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Strategic management of water-filled tunnels

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ABSTRACT

In Scandinavia and worldwide, rock tunnels are largely used to transport water in many industries and municipal activities, e.g. hydro and nuclear power, water transport for drinking and wastewater, raw water supply to industrial facilities, etc. These tunnels are usually constantly filled with water but need monitoring and maintenance inspections at regular intervals.
According to the Swedish Energiforsk report (2021:730) "Inner waterways in a hydropower plant commonly have very limited access for inspections and some have never been inspected since the commissioning. Many plant owners lack systematic management of the inner waterways”. We do believe that this problem exists not only in Sweden and not only in hydropower plants.
Degradation of tunnel structure has many similarities in dry and water-filled tunnels; in the water-filled state, however, the hydrostatic pressure and its variation as well as physical erosion by flowing water are also added as possible negative factors.
Tunnel inspections must affect operations as little as possible. This can be achieved by performing inspection and maintenance with a ROV (Remotely operated vehicle) equipped with sonar, cameras and measuring instruments without emptying the tunnel of water and under safe working conditions. The combination of the correct size of the ROV and the length of the cable allows the inspection of tunnels of up to 20 km from a single-entry point.
We present the technical capacity of ROVs equipped with 3D sonar and examples of geological interpretation of inspection results from water-filled tunnels and maintenance solutions. We argue that a ROV equipped with 3D multibeam sonar is currently the most advanced instrument for performing inspections of water-filled tunnels in a safe work environment manner and should be considered as one of the tools for strategic management of inner waterways.

KEYWORDS

Hydropower; ROV; sonar; inspection; tunnel

INTRODUCTION

In Scandinavia and worldwide, rock tunnels are largely used to transport water in many industries and municipal activities, e.g. hydro and nuclear power, water transport for drinking and wastewater, raw water supply to industrial facilities, etc. These tunnels are constantly filled with water but need monitoring and maintenance inspections at regular intervals. Due to limited accessibility, challenging dewatering procedures and associated work environment risk, conventional inspections in dry conditions are rare or executed at irregular intervals.

The strategic management plans for any industry must indicate the risks and plan for mitigating actions to secure continuous operations and long-term safety. An accident that affects operation can cause a long rehabilitation time and associated high costs as well as production break which can become more costly than rehabilitation itself.

When it comes to tunnels, many parameters must be encountered to produce a reliable risk assessment. Some of these parameters depend on geotechnical conditions, construction methods or material types and can be challenging to assess without proper documentation and monitoring.

Developing a strategic management plan with regular inspection and maintenance plans might contribute to secure operation and avoidance of unexpected failures. In water-filled tunnels, an inspection with the ROV should be considered an important tool and should be considered a necessary part of the management plan.

1. DEGRADATION OF TUNNEL STRUCTURAL INTEGRITY

Degradation of a tunnel structure has many similarities, regardless of whether it occurs in dry or water-filled tunnels. In a water-filled state, the hydrostatic pressure and its variations, as well as abrasive water flow, are added as possible influencing factors. The main features affecting the structural integrity of a water-filled tunnel can be summarized as:

- Degradation of the rock mass (e.g. due to poor rock quality, swelling clays, blasting damage and rock stresses).
- Degradation of rock bolts (e.g. corrosion of unmolded bolts, leaching of cement mortar, chemical degradation of cement mortar)
- Degradation of shotcrete/cast concrete/lining (e.g. carbonation, leaching, erosion, corrosion of fibers/mesh, spalling).
- Variations in hydrostatic water pressure (e.g. pressure stroke, swelling or negative pressure during load changes or shutdowns).

2. MAINTENANCE STRATEGY FOR WATER-FILLED TUNNELS

At present, to our knowledge, there are no industry practices, manuals/guidelines or international/national regulatory requirements for the inspection of water-filled tunnels. Tunnel owners handle the maintenance based on their own best practice. The Swedish Energiforsk report (2021) suggested minimum inspection intervals for inner waterways in Hydropower plants depending on different parts of the power plant. The parts between the intake gates and the draft tube gate should be inspected at an interval of 6 to 12 years. The parts outside these gates should be inspected for at least the interval of 25-50 years. The advice on planning, requirements, and execution is suggested in the report. It remains to see if the suggested management strategies will be adopted by the industry.

