NORWEGIAN TUNNELLING SOCIETY

Photo: Christian Alseth

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Small Sustainable Hydropower Projects

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Preface

The Norwegian Tunnelling Society (NFF) is open to individuals, companies, institutions, and government services engaged in or associated with the construction industry where use of the underground and related work tasks and disciplines are central.

NFF has the tradition to present an English publication every year. In these publications we focus on different topics we think are relevant to share with our international friends and colleagues around the world. This year's publication is devoted to small sustainable hydropower plants.

The publication is targeted towards both an international and national audience, - both industry members, politicians and the readers interested in sustainability and power plants in general. We hope the reader will be inspired to engage in finding sustainable solutions to the energy challenges we face in the world today.

The publication is written as a joint effort among the scientists, clients, contractors, consultants, and suppliers in the Norwegian tunnelling industry. It contains of a mix of general information and project specific details. We appreciate the willingness to share experience and thoughts through this written material. The authors are credited in front of each chapter. A special gratitude goes to the editorial committee:

Sindre Log, SINTEF
Werner Stefanussen, Stefanussen Consulting
Tone Nakstad, NFF

Oslo, September 2024

Norwegian Tunnelling Society (NFF)
The International Committee

1 Introduction

1.1 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.

The Norwegian Tunnelling Society (NFF) has shared two publications about hydropower earlier: Publication #03 Hydropower Tunnelling (1985) and Publication #22 Norwegian Hydropower Tunnelling II (2013).

In this publication we will focus on small hydropower projects, we will address why they are an effective way of generating electrical energy. We will also share tips and tricks we have found through several decades with development of this concept.

1.2 Definitions

1.2.1 Small Hydropower Plants

In Norway the definition of small hydropower plants is hydropower plants with an installed capacity of less than 10 MW. We know that other countries have other definitions.

In this publication, the Norwegian definition will be used when referring to numbers and prevalence of small hydropower plants. However, we have included project examples with installed capacity up to 50 MW since we believe they give the reader a broader range of experience to build their knowledge from.

1.3 Why Small Hydropower Plants

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 8 percent (see Figure 1.1.).

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).

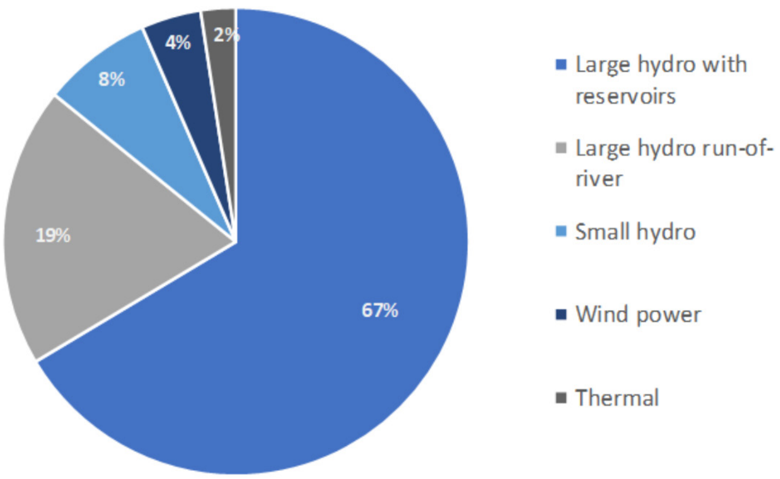

Figure 1.1. Power production by percentage in Norway (Normal year, OED, 2019).

2 The Construction of Small Hydropower Plants

2.1 Introduction to Construction

A significant amount of the existing Small Hydroelectric Power Projects (SHEPPs) has 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. Most of the Norwegian SHPP's are typically run-off the river projects with relatively high head (larger than 250 meters). The discharge is normally in the range of 1 to 10 m^3/sec, which requires quite small diameters for the tunnels, shafts and penstocks.

The traditional penstock above ground, or buried in a ditch, will normally be the cheapest and the less time-consuming solution. However, the governmental requirements and the topographical conditions may require alternative solutions. In Norway the governmental environmental requirements normally do not allow for a penstock above ground. In some projects, the topographical conditions do not allow construction of a buried penstock due to steeply inclined slopes with exposed rock, or risk of landslides. Then, the alternative solution with tunnel and shaft may be relevant. These governmental and topographical conditions are also relevant in other countries, and the "Norwegian solution" may be an alternative. During the last 10 years Sweco Norge AS has designed tens of small hydropower projects with tunnel and shaft solution. In most of these projects the power house has been constructed above ground, but it might also be possible to design and construct an underground power house located in a rock cavern.

2.2 Alternative Waterways

In the following, different and most common solutions for underground waterways (tunnel and shaft) are described. A combination with surface solutions can also be possible or preferable. Typical alternative design of the waterway is illustrated in Figure 2.2.

Figure 2.1. Installation of penstock in dich (Photo: Werner Stefanussen).

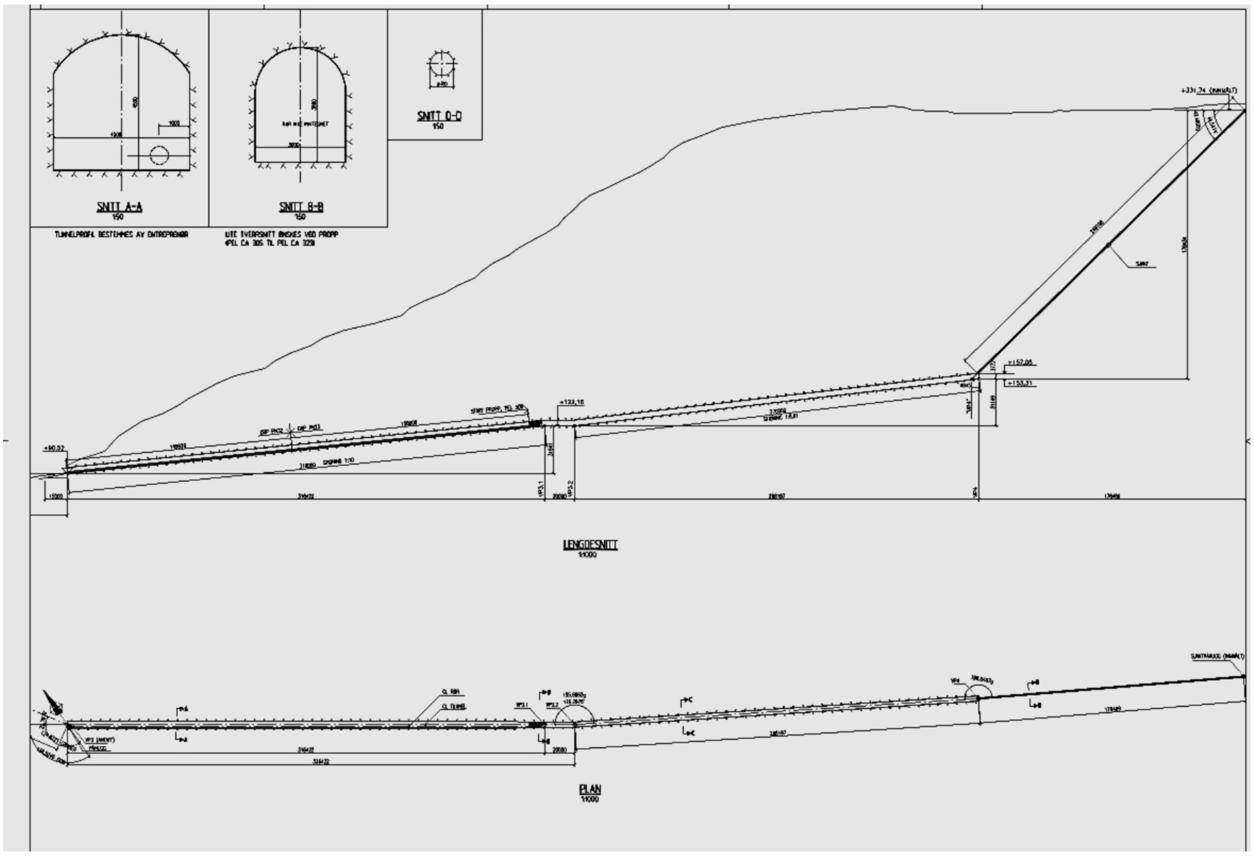

Figure 2.2. Alternative design with inclined shaft and unlined pressure headrace tunnel (Ref).

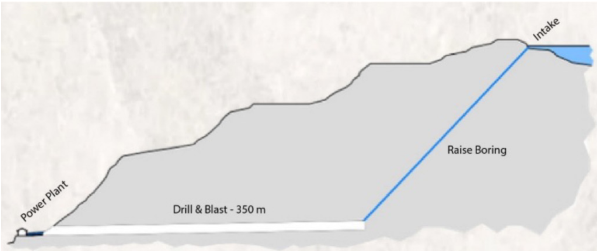

Figure 2.3. Typical small hydro layout (Norhard.no)

Normally the tunnel length is within 1 km, with a cross section of minimum size, like 12 to 14 m^2. The length of the shafts are normally 300 to 500 meters, and with diameters from 1 to 1,5 meters. The limitations in length are due to the economically aspects of a small hydropower, or technical reasons for the shaft drilling. When performing an economical evaluation of the project, the cost of the underground works will certainly be a limitation. The restricted length of the shaft is because of the present technology for the light weight equipment to be used in these projects without road access to the intake location. The weight restrictions of helicopters are setting the limitations of the equipment to be used for shaft drilling.

2.3 Several Possible Tunnelling Methods

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

- Trenching
- Drill and blast tunnelling
- 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 tunnelling, 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 (see Figure 2.3.), with limited inclination in the downstream portal and high inclination towards the upstream portal.

