tunneling for Hydropower

Mechanized tunneling offers some significant advantages on unlined hydroelectric power projects:

- Reduction of needed cross section, due to less surface roughness
- Better tunnel quality, resulting in less rock support and lower life cycle costs
- Less impact to the environment
- Reduction of tunnel construction time

Due to the lower surface roughness of the tunnel wall in a mechanically excavated tunnel, the water flows better, and the needed theoretical cross section can be reduced by 40 to 60 percent. A more detailed graph is given in Figure 5.

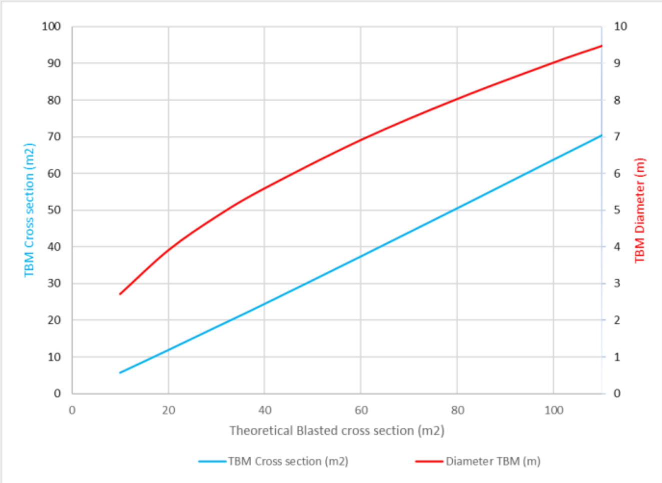

Figure 5. Reduction of theoretical cross section with mechanized tunneling (Log, modified based on NTNU, 1998)

The more efficient water flow, and the capability of using the tunnel as the water carrying pipe, reduces the need for excavated material significantly. This means less excavated material needs to be removed and stored and is also economically advantageous.

Less rock support is required in general in mechanically excavated tunnels, and because of the better tunnel quality there are lower lifecycle costs to maintain the tunnel. Mechanized tunneling also disturbs the environment far less than drill & blast operations. The empirical data from TBM-excavated hydropower projects in Norway support these points. Results show that there is a reduction in installed rock support of between 40 to 90 percent when boring a tunnel with a TBM instead of blasting it. The theory behind this result is that a lot of the rock support in blasted tunnels with small cross sections is installed to stabilize rock that has been damaged by the blasting. The TBM-bored tunnel walls are less damaged, which also increases tunnel quality, ultimately leading to lower maintenance cost of the tunnels and longer tunnel life. Also, the smaller tunnel dimension and the circularity of the hole increases the stability of the rock and decreases the need for rock support.

Excavation with TBMs also offers several environmental advantages. The TBM and muck haulage are typically run on 100 percent electric power from the grid, which in Norway consists of 94 percent renewable energy. In addition to the already mentioned environmental aspects that include reduced excavated material, mechanized tunneling eliminates the risk of nitrous run off and plastic waste that are present in D&B material deposits.

3. TBMS FOR SMALL HYDROPOWER

For the last 10 years there has been interest from owners, contractors and the government to develop TBM solutions for some of the upcoming SHEPPs in Norway. From a TBM design perspective there are some special challenges of the Norwegian SHEPPS:

1. The theoretically needed cross section is usually very small and requires TBMs smaller than 3 m.
2. Norwegian rock is often found to be extremely hard.
3. The geometry of the projects is frequently challenging, with the tunnels often containing high inclines, combined with vertical and horizontal curvature.
4. Some of the projects have very limited space on site and no road access at the upstream portal.
5. The length of the tunnel is typically between 500 m and 3000 m.
6. The budget of these projects is habitually extremely limited.

These challenges require a unique TBM design:

1. The TBM needs to be small, but still equipped with sufficient cutter sizes to efficiently break the rock.
2. The TBM cutter diameters must be as large as possible and the highest quality disc ring material must be used to reduce cutter changes, due to the limited space.
3. The machine needs to be able to negotiate steep inclines and the transitions between inclines.
4. The TBM needs to be able to backtrack through the tunnel.
5. The TBM must be optimized to be used on several projects, with limited service time in between.
6. The TBM package needs to be economically viable.
7. The TBM might need to be able to launch from an area with limited space.

These specific needs led Robbins to develop two separate solutions for the Norwegian hydro projects. One was based on Small Boring Units (SBUs), a line of trenchless boring equipment and machinery typically 2 m or smaller in diameter, while the other used more standard TBM technology.

3.1 Small Diameter Design: Holen Hydropower

The first tunneling machine for SHEPPs was ordered by Hardanger Maskin AS, for the project Holen Hydropower owned by Smaakraft AS in early 2018.

Robbins developed a new solution for the project using time-proven SBU technology. The Double Shield Rockhead (SBU-RHDS) provided for the tunnel includes 14-inch diameter cutters and is capable of self-propelled excavation through the use of a gripper system.

The novel 2.0 m (78-inch) diameter machine is equipped with unique features that allow it to drill at a steep incline, including electric power, modified oil and lubrication systems and a fail-safe safety gripper (secondary gripper), as well as a water-based spoil removal system, developed by the contractor (see Figure 6).

Figure 6. Double Shield Rockhead at Holen SHEPP (Photo: Endre Hilleren)

Due to local terrain, the tunnels had a small launch area of 4 m x 10 m, and the tunnel slope on the first 640 m long drive ranged from a slight upward tilt to 45 degrees at the breakthrough.