3. ROV/AUV

An ROV can operate in a tunnel without dewatering and under safe working conditions. A so-called ROV (Remotely Operated Vehicle) or AUV (Autonomous Underwater Vehicle) equipped with sonar, cameras, and instruments for measuring and sampling is used. The main difference between these vehicles is that ROV is operated with an external power supply and AUV is powered by an internal battery. An AUV (Figure 2) can run in fully automatic mode or be operated by a pilot. In piloted setup, the AUV uses a fiberoptic cable to enable communication between the pilot and a vehicle. An ROV has the advantage of an unlimited amount of time for operation but has distance limitations due to the power supply tether. A distance of up to 7 km from the entrance point is reachable with the ROV. An AUV, on the other hand, has a limitation on battery capacity and time of operation is limited, however distances of more than 20 km from the entrance point can be reached.

For tunnel inspections, so-called ‘inspection’ or ‘mid-sized ROVs’ are most often used (Figure 1). They usually weigh between 100kg and 1,000kg and are optimized for medium depth and long range.

The ROV/AUV can be adapted to specific needs and tunnel dimensions. Factors to be considered in the choice of ROV/AUV are tunnel length, size and layout; the size of the inspection hatch; and possible obstacles in the tunnel. The challenge is to achieve an optimal balance between the size and thrust power to be able to navigate in close spaces, and at the same time in the case of ROV, be able to pull the tether (data cable and power supply) for long distances from the access point.

The access point to the tunnel varies and can be an open water basin, swell tower, inspection hatch or access tunnel. At the water surface, the ROV/AUV is released and moves submerged in the water using thrusters. Tether for power and data transmission has the same density as water, providing neutral buoyancy and permitting long-distance runs. ROV/AUVs typically move at an average speed of 1km/h.

Figure 1. Several types of ROV. Loxus Explorer (left) 3D sonar, remote cameras, LED lights, range up to 7km; SEAMOR Marine Chinook - multibeam sonar, cameras, lighting, range up to 2000m.

Figure 2. AUV (Saab Sabertooth. Double hull) can be equipped with 3D sonar, remote cameras, LED lights, range of more than 20 km.

An important feature for correct sonar data calibration is an Inertial Navigation System (INS) used in ROV/AUV. Inertial Positioning System continuously calculates the position, orientation, and velocity, of the moving vehicle and associated sensors without the need for external references (Figure 3). The INS consists of a Ring Laser Gyro (RLG) or Fiber Optic Gyro (FOG) and a Doppler Velocity Log (DVL).

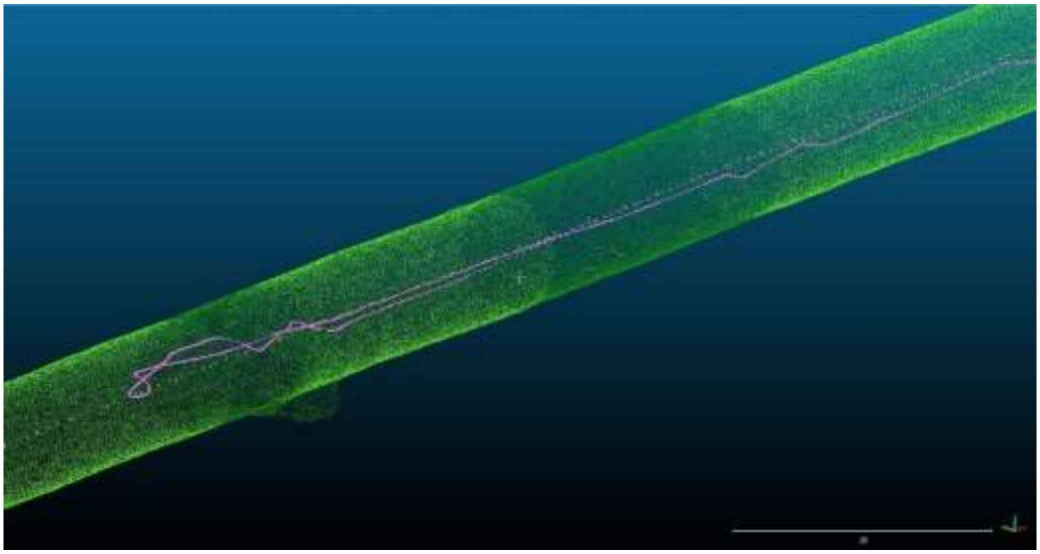

Figure 3. 3D model of a circular tunnel with the path of ROV. The 3D data set was collected in an 11.5 km water diversion tunnel, and the purple line shows the flight path of the ROV. The onboard INS system allows for the data set to remain smooth and consistent even if the path of the vehicle is irregular.