2.3.1 Trenching

Trenching is the most common way to lead water into the turbines when it comes to smaller hydropower plants

2.3.2 Drill and blast tunnelling

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 principal stress in the surrounding rock, and further through a pipe in the tunnel towards the powerhouse.

As indicated above, the required tunnel diameter is normally small, in the order of 8 to 10 m^2. However, to obtain high tunnel performance, the smallest tunnel profile is normally in the range of 12 to 14 m^2. With this cross section, small high performance two-boom jumbos can be used for drilling the blasting rounds. The loading and mucking equipment must be adapted to each other and to the tunnel profile.

Figure 2.4. Small size 2-boom tunnel machines (Photo: Werner Stefanussen).

Figure 2.5. Low height mucking and transport equipment (Photo: Werner Stefanussen).

Our experience is positive using front loaders with extra low height. They are efficient in loading, with a large volume scoop and have high maximum speed. These can be used for mucking and transport of the blasted rock mass for until 400 meters. If the tunnel is longer, construction of a turning niche is necessary every 250 meters. By using the correct equipment, the tunnels can be constructed with an upwards inclination of 1:5 (20%).

The most common blasted cross section is, however, 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.

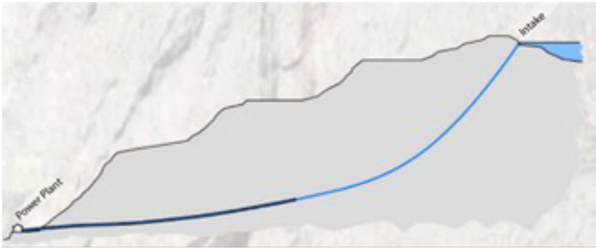

Figure 2.6. Typical small hydro layout (Norhard.no).

2.3.3 Raise drilling

The shafts are normally constructed by use of pilot hole and reaming (raise drilling) and are normally inclined (to about 45o). They can however be vertical in other situations. Due to the advantage of using light weight machinery to possibly use helicopter transport to the shaft location, the equipment has limited capacity by length. Normally, in our experience, the shaft length can be at a maximum of 600 meters. The diameters can be in the range of 0,7 meters to 4 meters. However, due to the water quantity, normally the shafts are constructed with a diameter of 1 to 2 meters. The shaft is connected to the tunnel at the end of the tunnel.

Lately, new developments in shaft drilling equipment have been developed in Norway. This gives the possibility to perform the drilling from the lower end, and upwards to the intake position. The length with this technology can be up to 1000 meters and even longer. Deviation controlled shaft drilling is also possible.

Figure 2.7. Raise drilling. Ready for reaming the shaft (Photo: Bård Skatvold).

Helicopter is used for transportation of equipment if no access road is possible.

2.3.4 Directional drilling

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 2.8).

Figure 2.8. Norhard breakthrough with pilot hole on Grytendal project (NGK, 2019).

2.3.5 TBM boring

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 of unlined tunnels has proven to have its own unique advantages:

- 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 2.9.

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.

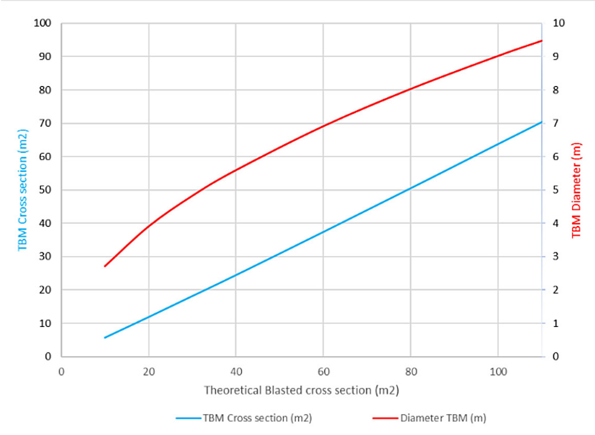

Figure 2.9. Reduction of theoretical cross section with mechanized tunnelling (Log, modified based on NTNU, 1998).

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 tunnelling 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 tunnelling eliminates the risk of nitrous run off and plastic waste that are present in D&B material deposits.

2.4 Investigations and design criteria

The geological and topographical investigations includes study of the geology by field survey and laboratory investigations of rock samples. Special focus is paid to the entrance area of the tunnel, and the intake area of the shaft. Relevant investigations are review of geological and topographical maps, experience from other projects in the area, field survey, investigation pits, core drilling, geophysical investigations.

To have exact topographical maps, it is recommended to perform aerial survey by scanning, and processing detailed topographical maps.

For the pressure tunnels, the rock cover must comply with the water head pressure to avoid hydraulic splitting. Norwegian splitting criteria is used, based on empirical formulas, or by performing hydraulic splitting tests.

In areas with severe geological conditions, it might be relevant to perform core drilling investigation. The core drilled hole may also be used to perform permeability tests of the rock mass.

2.5 Rock support

The Norwegian Tunnelling Method is based on unlined water pressure tunnels. The typical rock support methods in tunnels are rock bolts and fiber reinforced shotcrete. Norwegian reinforced shotcrete arches are also used to a certain extent. Full concrete lining is only used in special situations with severe fault zones with swelling clay materials.

The concrete plug (conus) is constructed at a location of the tunnel where the criteria to avoid hydrofracturing requirements are fulfilled. From this point a steel-, a cast-iron- or a GRP penstock is used to connect to the power station. The length of this penstock depends on the topographical conditions and can be from 50 meters to several hundreds of meters.

The rock support in the tunnels where the penstock is used, the rock support normally includes systematic pattern rock bolting and shotcrete with fiber.

Rock support in inclined drilled shafts is not used. If severe geological conditions are encountered, grouting is performed as down-stage grouting.

2.6 Cost and construction time

Construction cost and construction time is essential for all hydropower projects, and especially related to small hydropower plants. Construction of the intake dam is normally a small investment but may depend on the topographical and geological conditions. Small concrete dams are normally constructed with a dam height of 5 to 6 meters. The intake arrangement in projects in Norway needs special arrangement due to the cold climate with snow and ice.

The solution with buried pressure pipe is normally the most economical solution. However, use of high-performance tunnelling and shaft drilling equipment has shown to be competitive, due the possibly shorter (straight on) underground solution.

Lifetime, future maintenance cost and safety aspects of the waterway should also be taken into consideration.

From Sweco Norge experience with design of several small hydropower projects, the cost of the waterway by using underground design (tunnel and shaft) will normally be 20 to 50% higher than the buried penstock solution. In the case when only the underground solution is feasible, the cost is not an issue.

Based on the typical Norwegian tunnel excavation, an advance rate of 40 meters per week, and about 2 months for the construction of the drilled shaft, the time schedule can in some projects be more favourable by using the underground solution, compared to the traditional solution.

References chapter 1 and 2

- SSB (2016). Kryssløpstabeller - ESA Questionnaire 1850 – Symetric input-output table for domestic production (industry*industry).
- Småkraftforeninga (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
- S. Log (2022) A Clean Solution for Renewable Energy: Small Diameter Hydro Tunnelling
- W. Stefanussen and T. Gjermundsen: Tunnels and shafts in Small Hydropower Projects

3 Tips and tricks

3.1 Introduction

In this chapter for tips and tricks, we have included examples of best practises. The examples are collected from both small and larger hydropower plants. We believe that the principles can be used by all sizes of projects.

3.2 More salmon and more power in Palmafossen

This chapter is based on an presentation given by Yngve Tranøy, Voss Energy and a presentation given by Morten Kraabøl, Multiconsult.

It is a story about improving the conditions of wild salmon, and at the same time increasing the energy production from the same waterfall.

3.2.1 Facts about the renovated Palmafossen

Precipitation field:	532 km^2
Mean flow:	36 m^3/sec
Max. flow capacity:	30 m^3/sec
Min. flow ability:	6 m^3/sec
Installed effect:	3.6 MW
Pipe diameter:	3.6 metre
Annual production:	14.0 GWh

3.2.2 Public-friendly facility

The facility and the area around are open to the public and is organized to facilitate both relaxation, display, and teaching:

- Outdoors area with installations from the old power plant.
- Outdoors information boards with storytelling about the conservation decision, the salmon from Voss, Voss Herad's power plants and the construction period for the new Palmafossen power plant.
- Display screen with fishing videos and photos.
- The public can come down to the roof of the power plant for a picnic and feel close contact with the river.
- Outdoor amphitheatre with seating for 40 people, which can be used for teaching and tours for school classes.

3.2.3 Salmon solution

The project is designed to secure safe ascent and descent for all fish including eels. It is the first project in Norway that includes safe design for the fish in both directions. The solution has expanded the spawning and rearing area for the fish with 8 kilometres.

Figure 3.1. Palmafossen with the salmon ladder to the right of the waterfall (Photo: Voss Energy).