The Rockhead launched in July of 2018 with Robbins Field Service onsite assisting Hardanger Maskin AS with assembly, setup, and launch of the equipment. As tunneling began the slope was near horizontal, but as the tunnel got steeper, the special safety gripper system was employed. The safety gripper system was designed with interlocks to ensure primary grippers were never released while the safety grippers were engaged, and with an additional safety mechanism that allowed for mechanical locking in the event that hydraulic pressure was lost.

While the excavation rate of the machine was good, the newly developed design experienced some reliability issues during tunneling in the hard granite. Despite the challenges, the machine completed a daring breakthrough at a steep 45-degree incline on January 1, 2019. It has since bored a second, 1,750 m long tunnel and was then transported by helicopter for refurbishment and launch in a remote part of Norway on a third small hydro tunnel. The tunnel, known as Blindtarmen, is accessible only by snowmobile in the winter. The machine was refurbished in early 2021 in a heated enclosure that warmed the environment to 0 degrees Celsius from cold outside temperatures that dropped as low as -30 degrees Celsius. The machine is now well on its way into the third tunnel (see Figure 7).

Figure 7. Breakthough at Holen SHEPP (Photo: Hardanger Maskin AS)

3.2 Unique TBM & Conveyor Solutions: Salvasskardelva SHEPP

The other solution, based on the more standard TBM technology, was launched in summer 2019. Robbins supplied the 2.8 m diameter specialized Main Beam TBM "Snøhvit" to Norsk Grønnkraft to use on several of their hydroelectric tunnels. In addition to investing in a TBM, Norsk Grønnkraft also started a specialized contracting company, NGK Boring, that worked alongside Entreprenørservice AS to construct the tunnels.

The first tunnel, the 2.8 km long Salvasskardelva HEPP located in Bardu, Norway, has a modest positive gradient of 5.2 percent. To combat boring on a grade, the small Main Beam TBM was designed for adaptability, with an option to add a safety gripper on future tunnels for boring at high inclines.

The TBM is equipped with 19 17" (432 mm) cutters with a load rating of 267 kN each (see Figure 8). The 2.8 m diameter cutterhead is powered by four 210 kW Variable Frequency Drives (VFDs).

Figure 8. TBM ready to start boring Salvasskardelva (Photo: Kalle Punsvik)

A continuous conveyor was provided for muck removal, making it the smallest conveyor belt Robbins has ever provided. The 450 mm wide conveyor belt had to travel through curves, which began at the 650 m mark at Salvasskardelva. The structure was designed to minimize muck spillage in curves despite its narrow width and was within its design limits. The small jobsite also required the use of a double stack belt storage cassette standing 5 m tall. The unique system is planned to be reused at each of the tunnel sites (see Figure 9).

NGK and Robbins worked together during the design period to create a launch frame instead of excavating a starter tunnel, this allowed the machine to advance until it was well enough into the tunnel to grip the tunnel walls. The launch frame is planned for reuse on subsequent tunnels as well.

Figure 9. Crown-mounted conveyor at Salvasskardelva

The TBM completed its first tunnel on June 16, 2020 after boring up to 44 m in 24 hours and 150 m in one week. The second tunnel, a 3 km long bore for the Mork HEPP in Sogn og Fjordane, Norway, will be steeper with a positive gradient up to 10 percent. Future tunnels are anticipated to have moderately steep gradients up to 25 percent.

A third TBM, a 2.6 m diameter Robbins Double Shield TBM with a safety gripper, began excavation in Winter 2019 at the Tokagjelet SHEPP. The alignment of the 2.2 km long tunnel increases gradually from near-horizontal to a 45-degree incline.

After the success of the newly developed TBMs, small diameter hydro tunneling looks poised to continue making a big impact in Norway.

4. CONCLUSION

Hydroelectric power generation has historically required large initial investment, as well as mountainous topography with water in abundance. Unfortunately, the size and complexity of traditional hydropower projects also tended to have a negative impact on the surrounding environment.

The small hydro project approach gives an opportunity to construct renewable energy with limited investment and limited negative consequences on the local environment. Given the increasing interest in small hydro tunnels, and the fine-tuning of effective designs for rock tunnels at steep inclines, there is a huge potential for continued projects in Norway and in other locations in Europe. Renewable energy with a reduced initial investment and construction time could become essential wherever the terrain is hilly or mountainous and water features abound.

Small hydropower is likely to become more popular in Europe, as it offers the best of several worlds: it is an environmentally friendly way of generating power, is less taxing on natural resources, and is cost-effective and quick to implement. It does not require the large waterfalls and high mountains that big hydropower schemes require.

5. REFERENCES

SSB (2016). Kryssløpstabeller - ESA Questionnaire 1850 - Symetric input-output table for domestic production (industry*industry). Tilgjengelig på https://ssb.no/en/nasjonalregnskap-ogkonjunkturer/tables/supply-and-use-and-input-output

måkraftforeninga (2016). "Samfunnsnytte av småkraft". Thema Consulting group

NTNU (1998). NTNU-Anleggsdrift: Project Report 1A-98 HARD ROCK TUNNEL BORING Design and Construction.

Norhard (2019). Pictures from Norhard.no

NGK (2019). Picture courtesy of Norsk Grønnkraft