4. SONAR TECHNOLOGY

A device using sound to identify objects in the water column is referred to as a SONAR (SOund NAvigation and Ranging). Active sonars produce their specific sound waves and analyze the reflection of the emitted waves. The multibeam sonar is used to visualize surfaces and objects. With low-frequency waves generated image can have a lower resolution but covers large area scans as compared to ultra-high-resolution imaging with high-frequency waves which has a limitation of a small view field and a short distance to the object. Equipping an ROV/AUV with sonar makes it possible to scan tunnel geometry and produce ultra-high-resolution imaging even in poor or zero-visibility conditions.

5. INSPECTIONS DATA

During the inspection, tunnel condition is assessed by a rock/tunnel engineer via live streaming of sonar and video data. Video inspection is easy to interpret directly, however, may be unusable in high turbidity water and poor visibility. The biggest advantage of sonar data is that the technology works in poor visibility conditions and is independent of lighting and water quality.

5.1. Video data

During the inspection, the tunnel engineer has the opportunity to follow the ROV inspection through streaming video received from several cameras. The video streams are usually directed towards the tunnel bottom, walls and roof. In good visibility, these different streams can be important tools to evaluate geological parameters (e.g. lithology, blockiness etc.) and the status of the reinforcement (e.g. exposed parts on bolts, shotcrete, and concrete/steel elements) (Figure 4).