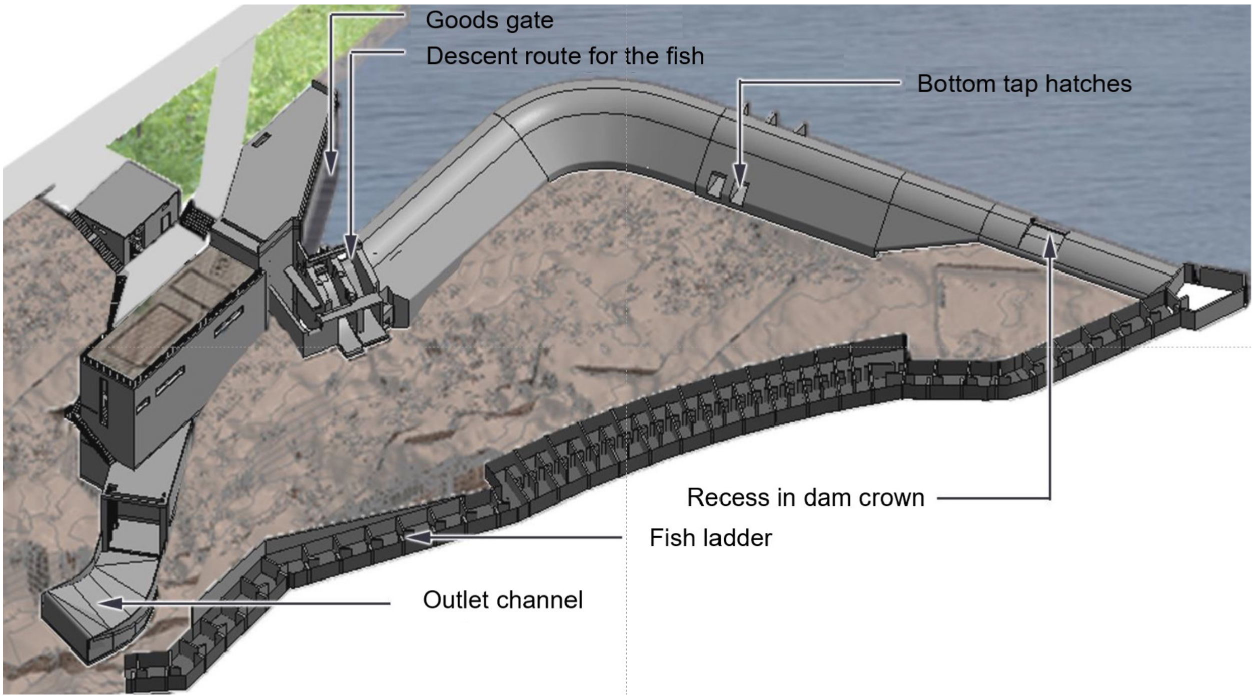

Figure 3.2. The principal design of a hydropower plant with safe ascent and descent for all fish (Photo: Multiconsult).

Figure 3.3. The grid with small slits in front of the water intake. (Photos: Voss Energy and Multiconsult).

The project design also facilitates further research of the fish in the river, by installing i.e. cameras for monitoring and counting the fish and solutions for catching, counting, and tagging fish for research purposes.

Above, the principal design of a hydropower plant with a safe ascent and descent for all fish is shown. On the waterside of the bottom tap hatches it is installed a grid with small slits to ensure that the fish is not drawn into the turbines.

3.2.4 Award winning project

The Palmafossen hydropower plant at Voss Energi received the Damkrona 2022 award for "outstanding construction art and environmental design" at the Water Resources Engineering Forum in Oslo in 2022. NORCE LFI received the award together with Voss Energi, NINA, SINTEF and Multiconsult.

The Damkrona is an honorary award that has been established to promote innovative and engineering-wise good solutions that safeguard good dam safety as well as landscape, aesthetic and/or environmental qualities with good implementation in terms of HSE.

Large resources are used to obtain good solutions in connection with the new construction and rehabilitation of dams. An important purpose of Damkrona is to make this work visible.

3.3 Underwater piercing – the Norwegian method

This chapter is an extract from a proceeding from the Norwegian Rockblasting Conference in 2017. The original proceeding was written by Espen Hugaas and Olaf Rømcke, Orica.

3.3.1 History

Norway's topography has made it natural to utilize the many high-lying large lakes for hydropower reservoirs. To lead the water into power plants, tunnels have then been driven under and out into the water reservoirs. Tunnelling under water is a common method used in this country. Historically, this method goes back a long way. The first underwater piercing was probably carried out around the 1890s when a tunnel was blasted under Demmevatn west of Hardangerjøkulen. The reason why there was a desire to be able to lower Demmevatnet was not electricity, but to prevent floods. Around ten years later, the first underwater piercing was executed in connection with hydropower. Since that time, many piercings have been carried out under water. Especially in the sixties, seventies and eighties when Norway constructed large parts of its current hydropower production. It is somewhat uncertain how many underwater piercings that have been blasted over the years, but there are several hundred (probably over 600). The deepest breakthrough related to hydropower is a little over 100 meters (approx. 120 meters depth to the hatch construction). The deepest breakthrough for all purposes were made in the North Sea for construction of a pipeline's landfall. The water pressure here was close to 200 metres.

3.3.2 Types of underwater piercing

The selection of piercing methods has been divided into two main methods: Open and closed breakthrough. Open breakthrough means that the tunnel system that is breaking out into the water is connected to the atmosphere either through an open shaft or through an access tunnel. With open breakthroughs, , the water can flow in freely and gain a tremendous force together with the rock masses that enter the tunnel system. When choosing this impact method, it is therefore important to be able to slow down these forces. This is mitigated by, blasting with a water-filled tunnel, and also a partially water-filled shaft. How much water and the level of water in the shaft depends on the water pressure on the outside of the breakthrough blast. It is also important to ensure that the water that is filled into the tunnel system does not reach the explosives. The explosives must under all circumstances be left dry. This is not because of the waterproofness of the explosives and detonators, but to avoid a detonation directly against water that will cause a violent pressure propagation through the water towards the hatch.

A closed breakthrough means that the tunnel system is closed to the atmosphere prior to blasting. Normally, with this method, the hatch is closed upstream of the hatch shaft. Then the tunnel between the blast and the hatch is to be considered a closed space. Depending on the water pressure on the outside of the piercing and the length of the tunnel into the hatch, this blowout method can been blasted with a dry tunnel, sometimes only with the closed volume having atmospheric pressure and other times the air volume can be pressurized by pumping in extra air (pre-compression.) If there is a long distance between the breakthrough blast and the hatch, this can be a simple and straightforward method. In such a case a collection pit for the rock masses has no mission Since the rock masses are simply dragged into the tunnel together with the water that flows in. It is, however, common for the tunnel to be completely or partially filled with water also when the breakthrough is closed. Then the rock masses from the blast are slowed down and most of it is left in the pit. How much water and possibly compressed air is pumped in depends on the water pressure on the outside and the length of the tunnel towards the hatch.

3.3.3 The choice of ignition system

An underwater piercing is considered a critical part of a hydropower plant development, and therefore measures are taken to be absolutely sure that the breakthrough blast goes as planned and that, ultimately, the end result is an opening that is satisfactory for the power plant's capacity. It is therefore very important that the products (igniting system and explosives) that are used, work as intended . Compared to a normal blast, a breakthrough blast is significantly overcharged. In cases where the blast is to be pressurized, it must be ensured that both explosives and ignition system can withstand this pressure. In addition, there will also be two or more initiation points ignition points per hole to ensure initiation of all the explosives.

Until the nineties, it was common to use electric ignition systems. These systems are measurable, but

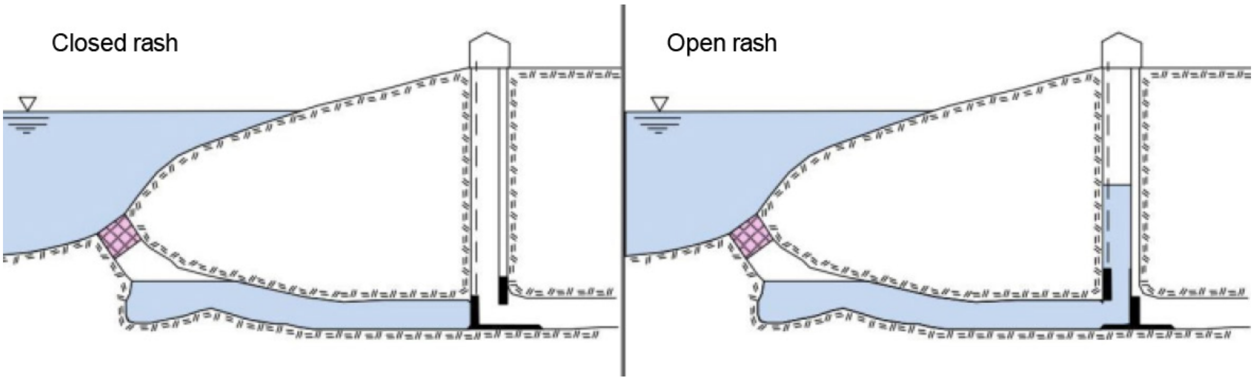

Figure 3.4. The main types of underwater piercings are open and closed.

vulnerable to electrical stray currents and possible earth faults. From the nineties onwards, in line with the rest of the tunnel operation, it was switched over to using non-electric systems (non-el), which provided good safety against electricity and untimely ignition. Non-el systems, on the other hand, are not measurable and there is no no other control options than the visual one.

Today, again in line with the rest of the tunnel operation, electronic initiation systems are recommended.. These systems are measurable, and much less vulnerable to electrical stay currents. By using electronic initiation systems, uncertainty about the ignition of the breakthrough blast is avoided. The fact that the electronic systems are measurable, all detonators are connected to a common shooting cable which can continuously be measured so that possible connection and earth faults on the circuit can be eliminated. On these blasts, a simple firing cable is stretched out past the hatch and to the firing point. This is considered safe as, for each work step carried out after the detonators have been connected, the circuit can be measured and thereby confirmed that it is intact.

3.4 Full-scale use of BIM – Experiences from Vamma hydropower plant

This chapter is an extract from a proceeding from the Norwegian Rockblasting Conference in 2016. The original proceeding was written by Øyvind Engelstad, Head of Hydropower Civil Works in Norconsult AS and Inge Handagard, Head of BIM in AF Anlegg AS.

3.4.1 Introduction

The utilisation of Virtual Design and Construction with support of Building information modelling (BIM) has arrived in the construction industry. In the Vamma 12 Hydropower Project in the Glomma river the whole plant was constructed without the use of 2D drawing, but based directly on 3D models enriched with production critical information, namely BIM. BIM safeguarded good coordination, information exchange and collaboration between all parties in the project.

