MONITORING OF THE SUBMERGED STRUCTURES OF DAMS

E Isomäki[1] and K Hänninen[2]
1. ELY Centre for Häme, Hämeenlinna, Finland
2. VRT Finland, Jyväskylä, Finland

PUBLISHED IN ICOLD SYMPOSIUM 2016, SOUTH AFRICA

ABSTRACT

There are about 450 dams in Finland that are classified as set out in the Dam Safety Act. All classified dams must have a monitoring program approved by the dam safety authority. Monitoring of the underwater structures of concrete dams is generally included in the monitoring program. Typically, the interval for underwater monitoring is ten years.

It is seldom possible to empty the dam reservoir in Finland. So far, underwater inspections have been conducted by a diver. Water is often murky in Finland (the percentage of solids is high) and therefore the diver’s view of the dam is insufficient. Recently, sonar scans have been introduced as a technique to perform underwater monitoring. The dam safety authority of Finland wanted to find out about the basics of the sonar technology in question and how well sonar scans work when investigating the underwater structures of dams. VRT Finland Oy submitted a report to the dam safety authority on the subject. The report gives examples for producing 2-dimensional and 3-dimensional models of underwater structures. There are several examples for different dam types and types of damage that have been discovered by sonar scans.

1. INTRODUCTION

In some countries the underwater parts of dams are inspected by emptying the reservoir on a regular basis and in other countries this is done if necessary. In Finland emptying the reservoir is in most cases not possible. Many dams are located on rivers. Emptying the reservoir could create problems for other dams upstream or downstream, and could destroy fauna and flora in parts of the river.

All classified dams must have a monitoring program in Finland. Monitoring the underwater structures of concrete dams is included in the monitoring program. Typically, the interval for underwater monitoring is ten years.

Water in Finland has a high percentage of solids and the colour of the water is dark. The diver can usually see very little of the dam and sometimes inspections are undertaken virtually by feel. A strong current, deep water, lack of visibility and debris accumulation complicate the work of the diver.

This paper provides an alternative to inspecting underwater structures without emptying the reservoir. The alternative is the sonar scan.

The dam safety authority in Finland requested a report on sonar scans from VRT Finland Oy. This paper represents the completed report. (Hänninen & Auer 2015)

2. SONAR BASICS

Sonar is an acronym for SOund Navigation And Ranging. It is acoustic location in which sound in used to determine the distance and direction of an object.

Sonar scans are based on an acoustic pulse. An active sonar uses a sound transmitter and a receiver. By sending a specific pulse of sound and then listening to the reflection (echo) as it returns, the sonar can provide data points on the target object. The data points are then used to produce a two-dimensional (2D) or three-dimensional (3D) model of the target. A 2D image is a surface projection of the target.

Deformations can be shown as changes in colour and true shadows. 3D data points are collected as a point cloud. These points are defined by X, Y, and Z coordinates. The device measures a large number of points on the surface of an object and outputs the measurements in the form of a data file. The point cloud represents the set of points that the device has measured.

There are five factors that affect the results of a sonar inspection:

- The velocity of the sound pulse in water
- The frequency of the sound pulse
- The shape and opening angle of the sound beam
- The acoustic footprint
- The shape and the material of the target object.

The sound velocity (the acoustic pulse) is very important, because data calculations are based on it. Sonar measures the time the acoustic pulse travels between the target and the sensor. The velocity of the acoustic pulse in water is 1410 m/s – 1550 m/s under normal conditions. The water temperature, pressure (depth) and salinity modify the velocity of sound. These three factors must be known when sonar inspections are undertaken. The sound velocity must be verified on a regular basis during the sonar inspection.

The frequency of the acoustic pulse (sound beam) affects the results. The frequency of the sonar beam can vary between 2 and 2000 kHz. With higher frequencies the sound beam is narrower. With lower frequencies the sound beam is wider. Lower frequencies have longer range and frequencies under 100 kHz go through sediment layers. Therefore a low frequency sonar is used for creating sub-bottom profiling systems. On the other hand, a high frequency pulse dampens less and the end result is therefore more defined. The sound frequency and the pulse must be modified and calibrated to suit the conditions.

Typically, sonar creates one pulse of sound and the echo is listened fan-shaped or conically. Hundreds of data points are received simultaneously. A fan-shaped is used to create 2D material and a conical for 3D material. The latter is narrower and therefore the geometrical distortion is insignificant. The acoustic pulse expands as it travels.

An acoustic footprint is the area that an acoustic pulse catches. With longer distances the acoustic footprint grows larger. With a smaller acoustic footprint the results are more sharply defined. Data points for the results are saved from the middle of the footprint.