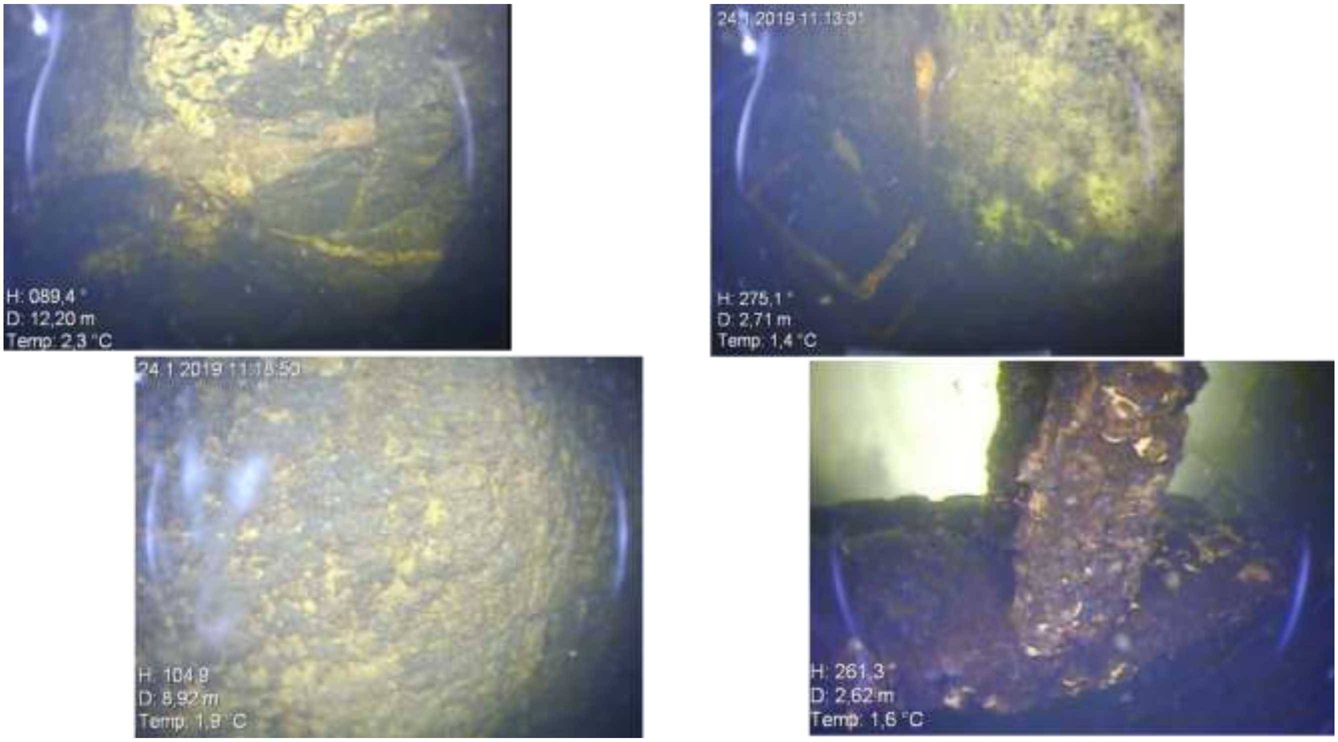

Figure 4. Still images from the video cameras. Top left- a lithological variation of the granitic gneiss; top right- cast concrete structure with an indication of porosity and miscolouring; lower left- the surface of the shotcrete reinforcement with no signs of degradation besides small cracks; lower right- heavily corroded steel structure.

5.2. Sonar scanning

A single beam-scanning sonar can be used to provide line profiles at periodic intervals. This required the ROV to be held in position for the conduction of every single scan. It generated limited coverage, pure data traceability and slow inspection speed. The development of multibeam sonar (ex. Teledyne Marine, BlueView T2250) proved to be ideal for tunnel inspections. Loxus 3D Tunnel Inspections was the first ROV operator to equip its ROVs with this new 3D multibeam sonar. The BlueView T2250 is a state-of-the-art, compact system, specifically designed to produce 3D data suitable for the inspection of tunnels with centimetre precision. The system uses high-frequency, low-power acoustic multi-beam technology and uses 2,100 overlapping narrow 'beams' to create a continuous 360° profile. The multibeam sonar operates at a frequency of 20Hz and creates a dense 3D point cloud. BlueView T2250 sonar is suitable for use in tunnels with a diameter of 2m-15m. Accuracy within the range of some centimetres that is achievable with 3D multibeam sonar is sufficient to document the tunnel geometry and the reinforcing elements of concrete/steel, and identify and quantify rock bursts, tunnel collapses, sediment accumulation and other phenomena (Figure 5).
The 3D sonar data can later be used to create a full 3D model of the whole inspection interval from the point cloud data. The detailed analysis of collected sonar data can be analyzed by a rock/tunnel engineer to indicate and qualify observed failures in a 3-D model (Figure 6).