For tunnels and underground facilities, the BIM is used directly for data operation of machinery (drilling jumbo) and data automated collection (scanning, bore logs, MWD, etc.) and manually collected data (surveying, photography, etc.) can be fed back into the BIM for ongoing assessments and adjustments ("design as you go" revisions), and form basis for "as built" documentation for the operation phase. BIM helps to change the work process and to ensure good productivity, right quality and reduce rework and conflicts between the stakeholders.

3.4.2 Design

At Vamma 12 HPP, Norconsult used a variety of tools to design the facility.

The concrete structures were primarily modelled in Revit, while the various components interfacing with the concrete works from the suppliers were designed in Inventor, Microstation and Solidworks. As the open format, IFC, was not currently adapted to the complicated geometry of this type of facility, Norconsult chose to use other formats such as SAT and STEP to convert the models into Revit. The coordination of all models was done in Nawisworks, and it was this platform that forms the starting point for communication with the contractors/suppliers as well as the Employer (Hafslund ECO) and other stakeholders involved in the design and construction of the plant.

For terrain and excavation works, Powel Gemini Terrain and Contractor was utilized in the planning and design process. As the contractors also used this tool for production at the site, this approach ensured good communication and data flow. The fact that Powel is a Norwegian supplier who knows the industry and was closely involved in the process, contributed to the team being able to carry out ongoing upgrades and adaptation of the software to the needs that was uncovered during the process.

To ensure that production-critical information is easily accessible to the contractor, Norconsult used the plug in tool iConstruct to sort out and present quality-assured data for each element in the model.

In this context, Norconsult AS, through its subsidiary Norconsult Digital AS, developed an application for dynamic linking between the bill of quantities (BoQ) and each of the elements in the model. This also ensured a clear contractual link between the model

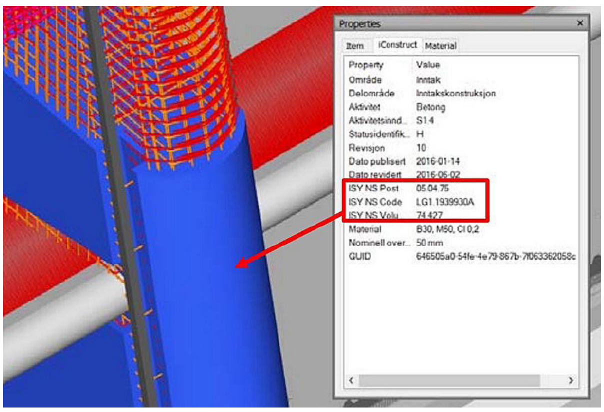

Figure 3.5. Information directly on the elements in BIM (with link to item in list of quantities).

and the requirements in the contract. Each element such as excavation of soil, blasting and excavation of rock, formwork, concrete, reinforcement, embedded components etc. was linked to the relevant item number in the BoQ and the associated NS code (according to NS3420). In this way, the team ensured traceability between NS3420 and referenced standards (material requirements, execution requirements etc.) and the elements in BIM.

Each element in the model is also given a status identification. Only elements with the status H = "for construction" are released for construction. The revision number and date also appear.

All reinforcement is designed in BIM and each bar therefore appears with bending code, dimension, centre distance etc. in the model.

3.4.3 Construction

AF Anlegg uses BIM directly as a basis for construction at the facility. In addition to access to the model in the site office, BIM kiosks were established in the construction pit where the work team could plan the work and study each detail. Furthermore, the models were made available through A360 Glue and could as such be studied on the iPads that the crew carried with them at the work site.

Survey data was obtained directly from the model using Autodesk Point Layout and Gemini Entreprenør. Reinforcement was ordered directly ready bend from the supplier (of site bar bending workshop) by exporting electronic bar bending lists directly from BIM without going through the step of producing traditional bat bending lists in pdf. The XML file was sent to the bending plant and fed directly into the bending machine for production without manual input of data. For the excavation and blasting works, the contractor used data directly from Gemini Terrain and Contractor as a basis for machine control and as a basis for drilling plans via Bevercontrol.

3.4.4 Rockblasting

As described above, AF Anlegg used the BIM model directly as a basis for preparing drilling plans for the blasting of cuts, pits and tunnels. After extraction of the profile, scanning of the rock surface was carried out for geometric control. High resolution and precision point clouds and triangulated surfaces were produced and sent to Norconsult for implementation in the models for adapting structures to the rock face. Here, Norconsult developed its own automated tools for effectively joining/adopting concrete construction to the rock surface.

Based on the scanned surfaces, it was possible to check drilling and blasting induced overbreak (excavation outside the theoretical surface) and any additional slippage and overexcavation caused by geologically conditions. The resolution also makes it possible to automatically categorize fracture planes (based on strike and dip) and geological zones.

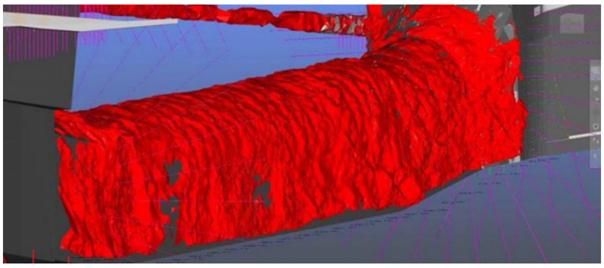

Figure 3.7. Scanned rock surface in access tunnel (grey fields show where the rock surface lies within the theoretical contour).

Figure 3.6. Working with BIM into the field.

Scans may be made before and after application of shotcrete to document the thickness of the shotcrete. Installed bolts was imported directly into the model on the basis of the Bevercontrol data log from the drilling rig or bolting rig. Data from the MWD log on the drilling rig can also be interpreted and brought into the model and produced as a 3D volume to indicate observed geological conditions.

Data from mapping and photo documentation from geological inspection during tunnelling and/or high-resolution orthophoto taken in conjunction with laser scanning can also be combined to document the geology. Furthermore, operating protocols and other data can also be linked into the model. In the future, this process should be automated to the greatest extent possible, but one cannot avoid the fact that expert engineering geologists and staff must go in to "touch and feel" the rock mass in order to form a picture of the challenges – "at the faces of the excavation" and perform evaluations to decide on recommended excavation procedure and initial support measures to be applied. Furthermore, it is important that the data is used in analysis and as a basis for permanent support, and not just collected and left as "dead data".

Novapoint Tunnel is one of the tools used to collect and systematize the "as built" documentation for tunnels and underground structures. For Vamma 12, data was collected and systematised in Gemini Terrain and Contractor.

3.4.5 Conclusion

Using BIM as a basis for planning and directly as a basis for construction worked very well and contributed to ensuring good collaboration, good data flow and good production at Vamma 12 HPP. Although the experiences were very positive during the execution of the project, the future will show whether the industry is able to exploit the full potential of the approach. BIM is a very useful aid also for excavation and construction of underground facilities, and the integration of data from several sources into a documentation tool used actively in the follow-up during construction and as a basis for future operation of the plant can help solve several of the challenges we face in such projects. However, it is important to note that BIM is a tool and not an end in itself. Without adaptation of the processes, trust between the stakeholders involved and a focus on common goals, every system will fail. However, BIM can contribute to "all parties working on the same project" and will therefore be a good foundation for collaboration.

3.4.6 Project nominated in ITA-Awards

This project was one of the finalists in ITA Tunnelling Awards in 2018. It was nominated for the title as project of the year with a budget between 50 and 500 M€.

3.5 Water supply in combination with hydropower plants

This chapter is an extract from a proceeding from the Norwegian Rockblasting Conference in 2022. The original proceeding was written by Mårten Kyte, Glitrevannverket IKS

3.5.1 Introduction

Glitrevannverket IKS (Glitre Water Supply) is an inter-municipal company which from 01.01.2020 is owned by the municipalities of Asker, Drammen and Lier. The main purpose of the Glitre Water Supply is to supply the owner municipalities with good, sufficient and safe water through environmentally focused, competent and systematic management of water sources and water supply systems. Glitre Water Supply owns and operates four water treatment plants that supply water to approx. 155,000 people in the owner municipalities, in Frogn and parts of Holmestrand municipality.

The water sources are Glitre, Røysjø and Holsfjorden.

During the third and fourth quarter of 1978, the Glitre Water Supply was functionally tested and 11 November is considered the actual date of birth and the start of normal operations. From the start, there has always been continuous work at Glitre Water Supply to strengthen the water supply and plan for maintenance and new development, which is also reflected in the vision: Ensure safe, good and sufficient water for generations. Water supply security is again a common thread in our daily work and was also the starting point for the start of the project.

3.5.2 Safer water supply

Glitre Water Supply is a gravity waterworks. That is, most of the supply is based on gravity. This may be because both main sources are in the ground higher than the supply areas. Until today, all potential energy has been "strangled" either with reduction valves or in high-altitude basins. When it came time to reinforce the line from the Landfall water treatment plant down to one of the altitude basins, the opportunity came to also look at whether it was possible to utilize the fall energy.

Nevertheless, the main purpose of the project is to make the water supply safer. Raw water from the Glitre lake is led in a mountain tunnel to the Landfall water treatment plant. Since Glitre is a well-protected water source, the water only needs to go through a simple and environmentally friendly water treatment. From the Landfall water treatment plant, the water is distributed in two directions, towards Brakerøya and towards Åssiden. Towards Åssiden, water previously went through an inclined shaft in the mountain from the Landfall water treatment plant and straight down into the 530 meter long tunnel, Øvre Åssiden high basin, approx. 160 meters further down towards the city.