Coarse surfaces are usually easier to scan than smooth surfaces. If the target is parallel to the acoustic pulse, it is probably not detected and another scanning point is needed. If the target is perpendicular it is easy to detect. Various shapes and materials reflect the sound beam in different ways.

An inspection of a structure requires that all five factors are taken into account. The velocity, frequency angle and form of the sound pulse as well as the acoustic footprint are equipment technique attributes. The target shape and material must be understood by the operator in order to achieve the best results. The sonar equipment must be adjusted and positioned properly.

Air bubbles may disturb scanning. If scanning is performed on the back side of the hydropower plant or spillways, bubbles may block part of the scanning area.

3. DIFFERENT SONAR DEVICES

There are several different types of sonars for various purposes and of varying utility. Sonars have been developed to scan the seabed. Some sonars can be applied to inspect structures if both the sonar functions and basics of structure inspections are well understood.

Sonar scanning is a safe way to inspect underwater objects because only the scanning device is in the water. A hydropower plant can continue with production during the inspection.

3.1 Scanning sonar

A stationary scanning sonar can produce very precise 2D and 3D images. The sonar usually emits one sound beam at a time. When the sensor rotates around its axle, the scanned area is widened. A stationary sonar is relocated several times and new scan is completed. Scanning results are combined for a sharp and clear image. With a stationary sonar it is possible to re-position the sonar in such a way that no blind spots remain.

When underwater structures are inspected, the frequency used is typically 700 – 2000 kHz. With higher frequencies the acoustic pulse is narrower and the results sharper. If the frequency is higher, scanning must be performed closer to the target and the sonar must be re-located more frequently. Sonar is used for inspecting underwater structures but it is also used for example guiding a diver, searching missing persons and small scale seabed topography.

A scanning sonar can be used to create 2D or 3D images. In both cases the method is suitable for inspecting underwater structures.

3.2 Multibeam sonar

Multibeam sonar equipment is usually installed in a vessel. By using a Multibeam sonar in a moving vessel, a relatively extensive area can be scanned in a relatively short time. Typically, sonar creates one pulse of sound and echo is detected fan-shaped. Hundreds of data points are received simultaneously.

Scanning is done by steering a vessel along specified lines. GPS and inertial measurement units gather data for accurate location and position, simultaneously with the sonar observations. These data are combined with a timestamp to form a 3D point cloud.

The frequency of a multibeam sonar is typically 200 – 700 kHz. Due to the relatively low frequency, the sound wave does not weaken too fast. This allows target location in relatively deep waters. On the other hand, the final image is not very sharp and small details may not be detected. Multibeam sonar scanning requires a minimum water depth of around 1,2 metres.

The fast fieldwork of multibeam scanning has increased its use in structure inspections. The device is directed in such a way that the angle to the target structure can be optimised for data gathering. When inspecting structures, the scanning is performed as close to the target as possible and with the highest possible frequency (~ 700 kHz). This way, the acoustic footprint remains as small as possible and the final result is as sharp as possible. One challenge in multibeam scanning is the fixed positioning of sonar equipment in the vessel. The optimum angle for scanning is occasionally hard to acquire and some blind spots may remain.

3.3 Low frequency sonar (Sub-bottom profiling system)

Low frequency sonar normally uses frequencies from 2 to 20 kHz. An acoustic pulse is sent and a receiver records the reflection. Some pulses are reflected from the bottom but some will penetrate the bottom and be reflected when hitting a change in density, for instance a pipeline or a sediment layer. Reflections from different sediment layers look different in the resulting picture.

This type of scanning is used for locating bedrock, different soil types and their layers. The results are 2D images. They show the soil type profiles of selected inspection lines. The results are useful when, for instance, structure foundations are planned and/or load carrying capacity is required. Borehole samples are often needed to complement the results.

3.4 Side-scan sonar

The frequency of a side-scan sonar is typically 400 – 1200 kHz. The side-scan sonar is often used to detect a wreck or other underwater objects. The scanning is performed in a moving vessel. The sonar equipment can be installed under a vessel or it can be trailed behind it. A blind area remains in the scanning area but this is rectified by using an array of multiple scanning lines.

A side-scan sonar produces 2D images. The inspection data is very similar to the 2D images of a rigid positioning sonar but the resolution is lower. Side-scan sonar is not recommended for inspection of underwater structures.

4. OPTICAL METHODS

Laser scanning (3D scanning) is a precise and speedy way to collect material on the structures above the water surface. Laser scanning is based on a laser pulse sent from the scanner and then scanned as the reflection of the pulse returns. Laser scanning equipment may be stationary or mobile. There are three factors that must be known; the velocity of the laser pulse, the angle at which the pulse is emitted and the angle of the return reflexion. As with sonar, the scanning result contains data points of distance and location. These data points create a three dimensional image (point cloud) of the target. The point cloud produced by the surface structures can be combined with a three-dimensional point cloud of underwater structures made using, for instance, sonar scanning. Together they produce an impressive and useful tool for inspecting the structures or as a tool for repair planning.