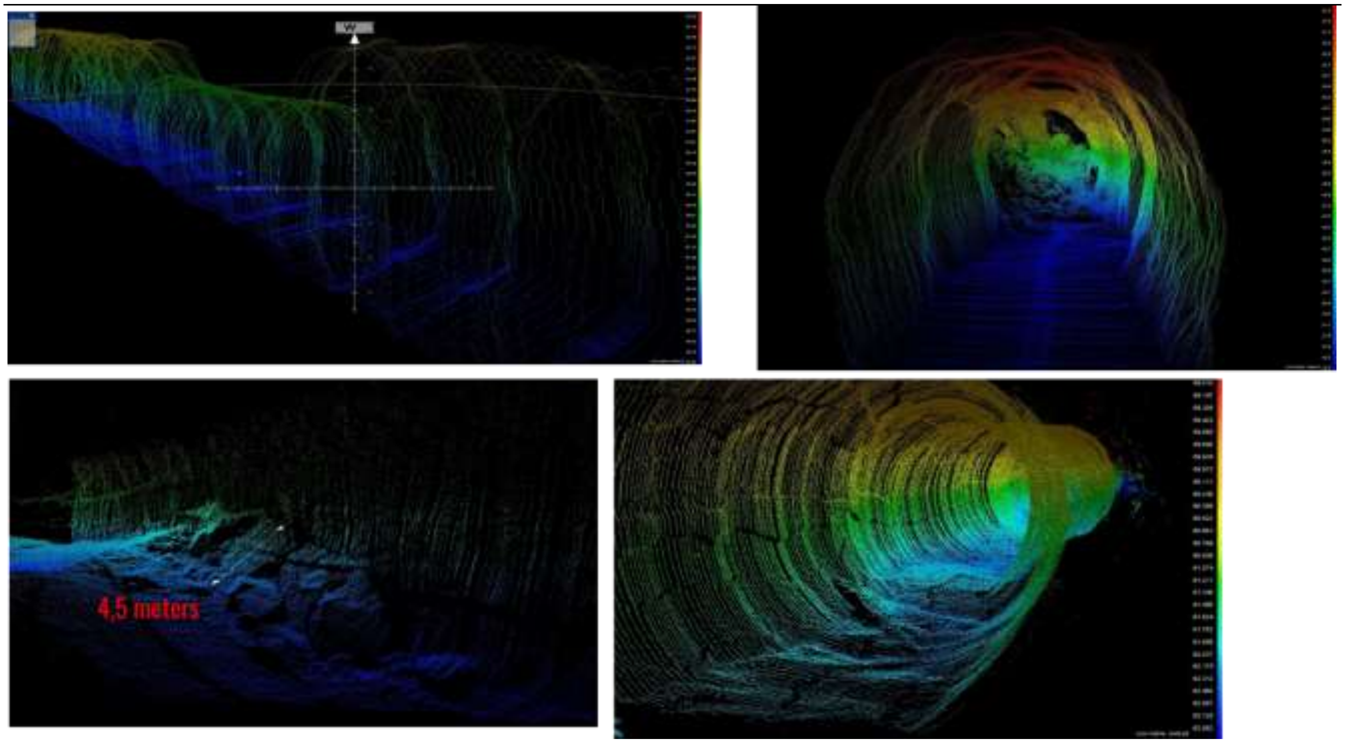

Figure 5. Multibeam sonar data showing various geometries of the scanned tunnel.

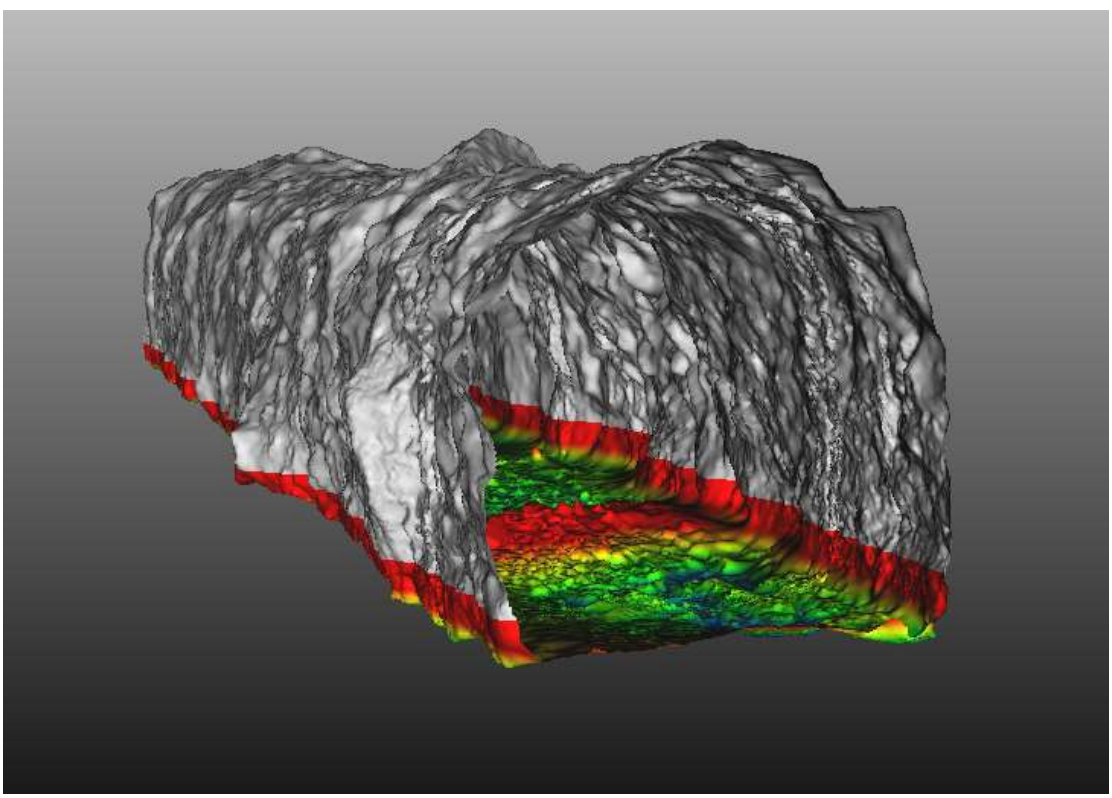

Figure 6. A 3-D model of the tunnel segment indicating the pile of debris under the crown feature.