It is on the stretch between the Landfall water treatment plant and down past the Øvre Åssiden basin that a new main water line has now been laid. With the new water line, the water is let into the Øvre Åssiden basin from the opposite side compared to before. If needed maintenance work, the water can then also pass without having to go through the Øvre Åssiden basin.

3.5.3 Water supply = hydropower?

This project was carried out primarily to ensure satisfactory operation and maintenance of the Øvre Åssiden basin according to current standards. The water supply from the Landfall water treatment plant to the Øvre Åssiden basin previously could not be taken out of operation for a long time, before the water supply to Konnerud and formerly Nedre Eiker became unstable.

With the new pipeline, this problem is solved and the Øvre Åssiden basin can be disconnected via a by-pass, as long as it is necessary for inspection, cleaning, maintenance etc.

As mentioned, the main purpose of the project is to secure access to the Øvre Åssiden basin so that it can be maintained and looked after. However, when the water still flows down the new pipes, the measure provides an additional effect with the possibility of producing clean, green electricity. The energy potential in the waterway from the Landfall water treatment plant down to the Øvre Åssiden basin and further down to the Nedre Åssiden basin is being utilised. This was not possible as the water supply was previously laid out.

At the Øvre Åssiden basin, a power station has been built with a pelton turbine that produces electricity. At the Lower Åssiden basin, a somewhat smaller power station has been built to take out the effect of the height difference from the Øvre Åssiden basin down to the Lower Åssiden, the low-pressure zone.

It is clean drinking water that goes through the power stations and in this order of magnitude there are not many power plants in Norway that use pre-treated drinking water for power production. In the two power plants, more electricity is produced than the total electricity demand in Glitre Water Supply, so that we are now more than energy neutral. Annual power production is expected to be up to 4,000 MWh.

An idea for other water supply facilities?

3.6 Recommended specifications for TBMS

By Sindre Log, SINTEF

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:

- The TBM needs to be small, but still equipped with sufficient cutter sizes to efficiently break the rock.
- 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.
- The machine needs to be able to negotiate steep inclines and the transitions between inclines.
- The TBM needs to be able to backtrack through the tunnel.
- The TBM must be optimized to be used on several projects, with limited service-time in between.
- The TBM package needs to be economically viable.
- The TBM might need to be able to launch from an area with limited space.

4 The Fjærland HPP Facilities – Sustainable Development without Road Access

Ola Kvammen, Incitu AS

4.1 Introduction to the Fjærland HPP Facilities

The Fjærland hydropower facilities were developed during the period 2015 to 2018 and comprised a total of 6 hydropower plants along the Fjærlandsfjord, a branch of the Sognefjord in Vestland county, Norway. Parts of the development took place in remote areas. The latter included the construction of the Lidal power plant and the Romøyri power plant, as well as the construction of intake structures for the Hatlestad and Bjåstad power plants respectively.

Figure 4.1. Fjærland on the map of southern Norway.

The development took place on both sides along the Fjærlandsfjord in scenic surroundings close to the Jostedalsbreen National Park. All encroachments in nature were subject to strict requirements on the environmental footprint both during development and by completion. There was no road access to any of these construction sites. For this reason, the development was particularly challenging.

All projects included in the development of the Fjærland facilities, were executed within a unit price contract frame. The client was responsible for all design and for obtaining all permits for the development, including the discharge permit for process water from the tunnel operations, and the permit to deposit the blasted rock masses in the seabed.

The development generated a lot of activity in Fjærland with contractors operating at all plants simultaneously including involvement from local construction companies and other local businesses.

This document discusses the challenges of implementing roadless development and provides an insight into how the contractor solved the task in interaction with the client.

4.2 The Fjærland Facilities

Fjærland is a rural community with approx. 300 inhabitants located in the municipality of Sogndal in Vestland county. The village is located at the head of Fjærlandsfjord, a 27 km long branch of the Sognefjord.

Along the Fjærlandsfjord, the local energy supplier Sognekraft AS developed 6 power plants. None of the facilities were developed with storage capacity. Hence all intake structures were placed directly in the watercourses (rivers), and from there a water conduit has been built to the powerhouse down by the fjord. The heads range from 260 to 636 m. For the intake dams, different design models were chosen, including both rockfill dam with concrete core, gravity threshold in concrete, concrete threshold and fill dam with core and spillway in wood material.

For the headrace the following options were implemented:

- penstock pipes in a trench from the intake to the powerhouse.
- penstock pipes in a trench in combination with a drilled shaft, and headrace tunnel.
- drilled pressure shafts in intakes in combination with a pressure tunnel.

The entire development was planned for a normal year production of 114 GWh and has a total installation of 41 MW.

Commissioning started in September 2017. The entire development was completed in April 2018.

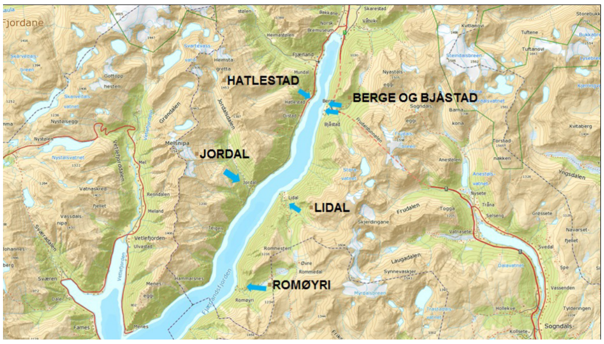

Figure 4.2. Fjærland facilities, location overview for all facilities in the development.

In order to extract the new energy from the Fjærland plants, the owner built a substation jointly with the Lidal Power Plant, followed by an associated 132 KV power line. A new main power line was established over an approximately 20 km long route crossing the mountain area between the substation in Lidal to the Grindsdalen substation in Leikanger. From the Grindsdalen substation, the power line is connected to Statnett's existing 420 kV grid, transferring the energy further to the market.

The Lidal Transformer Station is the hub for all the power plants in the Fjærland development. Prior to this hub, 22 KV subsea cables have been established on the seabed in the Fjærlandsfjord from each of the power plants to the Lidal hub – see Figure 4.3 below.

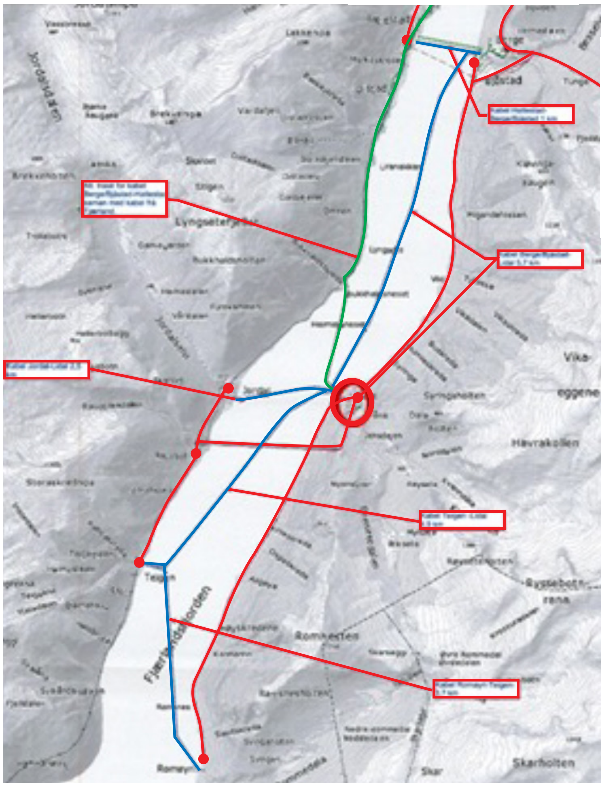

Figure 4.3. Routes for subsea cable to Lidal Substation.

4.2.1 Lidal power plant and Romøyri power plant

In the Fjærland hydropower development, the most complex ones were the Lidal and Romøyri facilities. A high degree of underground excavation and water conduit works in remote locations with no road access, made the development very challenging.

Strict environmental requirements formed the basis for the development. The areas made available for site installations were small and limited to the footprint for the completed facility, limiting the ability for normal performance during tunnel operations, thus challenging the creative ability of the contractor. Due to the complexity of the original project design, the schedule assumed a long development and construction process for the Fjærland hydropower facilities.

This chapter will provide an insight into how these challenges were solved through excellent interaction between the contracting parties during the development.

4.2.2 Lidal Hydropower Plant

A unique project with the following contents:

- Water conduit in Y-shape – penstock pipeline from the intakes to the pressure shaft, headrace tunnel and penstock.
- Powerhouse built as portal building partly in underground cavern, including substation with electrical transformer and switchgear.
- The first section of the 132KV power line from Lidal substation to the Grindsdalen hub was established in the underground area and further through a 200 m long drilled shaft to the connection point with the main power line.

Figure 4.4. Fjærlandsfjord.