Laser scanning is also possible under the surface. However, particles suspended in water reflect the laser light and create noise points. In Finland the surface waters are usually murky and therefore underwater laser scanning would have to be performed very close to the target and it would be an extremely slow process, or even impossible.

Other ways to do the underwater inspections are the visual ways: photography and 3D photography and with a remotely operated vehicle. Of course, a diver can perform the inspection as well. These all are suitable methods, but murky water, a shortage of light and strong currents make the inspections more challenging. With these ways the inspections also have to be undertaken in very small sections. The benefits of using a diver is that the necessary samples can be taken at once.

5. FURTHER PROCESSING OF THE RESULTS

When scanning is completed, further processing is required. In 2D scanning this means combining images into panoramic displays. The images are analysed and the pertinent comments are added to the pictures. A written report is also added to the data.

The processing of 3D data takes a little more time but there is also added utility in the scanning results. 3D point clouds scanned at different times can be compared. CAD drawings are possible both in 2D and in 3D format. The coordinate and elevation set can be changed if necessary. The extent of damage, that is, the depth or volume, can be measured from the point cloud (3D) and sketches can be added later.

The processing of collected 3D data starts with the cleanup of noise points. If different scanning equipment have been used, the results are combined. Then illustrations are made. These images can be rotated and thus images can be viewed from different angles. Post processing can be taken all the way to BIM (building information model) where different types of detail - and additional information such as material or reinforcing bars - can be included in the model.

6. COMPARISON BETWEEN METHODS

Sonar scans have many advantages when comparing to visual inspections (diver, photography…). Sonar scans are relatively fast. The results are pinpointed accurately and extensive totalities can be illustrated. Sonar is a safe way to perform an underwater inspection because only the device is in the water. A hydropower plant can continue with production during inspection. Bubbles in the water do however disturb the scanning. Also, a diver is able to take samples during the inspection and clear the inspection target by hand.

The 2D method is best for permanent concrete, timber and stone structures. Long and thin parts, such as piles, are hard to detect. The image shows the area of possible damage but not the depth of damage. Scanning is best performed with a stationary scanning sonar. The perception is 5 – 20 cm depending on the equipment and personnel skills. It takes 4 – 10 days to scan 500 metres of dam.

The 3D method presents possible damage and depth of damage. The results can be entered when calculating the volumes or tracking changes, for instance. 3D scanning is performed using stationary scanning sonar or multibeam sonar. Perception with a scanning sonar is 2 – 5 cm and with a multibeam sonar 5 – 10 cm. The multibeam sonar is faster. 500 metres of a dam structure can be scanned in an hour. With a scanning sonar, around 10 metres of dam takes about an hour. Multibeam sonar is installed beneath a vessel. There may be some blind spots in the results. Such blind spots can be separately scanned using a stationary scanning sonar and the 3D results can then be combined.

In Finland it is not possible to use laser scanning for inspecting underwater structures. The structures above water can be scanned using a laser scan or 3D camera. This material can be combined with underwater 3D material and create a functional work tool.

7. CASE STUDIES

7.1 Small hydropower plant

Case 1 is a relatively small hydropower plant. There is 30 metres of concrete structures and 100 metres of embankment dam. The scanning was performed using a multibeam sonar. The results, presented in Figure 1, give an extensive image of the dam. There are some blind spots in the picture on the side of the pier. If there is a need to inspect these blind spots, stationary scanning sonar would solve the problem and it would be possible to combine the sonar scanning data with the multibeam sonar data.