The same multibeam data can even be used to create a digital twin model of a particular segment or elements of the facility. In hydro power plants an accurate model of ex. Penstock (Figure 7) or a draft tube (Figure 8) can be generated.

Figure 7. Model of a penstock generated from multibeam sonar data.

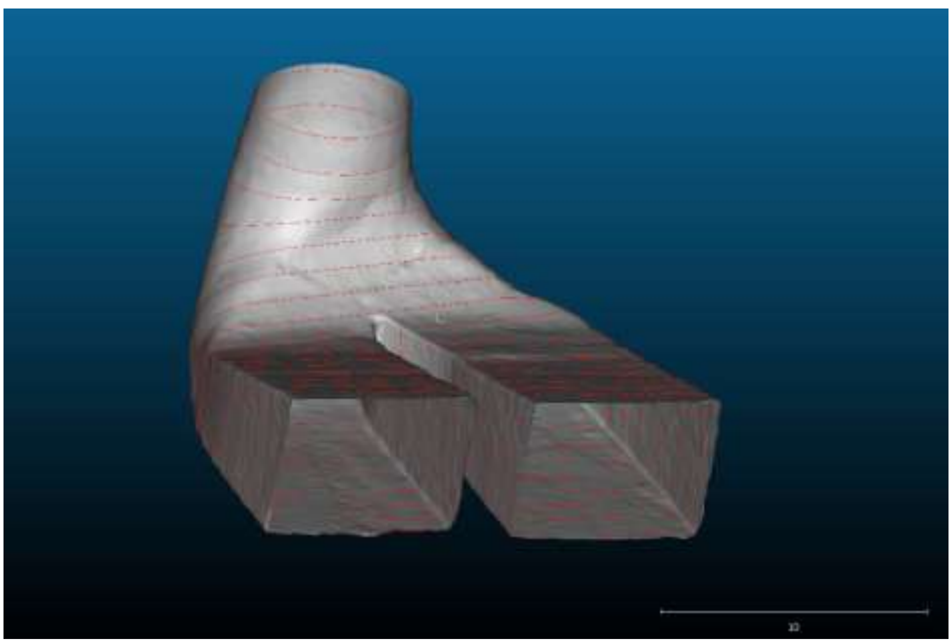

Figure 8. Model of a draft tube generated from multibeam sonar data.

5.3. Imaging sonar

High or ultra-high-resolution imaging sonar allows for images of damage underwater in low or zero-visibility conditions. These are also multibeam imaging sonar, only these are taken with a higher frequency unit. The downside of this sonar is that its field of view is smaller and most suitable to spot-check particular areas of known concern. This image data allows for smaller features such as cracking to be identified ex. inside pre-cast liner sections. This gives qualitative data on various features of interest along with allowing those features to be positioned by tunnel station and tunnel quadrant. These images (Figure 9) with feature locations identified allow comparing features in the same locations over multiple inspections to see if there have been any changes that may be cause for further monitoring or remediation.

