REPORT

# Review of dam monitoring and data management techniques

CLIENT

Statkraft Energi AS

SUBJECT

Review of dam monitoring and data management techniques

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**REPORT**

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**EXECUTIVE SUMMARY**

The current study was conducted for Energi Norge as part of the project “Dam safety in a holistic perspective” and has been translated from the original Norwegian version. The translation was commissioned by Statkraft Energi AS.

The report gives an overview of real problems, threats, and failure mechanisms faced by dams. The study is a desktop study of Norwegian and international practice, and focuses specifically on the main types of instrumentation - from traditional to experimental - especially those that can be remotely monitored and easily integrated with other systems. A review of available software tools for dam monitoring was conducted and advice for dam owners who wish to set up such a system is given. Furthermore, the report contains practical examples on the presentation of data from different monitoring instruments.

The report makes recommendations for the setting of threshold values and their reliability, and refers to multiple examples, both international and Norwegian.


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# Table of Contents

# Figures

# Tables

# Acronyms and Abbreviations

| | |
|---|---|
| 3G / 5G | 3rd / 5th generation mobile technology |
| AAS | Automated Auscultation System |
| ADAS | Automated Data Acquisition System |
| AI | Artificial Intelligence |
| BIM | Building Information Modelling |
| DAS | Data Acquisition System |
| Defra | Department for Environment Food and Rural Affairs (UK) |
| DSF | Dam safety law (Damsikkerhetsforskriften) |
| DSHP | Dam safety in a holistic perspective (Dam sikkerhet i et helhetlig perspektiv) |
| GIS | Geographic Information System |
| GPRS | General Packet Radio Service |
| ICOLD | International Commission on Large Dams |
| IEC | International Electrotechnical Commission |
| IP code | Ingress Protection Code |
| OFITECO | OFICINA TÉCNICA De ESTUDIOS Y CONTROL De OBRAS, S.A. |
| NVE | Norwegian Water Resources and Energy Directorate (Norges Vassdrags- og Energidirektorat) |
| RST | RST Instruments Ltd. |
| SCADA | Supervisory Control and Data Acquisition |
| SINTEF | Centre for Industrial and Technical Research (Selskapet for Industriell og Teknisk Forskning) |
| SPANCOLD | Spanish Commission on Large Dams |
| UPS | Uninterruptible Power Supply |
| USSD | United States Society on Dams |
| VTA | Vassdragsteknisk ansvarlig (Norwegian term for dam safety engineer) |

# 1 Introduction

## General

Multiconsult Norge AS were engaged by Energi Norge to conduct a feasibility study on dam monitoring and instrumentation. The work is part of a large project titled "Dam Safety in a Holistic Perspective" (DSHP in Norwegian). Multiconsult Norge AS engaged OFITECO from Spain as a sub-consult of Multiconsult to assist in the project. Statkraft Energi AS commissioned the English translation of the report. Minor differences exist between the English and Norwegian version of the report, with the intention to make the text more suitable for the international readers.

**OFICINA TECNICA OE ESTUOIOS Y CONTROL OE OBRAS, S.A.** (OFITECO) is a Spanish engineering company founded in 1971, due to the growing concern about dam and reservoir safety in the country. The main fields of activity comprise hydraulic and transport infrastructures.

Backed by the experience acquired over more than 50 years in the dam engineering sector OFITECO provides a comprehensive dam and reservoir safety management program, including surveillance, O&M Standards, Emergency Action Plans, Safety Reviews and Risk Assessments.

OFITECO is highly experienced in Dam Monitoring, covering all services like design, implementation, upgrade and automation of monitoring systems, data management, data evaluation and safety assessments.

**Multiconsult Norge AS** is one of the leading firms of consulting engineers and designers in Norway. With roots going back to 1908, the company has played an important role in Norway's development and economic growth. Thanks to its 2.850 highly skilled members of staff, the company is able to provide a range of services including multidisciplinary consulting and design, project engineering and management, verification, inspection, supervision and architecture - both in Norway and overseas.

Multiconsult's experience includes all aspects of dam engineering, from safety reviews, rehabilitation and re-building, to detailed design and planning of new constructions.

Multiconsult also has a long history and experience with geotechnics and detailed design of instrumentation in building, construction, and infrastructure projects

## Background of the study

Worldwide there are over 58,000 large dams registered with ICOLD. The failure of a dam can have disastrous effects downstream, including loss of live, damage to properties and environmental damage. According to the independent research institute SINTEF's safety and reliability report from 1997, *Large Accidents in Norway*, it was concluded that "dams represent one of the largest potentials for accidents in Norway" [2]. This holds true for many countries around the world. Dam safety is therefore highly prioritized by society and well monitored by government agencies.