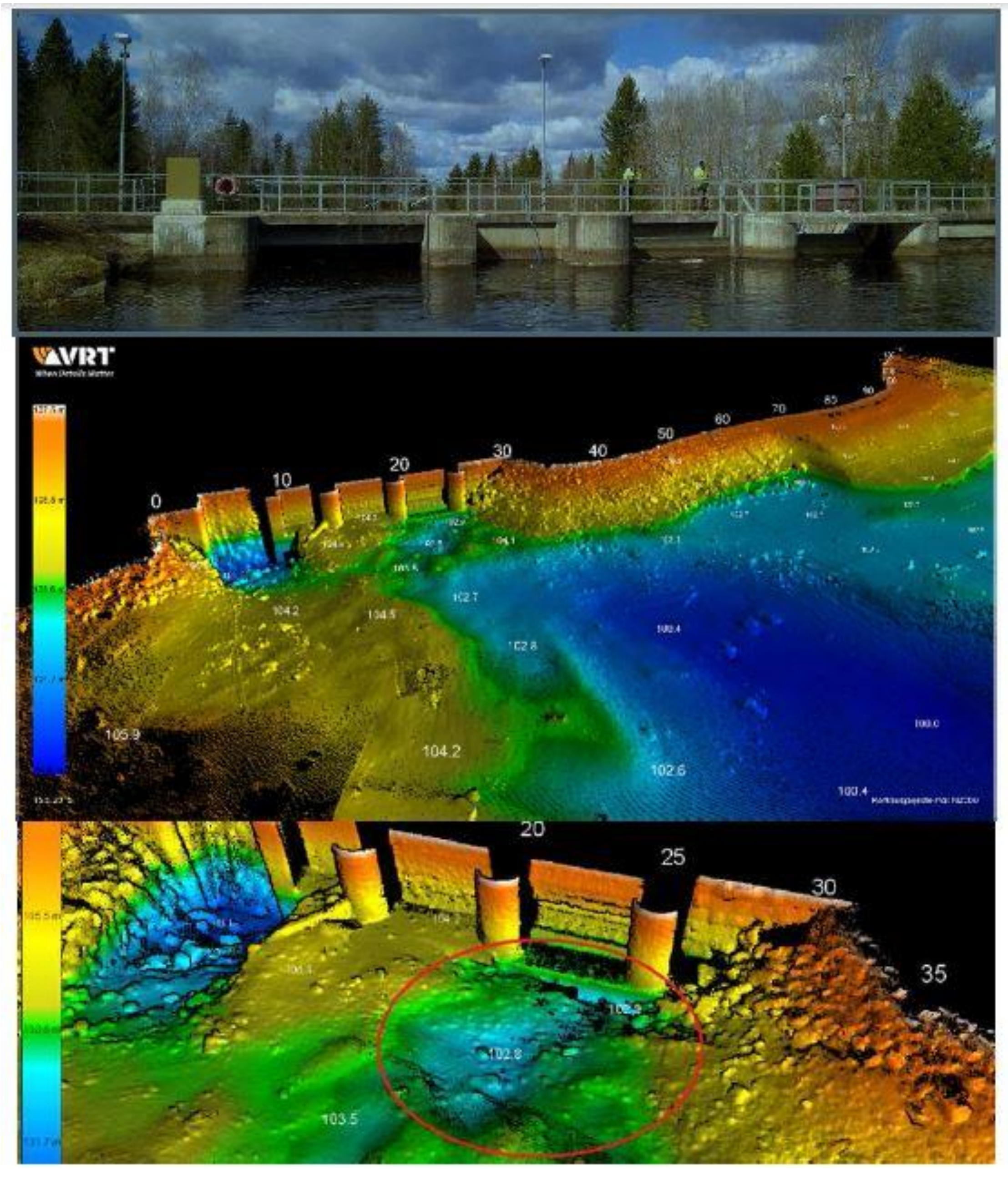

Figure 1. Relatively small hydropower dam. Under the spillway, concrete structures are uncovered. (Case 1)

7.2 Dam wall

Case 2 is the stone wall of a hydropower plan (Figure 2). Scanning was performed using a 2D stationary scanning sonar. The method is a good choice for relatively small, vertical structures. The scanning can be done faster than a 3D stationary scan. Cross section locations must be chosen in advance (Figure 3).

If you compare 2D stationary scanning and multibeam sonar 3D scanning from a moving vessel, the multibeam scan proves faster as target size increases. 500 metres of structure is scanned and the data is processed in 7 – 8 days. These structures are scanned using 3D multibeam sonar from a moving vessel and the data is processed in 3 – 4 days.