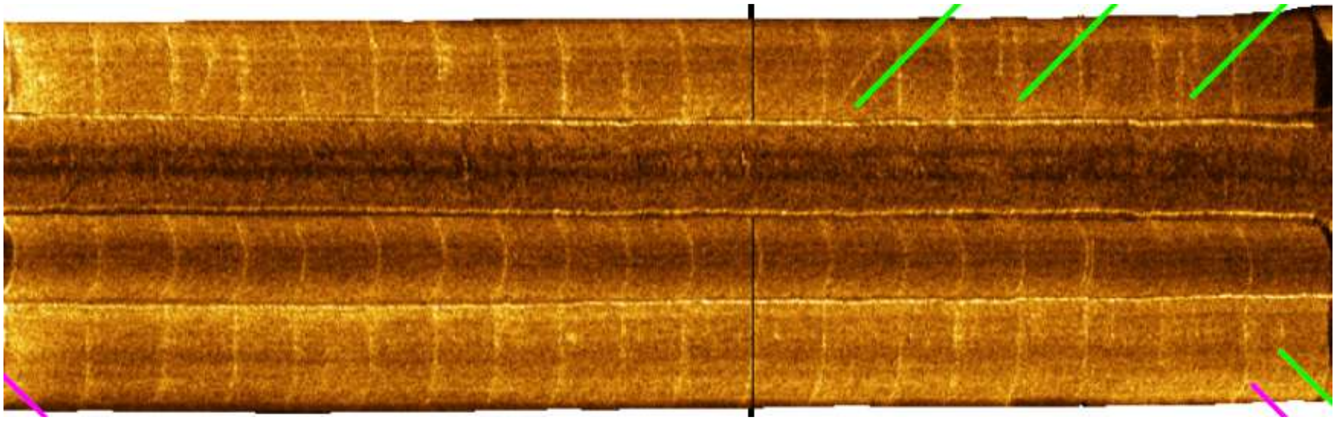

Figure 9. Sonar mosaic captured with multibeam sonar of unrolled concrete-lined tunnel (ca 50 m long section). Mosaicked multibeam imaging sonar images of the internal tunnel surfaces from the 9 o'clock, 12 o'clock, 3 o'clock, and 6 o'clock positions concurrently, geopositioned within the tunnel. This image data allows for smaller features such as cracking to be identified inside pre-cast liner sections.

This imagery can be collected at the same time as the 3D sonar scanning allowing for better characterization of anomalies that don't have large dimensional variance such as minor spalling (Figure 10), cracking and exposed steel structures (Figure 11).

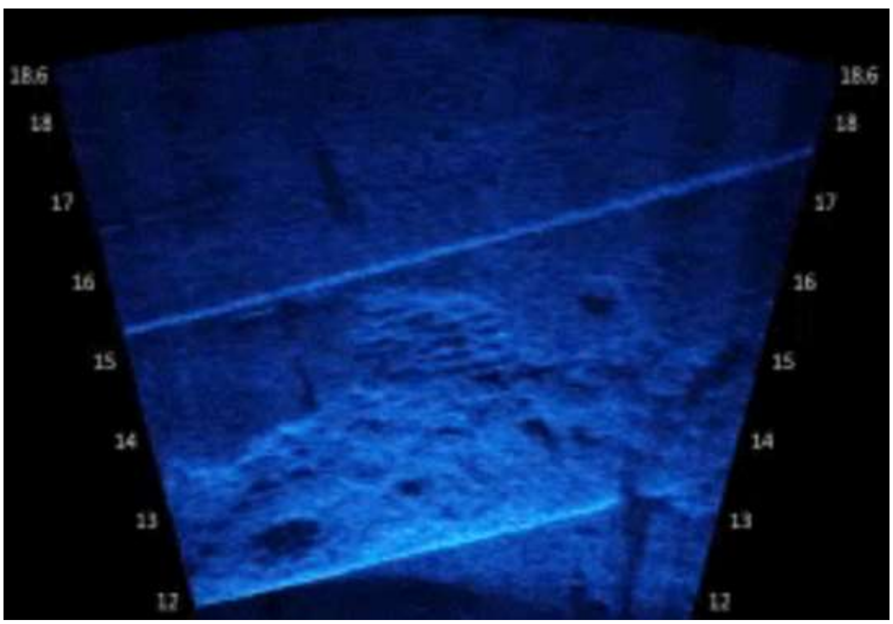

Figure 10. Spalling of cast concrete surface with exposed rebar shown with ultra-high-resolution imaging sonar.