Like in many countries across the world, Norway's dam safety regulator (NVE) provides and enforces a legal framework that clarifies the duties and responsibilities of the different parties for the safe operation of dams and other hydraulic facilities. The dam owner has the main responsibility for all aspects of dam safety [3], including identifying, assessing, and reducing risks to an acceptable level. Energi Norge, as the union representing most dam owners, engaged the consulting services of Multiconsult and OFITECO.

### Objective of the study

Monitoring of dams is an important tool to reduce the risk for a dam failure and limit damages in case of a failure. With the latest advances in technology, Energi Norge is looking for more advanced, reliable, accurate, and fast methods to monitor dams and manage the associated risks, particularly for older dams. The report contains a review of state-of-the-art techniques used internationally.

### Earlier studies initiated by Energi Norge

One of the first reports on dam instrumentation and monitoring in Norway dates from 2000, when *Energibedriftenes Landsforening* (EBL) released publication 466-2000 "*Håndbok for etterinstrumentering av dammer"* (*Handbook for instrumentation of dams*) [4].

The current report is part of the DSHP project, earlier studies were completed by consulting firms Sweco/Norconsult [5] and energy producer BKK [6]. BKK collected example studies specifically from the point of view of a dam owner [6]. Advances in instrumentation technology were documented by the Sweco/Norconsult studies [5]. These studies are not discussed in detail in this report and are only available in Norwegian.

### International studies – ICOLD

Internationally, ICOLD has been the driving force behind amalgamating international best practice on dam safety, instrumentation, and monitoring. ICOLD's "Technical Committees" have published 9 bulletins related to dam monitoring from 1969 – 2017:

- B21 General considerations applicable to instrumentation for earth and rockfill dams (1969)
- B23 General considerations on instrumentation for concrete dams. Note on the application of geodetic methods to the determination of the movements of dams (1972)
- B60 Dam monitoring. General considerations (1988)
- B68 Monitoring of dams and their foundations – State of the art (1989)
- B87 Improvement of existing dam monitoring (1992)
- B118 Automated dam monitoring systems (2000) [7]
- B138 Surveillance: Basic elements in "Dam Safety" process (2009) [8]
- B154 Dam Safety Management: Operation phase of the dam life cycle (2017) [9]
- B158 Dam Surveillance guide (2011) [10]

### Scope and limitations of this report

The focus of this study is not on advanced instrumentation per se, as this work has previously been conducted in detail. The focus will rather be on the automation of these advanced instruments, data collection, and its presentation. Moreover, data interpretation, calibration of potential threshold values, and some typical potential dam failure mechanism are discussed from the point of view of dam monitoring. When interpreting monitoring data it is inevitable to want to consider the entire system of dam monitoring and potential breach mechanisms, however, these issues were considered outside the scope of this study.

# 2 Research Strategy and Content

## 2.1 Research strategy

The current report presents a review of existing literature mixed with the practical international experience of the two contributing companies. The focus of the study was on state-of-practice technology that is already in commercial use. Technology that is currently in an early development or research phase, such as artificial intelligence, was not focused on.

Instrumentation for the monitoring of dams and software related to the acquisition, presentation, and interpretation of gathered data has been extensively studied by ICOLD [9][10], Defra [11], USSD [12][13], ANCOLD [14] and SPANCOLD [15] before. Data acquisition and presentation technology has in the past largely been the domain of suppliers. It is for this reason that OFITECO were involved in this study.

There is a clear strategy in all these previous studies on dam monitoring and surveillance [9][10][11][12][13] that typical potential failure modes of dams are presented and discussed. Observations from all aspects of dam monitoring (not simply instrumentation) are recognised as critical for assuring the safety of a dam. This approach was also adopted for this report.

## 2.2 Research content

The conclusions and findings of this report are presented in chapters 3 – 6. A brief summary of those chapters is as follows:

**<u>Dam surveillance (Chapter 3)</u>**

This chapter introduces dam surveillance, discussing dam monitoring in detail and its place within a more complete surveillance program. The goal of dam surveillance is to obtain an understanding of the dam's current state, and how monitoring contributes to this goal is briefly discussed. The relevant regulations regarding dam monitoring and surveillance in Norway are also presented and discussed.

**<u>Monitoring and data acquisition (Chapter 4)</u>**

Instrumentation for dam monitoring is introduced in chapter 4. Supporting instruments, automatic data acquisition, and transmission instruments are highlighted. The reliability of data acquisition is discussed in detail.

**<u>Data management and presentation (Chapter 5)</u>**

Data management, storage, and presentation is discussed in chapter 5. Various methods of presenting and displaying data that can aid in interpretation are presented.

**<u>Data interpretation and analysis (Chapter 6)</u>**

In chapter 6, typical properties and characteristics of different monitoring data types are discussed. Potential mechanisms for dam failure from literature studies are summarised and assessed with regards to their relevance to Norwegian dams. Finally, how the interpretation of different types of monitoring data can be related to dam stability is discussed with a number of examples from both Norwegian and international dams. Recommended procedures for establishing threshold or triggering values are also presented.