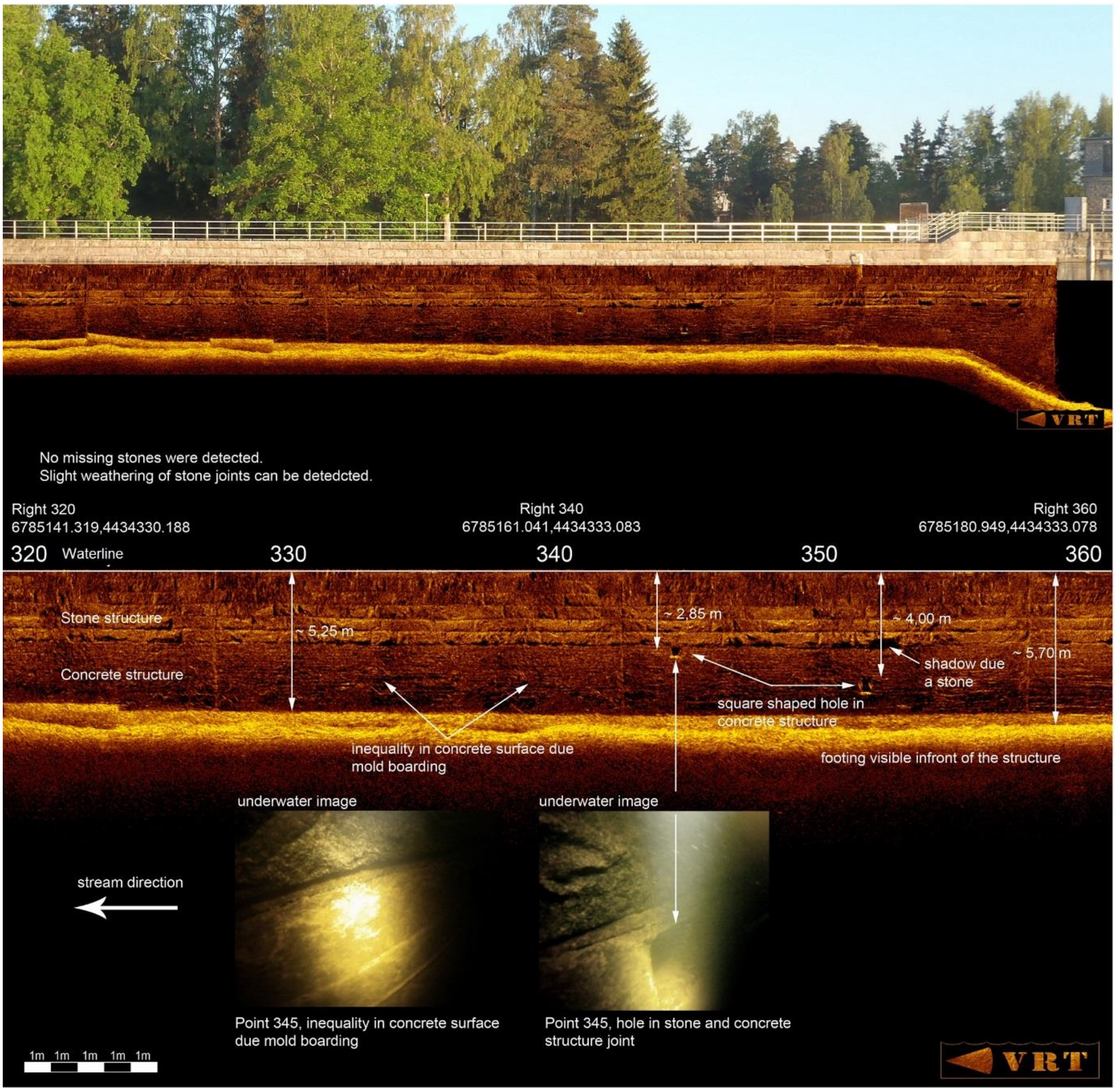

Figure 2. 2D Stationary sonar scan of vertical dam wall. Underwater pictures inset (case 2).

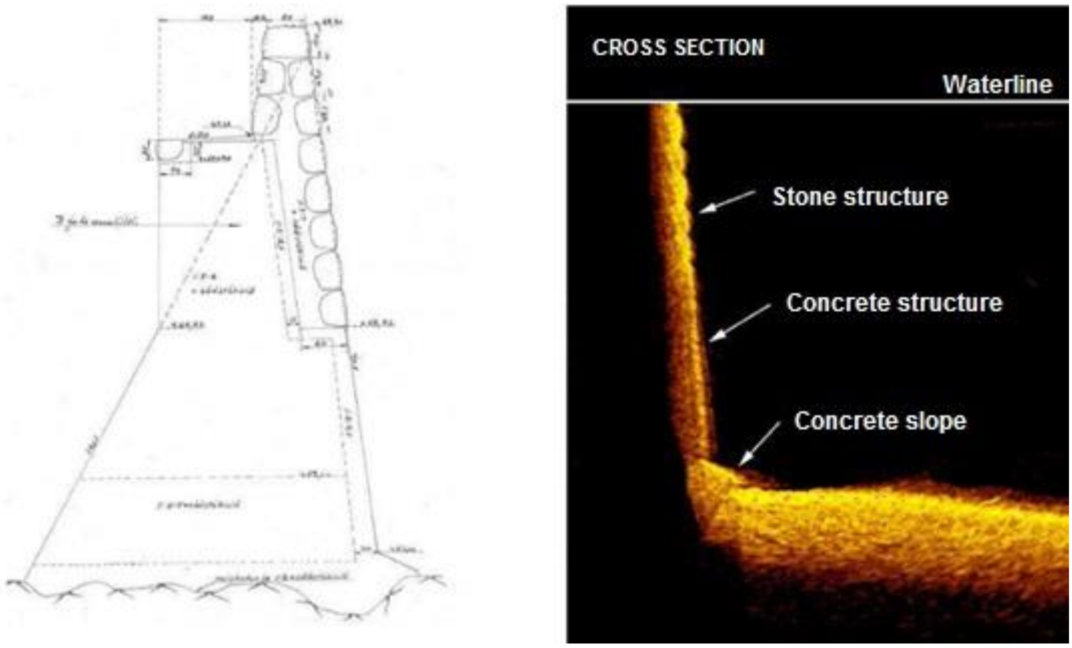

Figure 3. Sketches based on 2D sonar scan (case 2).