Key figures for Lidal Hydropower Plant:

Head:	636 meters
Headrace/water conduit:	Tunnel 1420m / shaft 550 m / Penstock pipeline in Y-design 1392 m
Discharge:	1.5 m^3/s
Penstock pipe dimension:	700 mm
Installation:	7.7 MW Pelton
Production normal years:	22 GWh
Intake:	1 concrete mass threshold, 1 rock fill pond with sealing core and wooden spillway
Cable shaft:	200 m
Buildings:	Cast in place Concrete building, common to the powerhouse and the Switch/Transformer Plant

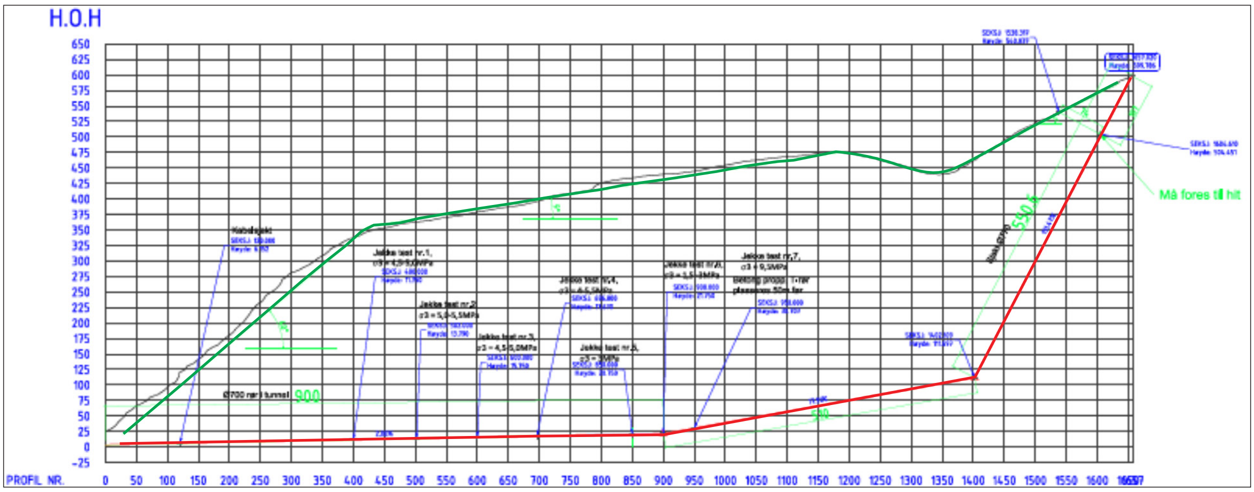

Figure 4.5. Lidal Waterway section.

4.2.3 Romøyri Hydropower Plant

The content of the hydropower plant is as follows:

- The Intake structure, established inside the intake pond.
- The waterway runs via pressure shafts established in connection with the intake structure, and through headrace tunnel and penstock to the powerhouse.
- The powerhouse building, partly as a portal building and partly underground.

Key figures for Romøyri Hydropower Plant:

Head	528 meters
Headrace/water conduit	926 m tunnel and 550 shaft
Discharge	1.9 m^3/s
Penstock pipe dimension	800 mm
Installation	8.7 MW Pelton
Production per year	24 GWh
Intake	Concrete gravity threshold
Buildings	Powerhouse and substation built as portal building partly underground, cast in place concrete.

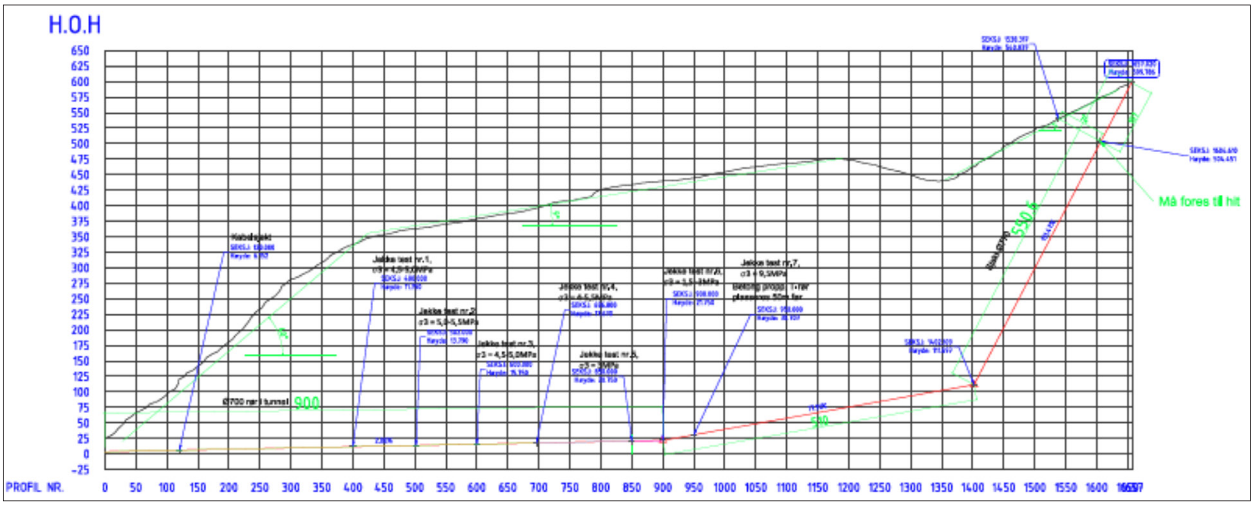

Figure 4.6. Romedal Waterway section.

4.3 Interaction and Development

Although a proper platform for interaction had not been defined initially, the players initiated their interaction dialog before signing the contract. As a result, the project engineering was further developed jointly, providing a very positive effect on both development costs and time schedule. The project's history and improvement process are illustrated below as follows:

The tender inspections were held on 12 and 13 November 2014. The deadline for tender submission was set to the 23.01.2015.

The contract for the construction of the Lidal Power plant, the Romøyri Power Plant, the intake constructions for the Bjåstad and Hatlestad power plants respectively, was granted and signed 3.7.2015.

The client's original progress plan (construction plan) assumed a significantly longer construction period than the result after the parties jointly reviewed and developed the project further. For the underground works in the project, the authorities stated 2 basic conditions for implementation in the engineering and planning as follows:

1. The water conduit on the roadless projects should be underground. In total, this involved the construction of 2 tunnels and 3 shafts. The Lidal HPP required shafts from 2 intakes connecting to a common headrace tunnel, i.e. a Y-shaped water conduit entirely in rock.
2. The discharge permit did not allow any deposit of rock masses from the tunnels in the seabed during the summer season.

In the client's main progress schedule, the construction start for the Lidal power plant was scheduled for 16.6.2015. Commissioning of the power plant was scheduled for 16.4.2018.

As a result of the parties' interaction, the water conduit for Lidal Power Plant was significantly changed. During this process, a favorable acceptance was obtained from the approving authority for an alternative "Y" solution for the intake structures at Lidal. The alternative allowed the "Y" to be carried out with a penstock pipe imbedded in a trench from the intakes of a common pressure shaft leading to the headrace tunnel. Hence, one shaft emanated from design, and the rock works were reduced both in scope and complexity.

In further planning, the contractor managed to compress the tunnel activities to last for only 1 autumn/winter/spring season. The chosen mobilization method made this timesaving possible using a barge with preinstalled tunnel setup, as a mobile mobilization platform. The chosen method made mobilization more efficient for the tunnel operations on both Lidal and Rømøyri respectively.

The above reduced the duration of the tunnel activities by at least one season compared to the original project schedule. A great example on how well-planned simple measures can provide considerable effect on both time and cost.

The original concept included the drilling of shafts from a cavern at the head of the headrace tunnel, from down and upwards. In such a concept, tunnelling and shaft drilling had to be carried out as successive activities. Changing the water conduit opened up the possibility of drilling the shafts in parallel to tunnelling.

Thus, the total construction time for Lidal HPP could be further reduced, and the deadline for completion and commissioning could be rescheduled to 5.6.17 in the project schedule, corresponding to approx. 10 months. reduced construction time.

In addition to the above, the startup point for the tunnel was moved/redesigned, and the work methodology for the cable shafts was changed. Each of the changes made a positive contribution to the project result.

In the tender documents for Romøyri Power Plant, commissioning of the power plant was scheduled for 12.2.2019.

The contractor's operational planning assumed that there were synergies to be gained by seeing the operation of Lidal and Romøyri as one unit. For this reason, construction start at Romøyri power plant was rescheduled. The update took into consideration that the units from the tunnel and shaft development at Lidal could easily be moved and reestablished at Romøyri after completing the prior. The choices posed a major and very positive impact on the progress of the project, allowing commissioning to start the 5.4.17, i.e. almost two years earlier than in client's original project schedule issued November 2014. A fantastic result from well performed planning foreseeing simple mitigative

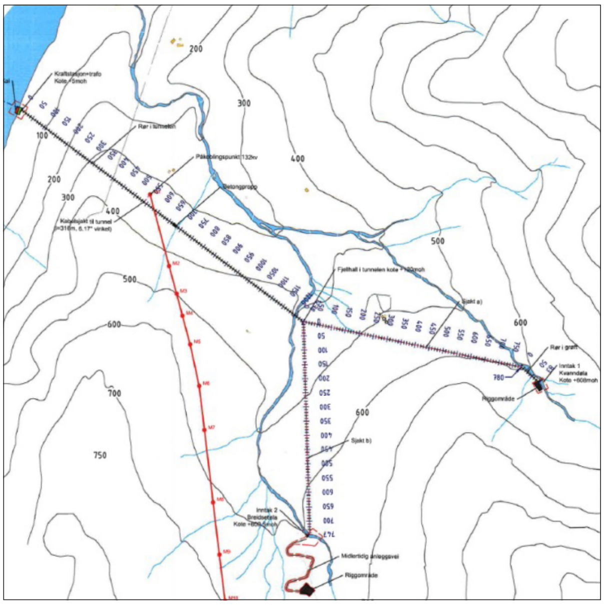

Figure 4.7. Original waterway.

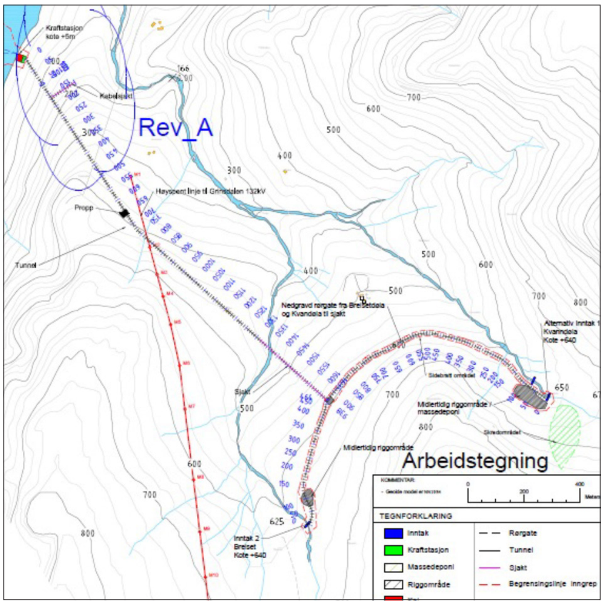

Figure 4.8. Final waterway.

actions providing added value for the project, due to an excellent result from the interaction between the parties.