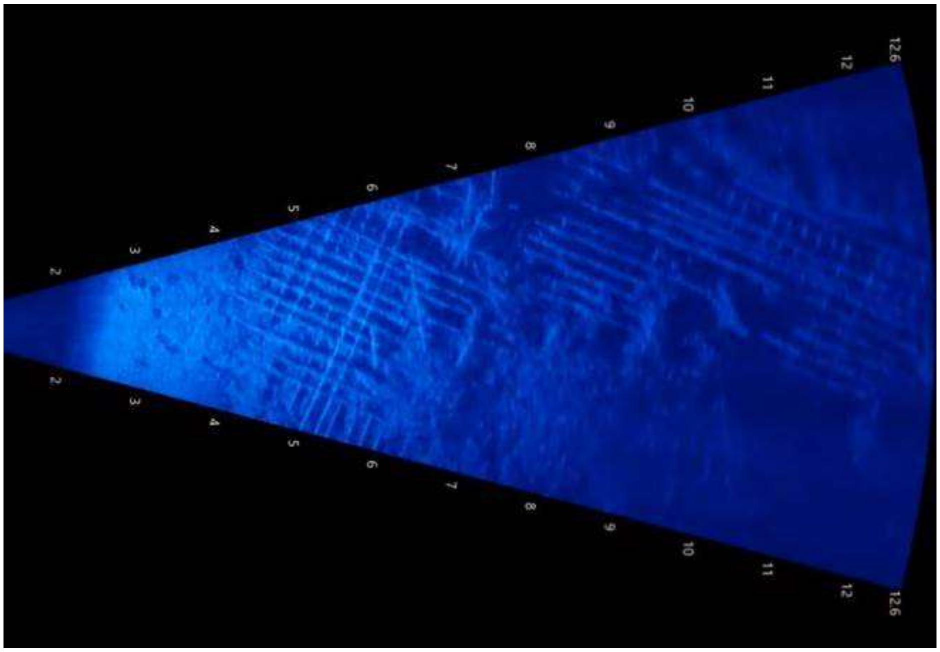

Figure 11. The exposed rebar is shown with ultra-high-resolution imaging sonar.

6. RISK ASSESSMENT OF STRUCTURAL INTEGRITY

Assessment of the structural integrity of the tunnel based on sonar and visual data collected with the ROV/AUV without dewatering brings an opportunity to identify and quantify the damages and base a risk assessment on actual observations rather than on historical data if any or subjective opinion. Relatively easy accessibility and short-time effect on facility operations caused by ROV/AUV inspection allow monitoring of the damage and assess its propagation on regular bases. Geological parameters (e.g., lithology, blockiness, orientation and character of fractures or weakness zones etc.) and the status of the reinforcement (e.g. exposed parts on bolts, shotcrete, and concrete/steel elements) or cracks and spalling in lining structure is a list of parameters which have to be used to evaluate the probability and possible consequences of the failure. Therefore, access to an experienced and trained rock/structural engineer and a careful analysis of all available data is required to be able to make an overall assessment of the structural integrity of the tunnel.

7. RECOMMENDATIONS ON ACCESS POINTS

Inspection with ROV/AUV requires access to the water surface at the waterway. The access point has to be formed in a way that allows to raise and lower the ROV/AUV directly to the water surface. There is a large variation between facilities concerning the access point for the ROV/AUV inspection. In general, access points can be summarized in the following groups:

-access from an open water reservoir,

-access through service tunnel,

-access through inspection hatch (indoor or outdoor).

Each type of access point requires a specific approach and detailed planning. In existing facilities preparation must be made by means of assess roads, lifting equipment, electricity supply etc.

In the case of the design of new facilities or major reconstruction works of the existing ones comes an opportunity to design the facility that includes even planning for future inspection works. Each type of access point requires a specific approach, but general recommendations could be summarized as follows.

1 -The access point has to be accessible by road design for truck transport.

2- At the access point outdoor requires an area for unloading the equipment, an establishment area for equipment and control center and if needed lift crane.

3- If access is through a service tunnel, the slope and pavement must be suitable for the wheel loader.

4- The size of the inspection hatch should be at least 2x3 m for easy access with any type of ROV/AUV.

5- If the inspection hatch is indoors there should be a possibility to transport the equipment with a wheel loader or traverse.

8. CONCLUSIONS

An ROV/AUV equipped with a multibeam sonar is currently the most advanced tool for the inspection of water-filled tunnels in an efficient and HSE-safe manner and should be considered one of the crucial tools for the Strategic management of inner waterways.
The combination of the sonar and video data provides an opportunity for a trained tunnel engineer to make an overall assessment of the structural integrity of the tunnel without the extremely costly and time-consuming process of dewatering and executing a physical inspection. Geological parameters, the status of the reinforcement or lining structure is a list of parameters which have to be used to evaluate the probability and possible consequences of the failure. Experienced and trained rock/structural engineers and a careful analysis of all available data are required to be able to make an overall assessment of the structural integrity of the tunnel.

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