7.3 Hydropower plant in 2D and in 3D

Case 3 is a hydropower dam which has been scanned using both 2D and 3D scans. Overviews of both scans are in Figure 4. Figure 5 gives a detailed comparison of the scans. The 2D images show a beam missing under a concrete cantilever plate. It is important that the field team understands how to position the sonar. In this case the beam wasn´t detectable above the water level. In addition, design drawings were unavailable. Therefore, the field team had no reason to adjust the positioning of the sonar. When a 3D scan from a moving vessel gave a better scanning angle, the beam was clearly noticeable.

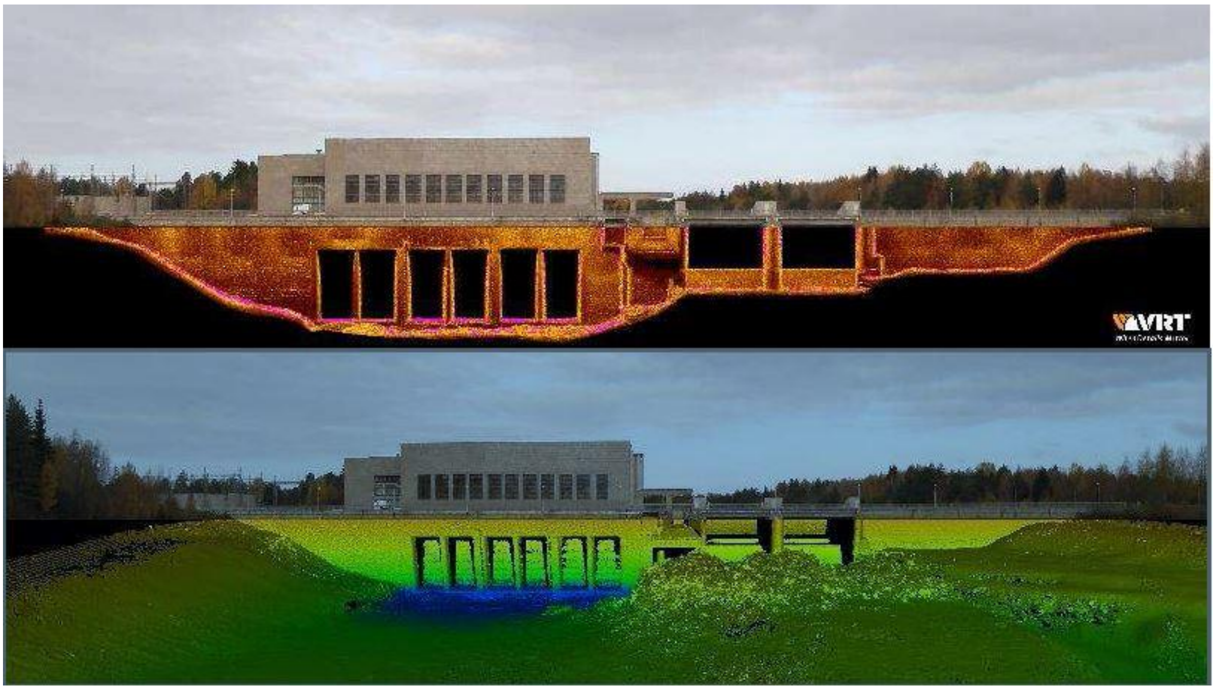

Figure 4. Hydropower dam scanned in 2D and in 3D (case 3).