However, some lastminute time changes had to be added after the above update. Increased construction volume and delays on the powerline construction, postponed the commissioning a few months. Despite this final delay, the project was completed a long time prior to originally planned completion. The benefits achieved for the owner have been substantial in view of early income from energy sales.

4.4 Operations without road access – Challenges and Logistics

The operations in the field started a little ahead of schedule in July 2015 with excavation and preparation of the construction site including the startup tunnel face for the headrace tunnel at Lidal. The tunnel excavation started on schedule at the end of August/September. Prior to this, major preparatory work had been carried out to make the mobilization and the following operation as efficient as possible.

Due to regulatory requirements from the authorities the construction site areas were limited and far smaller than required for a normal setup for tunnel operation. Thus, alternative methods had to be considered in order to mitigate the given conditions and the restrictions from the authorities.

As mitigative action to approach "normal" operational conditions, the contractor concluded to use a barge as mobilization and service area for the tunnel operations. The barge had a gross deck area of approx. 2500 m^2. This covered the contractor's requirements both for placement of necessary installations such as office and change facilities, workshop, emulsion storage, treatment plant for process water etc., as well as for the transport and disposal of muck in the sea in a safe and efficient manner.

After installing and filling the barge with equipment and machinery, the barge was towed to the Lidal site in the Fjærlandsfjord. Prior to arrival, the Lidal site was prepared for the reception of the barge. On arrival, anchors and moorings were placed, followed by mobilization work with connection of water, electricity, water purification facilities and a 20 m deep silt curtain installed around the deposit area to ensure that sediment from the muck did not go astray. All this had to be completed before the tunnel excavation could commence.

Four days after the barge's arrival, tunnel operations commenced, with a fully rigged support system. The chosen method developed in accordance with the environmental restrictions from the authorities and did not occupy areas beyond the assigned footprint. Using a barge as mobilization asea for the site installations made it extremely efficient to get started with the tunnel operations. Being able to utilize the same arrangement on 2 tunnel sites in succession, duplicated the time effect for both mobilization and demobilization.

The day-to-day operation of a construction facility on the "other side" of the fjord without road access places additional demands on logistics both on the transport of personnel and the supply of materials

Figure 4.9. Barge arrives at Lidal Power Plant (Photo: Christian Alseth).

and equipment. During winter, in particular during periods of unstable weather conditions, logistics were extra challenging. Under such conditions, the road from Fjærland to our shipping point was closed for days and weeks. Such incidents made transport by sea 9 km. longer than “normal”. To deal with these challenges, logistics were planned with a focus on establishing an as safe, efficient, and commercially advantageous transport route as possible.

As transport concepts the following were implemented in the project:

Staff transport was organized morning and evening and during shift rotation, with the "MB Vassvegen", a 35-foot combi boat, purchased for the purpose of transporting personnel.

For the operational staff, the project acquired an archipelago jeep as “foreman boat”. This boat added the desired mobility and largely replaced the “foreman pickup car” in use in a conventional facility.

For the heavier transport by sea to the Lidal and Romøyri sites, 2 alternatives were mainly used. Machine transport, transport of heavy equipment and material transport, as well as transport of the owner’s electromechanical equipment were carried out by ferry with landing possibilities. This solution was applied sporadically and only when the need for this type of transport was required and preferably when an accumulated and combined need was present in the project. The ferry handled transport up to approx. 150 tons, a very efficient transport method when large volumes had to be moved by sea. The ferry was also used as a quay for other vessels unable to deliver due to the lack of landing facility.

The day-to-day operations rarely handled very heavy supplies. The contractor came across a vacant fish farming boat named "Olivia" that fully settled his continuous transport requirements for the daily operations. The vessel had a large deck space for cargo as well as a crane for loading on and off supplies. With this boat, single supplies and machines with a gross weight of up to 8 tons could be moved efficiently. During tunnel operations, almost all deliveries were supplied with Olivia, including among others, all sprayed concrete. The contractor developed his own concept for these deliveries, which proved very efficient in every aspect.

Figure 4.10. MB Vassvegen (Photo: Christian Alseth).

In order to make the logistics as simple as possible, the project established a site for delivery and the reception of materials in Jordal. This site had road access, thus all deliveries to this site could take place using "normal" transport methods. The site was rigged for transport both by sea and air. The installation contained a quay, helicopter landing site, refueling facilities, etc. The site also contained a storage tent mobilized for any intermediate storage of materials, especially with regard to materials requiring dry and warm storage.

4.5 Tunnel Operations

The mountain massif in Fjærland is characterized by large rock stresses and rock bursts. The Lidal and Romøyri headrace tunnels were no exception. After about 200 m. of tunnel excavation rock burst entered as part of the daily operations on both tunnels. The amount of rock support (bolts and sprayed concrete) increased considerably. Despite the extra challenges these rock conditions posed to already tight logistics, the operations achieved excellent advance rates.

The tunnels were excavated with an average minimum cross section of approximately 22 m^2. The excavation was carried out with a 2 boom Atlas Copco M2 Jumbo with 16 feet feeders. The operational tunnel team consisted of 4 people holding multifunctional skills. This team-setup carried out all the occupations in the tunnel operations, working 2 shifts 12 hours each in a 12/16-day rotation (12 days at work and 16 days on leave. In total 4 teams were associated with the tunnel development including those on leave.

Very experienced teams performed the tunnel operations. The quality of work performed was excellent with good contour without deviation at the tunnel invert.

In the best production weeks, the operations achieved just above 120 m/week, and on average basis during the entire operation approx. 85 m/week advance rate.

The placement of the concrete plug in the headrace tunnel was determined by results from hydraulic jacking tests determining the minimum main stresses. For the Lidal site, the plug was planned to be placed at M 600. Satisfactory results from the hydraulic jacking tests determined new placement at M 950. This caused a significantly longer headrace pipeline than originally planned.

On Romøyri the plug placement went in the opposite direction. Satisfactory results were achieved at M 400 versus the originally planned at M 550. The final plug placement was decided at M 420.

4.6 Intakes and Shafts

Preparatory work for construction operations in the mountain areas at Lidal and Romøyri was carried out during the autumn of 2015, starting with the establishment of a site area for the shaft face for the Lidal Power Plant. Machines and equipment were flown into the site and assembled on site by helicopter. For accommodations, barracks were installed in the area. During this first stage, the contractor posed access to a "farmhouse" nearby for accommodation of the mobilization crew.

After completion of Lidal mountain site installation, machinery and equipment were moved to Romedal where the intake to Romøyri Power Plant is located, and the same work operations repeated.

The tunnel in Lidal ended at the bottom of the shaft. In order for this to fit as "hand in glove", drilling of the pilot shaft for Lidal power plant was planned to be completed simultaneously with the tunnel excavation. Hence drilling of the shaft had to be carried out during midwinter season. In order for this to be carried out safely, the contractor planned the installation of accommodation and a large work tent for the execution of the work at site.

The drilling required approx. 1000 l. water/min. A temporary intake was established 450 m beyond the work site, and water supply established in a winter insulated pipeline. For the process water, a sedimentation plant was established. Approximately 50% of the process water was reused in the drilling operation. Electrical energy was supplied through 2 major diesel generators installed on the work site.

The preparations for the site area were carried out in November 2015, below occasionally unstable weather conditions. On the 1st of December 2015 the mobilization of the Raiseborer equipment, accommodation barracks and work tents, started. The mobilization took place by helicopter. A total of 200 tons were flown in by about 90 flights. Flying in December is at the mercy of good flying conditions and acceptable lighting conditions. Luckily, good conditions were present, and within 3 days everything was in place. The time leading up to the Christmas holidays was used for mob. details, adjustment of Raiseborer and other preparations in order to facilitate the startup of the drilling after the Christmas holiday.

For the operations, all logistics, i.e. change of crew and supplies were carried out ones a week. There weren't always flying conditions on the scheduled flight day. Therefore, the contractor always planned with enough supplies on site in order to keep operations going for a few extra days if required.

As for emergency preparedness, a snowmobile was placed on the site. An emergency route was established from site to Grindsdalen in Leikanger, an approx. 18 km drive. The snowmobile was equipped with GPS instrument with pre-programmed driving route.

Later in the winter, when the snow had settled and conditions became more stable, a temporary winter road was established crossing the mountain area from Grindsdalen in Leikanger to the work site. On this road, heavier machinery and equipment were transported into the site for the work to be carried out the following summer, related to the intake structures and the pipe trenches for the waterway between the intake and the shaft. The road was also used to transport heavy equipment for the project owner.

The winter road was re-established the following winter, thus the machinery could return to the Grindsdalen area without causing visible wounds in nature.

Figure 4.11. Rig-installation at the Lidal shaft drilling site (Photo: Ola Kvammen).

Figure 4.12. Winter Road of snow (Photo: Ola Kvammen).

After establishing this, almost all site visits during winter season to the work facilities in the mountain area, took place using this road. At the most, the contractor had 4 snowmobiles operating on the winter road, some with sleds for simple operational transport.

After completing the drilling of the Lidal pressure shaft, the entire Raiseborer equipment was moved on the winter road from to the Romedal site, approx. 5 km. one way. The use of winter roads was very successful and efficient, and posed savings in the operations. The road was kept in roadworthy condition until the end of April, beginning of May.