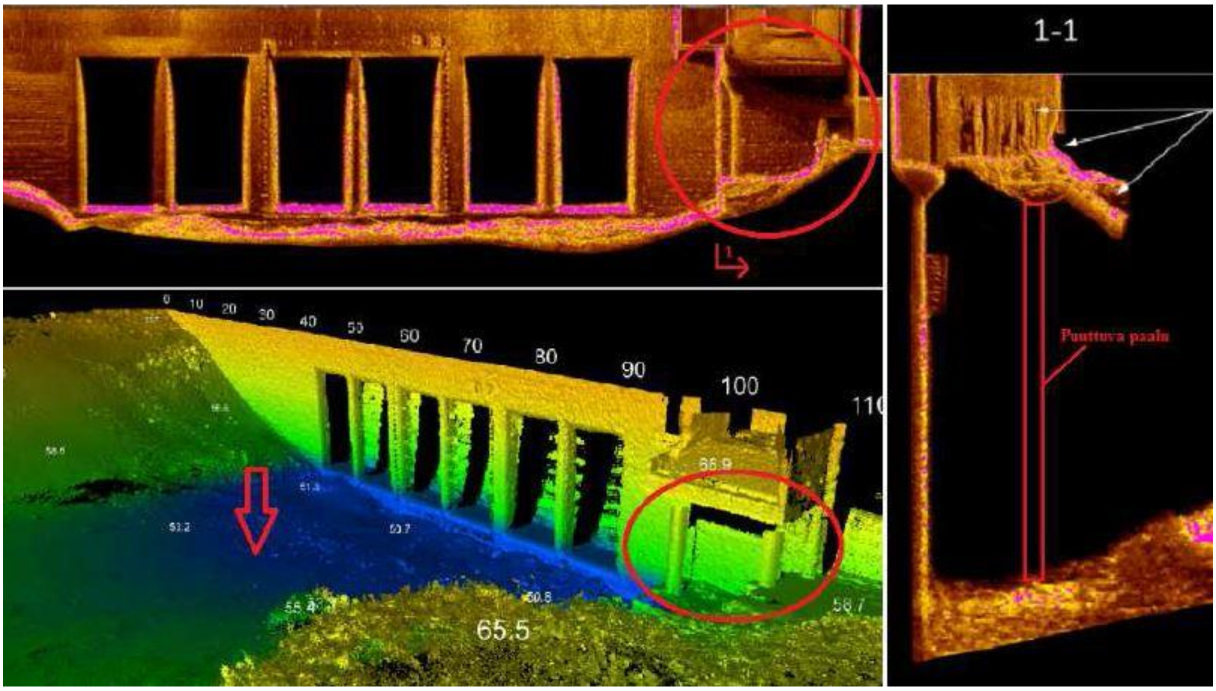

Figure 5. Comparison of details of 2D and 3D scans (case 3).

7.4 Process waste water pond

Case 4 is a process waste water pond. This waste water pond has been made by the surrounding waste dams. A 3D scanning was performed in order to monitor potential deformations. Figures 6 – 8 show the monitoring results.

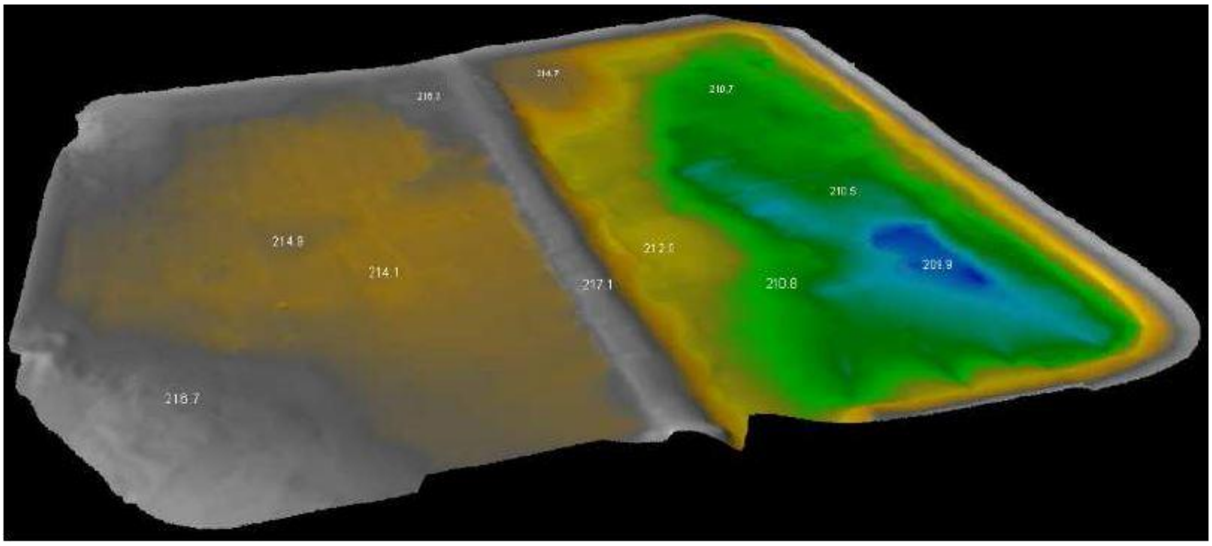

Figure 6. 3D illustration of a process waste water pond (case 4).

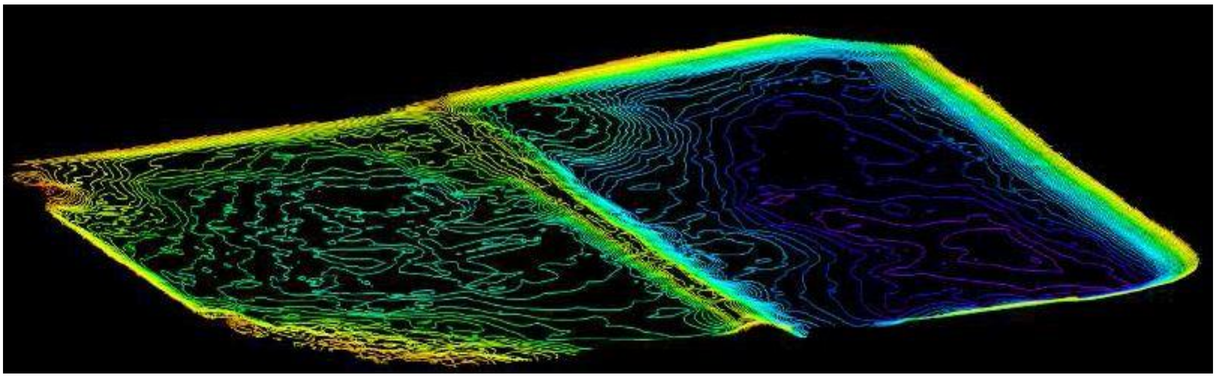

Figure 7. Depth contour lines in waste pond (case 4).

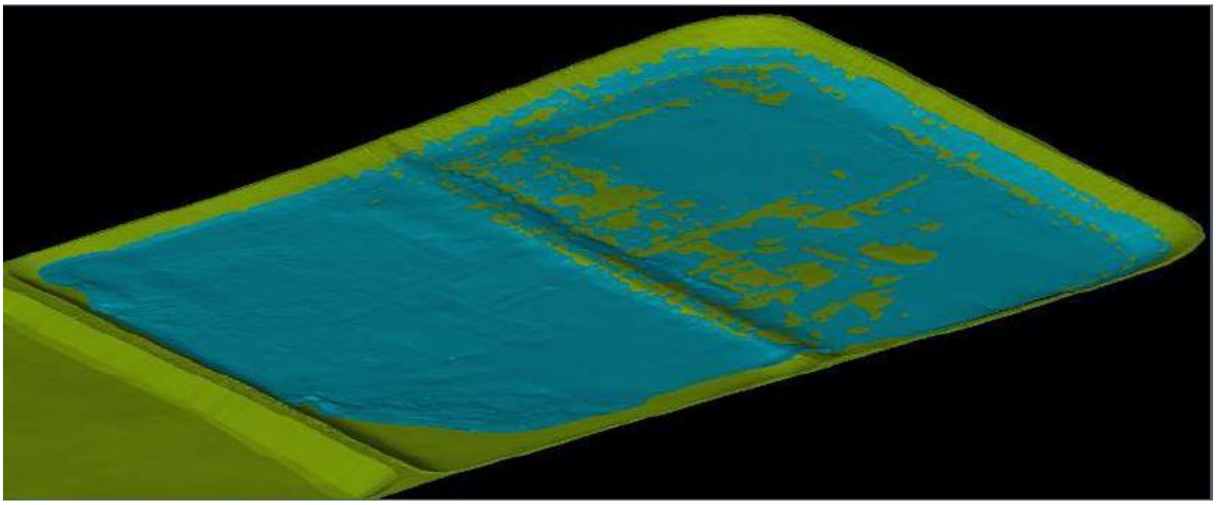

Figure 8. Comparison of two 3D models scanned at different times (case 4).

8. CONCLUSIONS

Acoustic scanning is a very good way to inspect a dam. In many situations it yields more than an inspection performed by a diver. With larger inspection targets, acoustic scanning becomes more economical and the results will be available in a shorter time. Scanning is safe. Old and new results are easy to compare.

9. ACKNOWLEDGEMENTS

The original text, report in Finnish was written by Mrs Kirsi Hänninen and Mr Olli Auer from VRT Finland Oy. The report was requested by The ELY Centre for Häme. The ELY Centre for Häme and VRT Finland Oy agreed to prepare this paper together to the ICOLD 2016 Symposium. This paper was edited by by Eija Isomäki and Kirsi Hänninen.

10. REFERENCES

Hänninen, K & Auer O (2015). Patorakenteiden tarkastusmenetelmät (Methods to inspect the structures of a dam). Published report. www.ymparisto.fi/patoturvallisuus