4.7 Penstock Pipe, Trench and Intake

Work on the intake and penstock pipe trench started in early May 2016. For the operations, barracks for accommodation and household were established. The barracks rig accommodated at the most 14 people.

Logistics for the works were handled as for the winter works, changing crew and delivering of supplies once a week. During the summer months, there was also access through a footpath for those who wanted to walk up or down to/from the mountain sites.

The main challenge with intake development is usually related to the handling of the water during construction. Good interim solutions were developed. For intakes Kvanndøla (Lidal) and Romedal, the river was deviated trough new river courses. For Breisete (Lidal), the water was handled through an opening in the threshold.

The pipe trench for the Lidal intakes had a total length of about 1392 m. This was 269 meters longer than assumed in the original plan. A considerable

Figure 4.13. Intake Kvanndøla - Lidal power plant (Photo: Ola Kvammen).

part of the trench route went through rough and steep terrain, and in rock during large sections of the route. The increased length came to light before the winter road was discontinued for the season. The project thus managed to mobilize the required capacity to handle this increase in quantity and workload.

There is a 35 m. head from the intakes at Lidal to the shaft inlet. The marginal head allowed the use of PE pipes as a penstock line. The pipeline was flown in as 18-meter section lengths, and later welded together in the trench-bed, before covering with gravel. After completing the installation, the trench surface was returned and reestablished to original terrain as before the development started.

PE pipes proved themselves to be an excellent product in roadless off-the-beaten-path installations, both robust and flexible.

4.8 Concrete Works

The powerhouses on both power plants are built as portal buildings, partly on surface and partly in rock cavern. The buildings are mainly built of cast in place concrete and furnishings in lighter building materials. The powerhouse at Lidal also includes the project owner's substation HUB. This substation accounted for about 1/3 of the building area at Lidal.

Quays were built for both powerhouses. For the Lidal plant, rail tracks were installed from the substation HUB to the quay front for any mob/demob of the main transformer. Outdoor areas are allocated with ground erosion control in the seafront, and all terrains surrounding the powerhouses restored to their original surface.

At Lidal power plant, the concrete plug in the headrace tunnel was cast over 3 days starting on the 14th of September 2016. The downstream location for the plug is at M 950 in the headrace tunnel. The plug is 17 meters long and is located with an 18% gradient. The casting volume was 490 m^3. Pumping in this volume took exactly 50 hours. The delivery of concrete took place by ferry from Fjærland. Along the way, there were some challenges with the delivery due to the high tide and strong currents in the fjord. Beyond this, there were no major challenges.

During casting of the plugs, the concrete was retarded to control the curing. Separate routines were established for monitoring casting pressure. We had 2 pressure gauges installed downstream. Both measured results well below what the contractor had assumed his design of the formwork.

4.8.1 Penstock in headrace tunnel

Between the concrete plug and the powerhouse, a ductile penstock pipeline was installed. Each pipe had a length of 6 meters and a curb weight of 2600 kg. The pipes were assembled on concrete brackets anchored in rock with bolts. Very strict requirements were imposed on accurate execution.

The installation work on the pipeline had an industrial character, with the use of prefabricated products and repetitive operations. Pipes were transported from the Fjærland village to the construction site by ferry, and from there to the assembly site with a special device for the purpose. On site the pipe was hoisted into place and fastened with clamps connected to anchoring bolts.

4.9 Organisation and collaboration

The considerations from this development show that good interaction between the parties (the client, the client's partners, and the contractor) is a premise for improving the project basis in a positive direction, improving sustainability and increased value on the investment for both parties.

In this project, the parties were motivated to interact. Without this as a starting point, it's likely to believe a similar result would have been more difficult to achieve.

Working at roadless facilities requires good planning to make logistics work efficiently. At the Fjærland facilities, simple solutions, and actions a little out of the ordinary, were developed and chosen. These measures proved to have the desired effect on both the project result and the progress.

4.10 ITA Awards

During a ceremony in Paris in November 2017, the Fjærland Hydropower plant received the ITA's project of the year award for projects valued below EUR 50 million.

The Fjærland Hydropower plant was nominated for developing tunnels without any road infrastructure, with very strict environmental requirements. The project was nominated for its innovative way of solving challenges, and for relatively small interventions in surrounding nature.

Figure 4.14. ITA Award.

References chapter 4

Småkraft AS (2014), tender basis Fjærlandsanleggene, project E2 Fjellanlegg, E6 Intake, E7 Structural works.

Småkraft AS (2015), contract basis Fjærlandsanleggene, project E2 Fjellanlegg, E6 Intake, E7 Structural works.

5 Other Examples of Small Hydropower Plants

5.1 Drill and blast tunnelling

5.1.1 SMISTO – Smibelg and Storåvatn hydropower plants

The SMISTO project is divided into two separate plants, Smibelg power plant and Storåvatn power plant on opposite sides of Gjervalen fjord. Both are high-pressure hydropower plants in mountains with large storage capacity without the use of large dams. The water is transferred to the two power plants through a total of 27 km of tunnels and shafts. Smibelg has an installed power of 33 MW and Storåvatn has two turbines with installed power of 8 MW and 25 MW respectively. Both power plants use pelton generators.

The facility has no existing road connection and was built by using a ferry (3 km). Power stations, pipes, plugs, pumping stations, dams, intakes, hatches and several underwater openings are carried out from the power plants' tunnel system. Other dams, shafts, thresholds and stream intakes on the mountain was constructed by helicopter operation.

Model-based planning and execution with paper free deliveries has been developed in close collaboration with the contractor through a focus on tools, work methodology and interdisciplinary collaboration. This involves building information modelling (BIM) and has facilitated a more efficient execution and better communication between the parties involved in the project.

The tunnels had mostly 25 square metres cross sections, with some variations. The contractor used mostly the small two booms rigs from Atlas Copco, (the M2-model). However, Atlas Copco's E2- model was also used for parts of the tunnel. Häggloaders were used for excavating the rock masses.

5.2 TBM

5.2.1 Small Diameter Design: Holen Hydropower

The first tunnelling 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 5.1).

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 tunnelling 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

Figure 5.1. Double Shield Rockhead at Holen SHEPP (Photo: Endre Hilleren).

Figure 5.2. Breakthough at Holen SHEPP (Photo: Hardanger Maskin AS).

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 tunnelling 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 5.2).

5.2.2 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 be used 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 5.3). The 2.8 m diameter cutterhead is powered by four 210 kW Variable Frequency Drives (VFDs).

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 5.4).

Figure 5.3. TBM ready to start boring Salvasskardelva (Photo: Kalle Punsvik).

Figure 5.4. Crown-mounted conveyor at Salvasskardelva (Photo: Kalle Punsvik)

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.

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.

5.2.3 Mork HEPP

Mork HEPP was the 2nd tunnel bored with "Snøhvit" and NGK Boring AS (now Hywer AS). The project is situated close to Lærdal in the western part of Norway. With experiences learned from the previous project, it was decided to redesign the cutterhead by increasing the number of cutters from 19 to 20 cutters, and stronger material in cutterhouses. Thus, reducing the forces on the gauge cutters, which had been causing issues on prior projects. The project consists of an intake, 2,8 m diameter TBM bored tunnel and powerhouse with a Pelton turbine. The length of the tunnel is 3100 m with a maximum inclination of 14 %.

The job site sits only 30 m from the river, Erdalselvi, with limited space for assembly of the TBM. Such a small job site requires meticulous planning of the logistics, rig area and assembly. To assemble the TBM and conveyor structure in an efficient way, it was built a 30 m long bridge in two levels over the river. A special start frame was used to start the TBM without the use of a start tunnel for the grippers. The geology in the area consists of mainly hard intact Granite with at UCS ranging from 113 to 270 MPa (results from core drill testing). Such high compressive strength and small tunnel diameter resulted in very stable tunnel walls and resulted in low use of rock bolts. In the whole length of the tunnel there is only used 3 rock bolts. The tunnel boring was finished on November 12, 2021, with a breakthrough in the intake. Afterwards the TBM was retraced through the tunnel and dismantled at the rig site at the start of the tunnel. Although the geology was challenging the TBM performed well, and key learning points were used for the next project.

5.2.4 Øvre Kvemma HEPP

"Snøhvit's" third project was Øvre Kvemma HEPP, also located close to Lærdal in the western part of Norway. Øvre Kvemma has a relative short tunnel, 2200 m, and a big height difference, 300 m. Normally hydropower tunnels are bored flat for the first part of the tunnel to get as much overburden early as possible to place a concrete plug. For Øvre Kvemma this was not possible due to the height difference and the tunnel length. Therefore, the tunnel had to be bored with an inclination of about 16 % from the very start of the tunnel. This combined with hard intact granite in the area made the project quite tough for the TBM.

Despite this, the TBM bored on average about 100 m/week with some weeks exceeding 190 m/ week and 46 m/day. The breakthrough point in the intake only had a margin for error of 1 m on each side of the breakthrough point. With good planning, experienced crew and continuously measurement of the TBM position with the Enzan system, the TBM hit the exact point where it was planned for. After the breakthrough the TBM retraced through the tunnel using the grippers in reverse and special sleepers to keep the TBM from riding up the tunnel walls. Øvre Kvemma stands out as a successful project for "Snøhvit" and small HEPP tunnel boring in Norway.

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 tunnelling looks poised to continue making a big impact in Norway.

6 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.

Underground solutions are becoming more and more common in SHPP's in Norway. The reasons can vary, but keywords are environmental aspects, topographical conditions, safety and lifetime cost. With a future development of equipment, underground solutions will be even more competitive in the future, and will definitely be adapted into the international market.

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.

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