# 3 Dam Surveillance

## 3.1 Threats to dams

Dams are assumed to be high maintenance structures by nature [13], due to the severe consequences to society with an eventual failure. Before further discussion on dam surveillance, it is useful to outline the various threats faced by dams.

A threat to a dam is defined as an event or condition that may result in a hazard occurring. Threats resulting in a hazard to a dam can result in dam failure if they are not identified. Defra's 2011 report on dam failures [11] has identified and summarised the threats as follows (Figure 1):

- ageing
- aircraft strike
- animal activity
- changes in groundwater flow/chemistry
- earthquake
- extreme rainfall/snow flood
- failure of nearby infrastructure
- failure of reservoir in cascade upstream
- human activity
- ice/frost
- layout, design or construction inadequate or inappropriate
- mal-operation
- mining/ mineral extraction
- sunlight
- terrorism/sabotage/accident
- water loading
- wind

*Figure 1: Threats to dams identified in Defra's report [11].*

Similarly to dams in the United Kingdom, Norwegian dams must withstand changing environmental and physical conditions in their lifetimes, for example due to climate change. The relevance of the individual threats listed above may change over time. Dam owners must be sure that their dams are stable and can withstand these threats. Dam surveillance programs allow them to achieve this.

Defra's report summarises 12 potential failure modes and a further 46 hazard modes [11]. The various deviations, or combinations of deviations, in monitoring data that may indicate a developing instability within the dam are discussed [11]. ICOLD [9][10][15], USSD [12][13], ANCOLD [14], and SPANCOLD [15] have all published studies with similar approaches. These topics are covered in a similar fashion in Chapter 6 of this report.

## 3.2 Dam surveillance and dam monitoring

Dam surveillance is a key risk mitigation tool, providing a means of early hazard identification to reduce the probability of undesirable events that could lead to failure [10][19] , and plays a central role in any dam safety program (Figure 2).

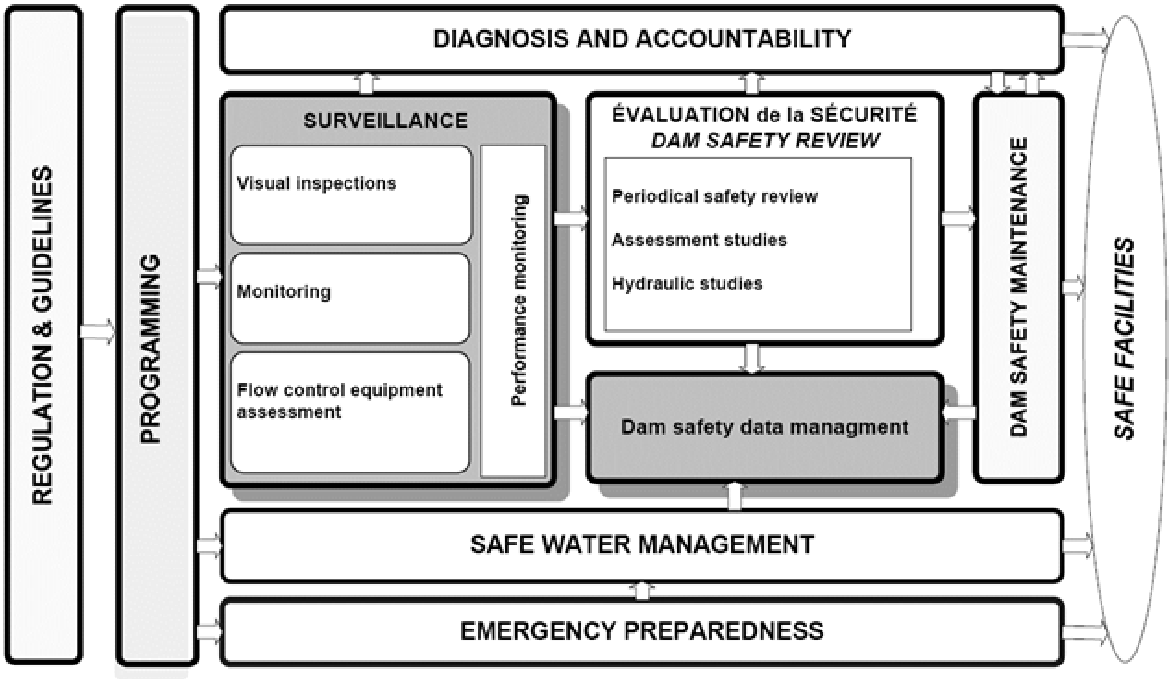


*Figure 2: Dam surveillance as part of a complete dam safety program [19].*

Internationally, dam surveillance is achieved through periodic safety reviews (often annual), inspections after extraordinary events such as earthquakes and floods [14], and comprehensive reviews every five to twenty years depending on local regulations. The ultimate goal is to identify anomalous behaviour which could reduce the safety of the dam.

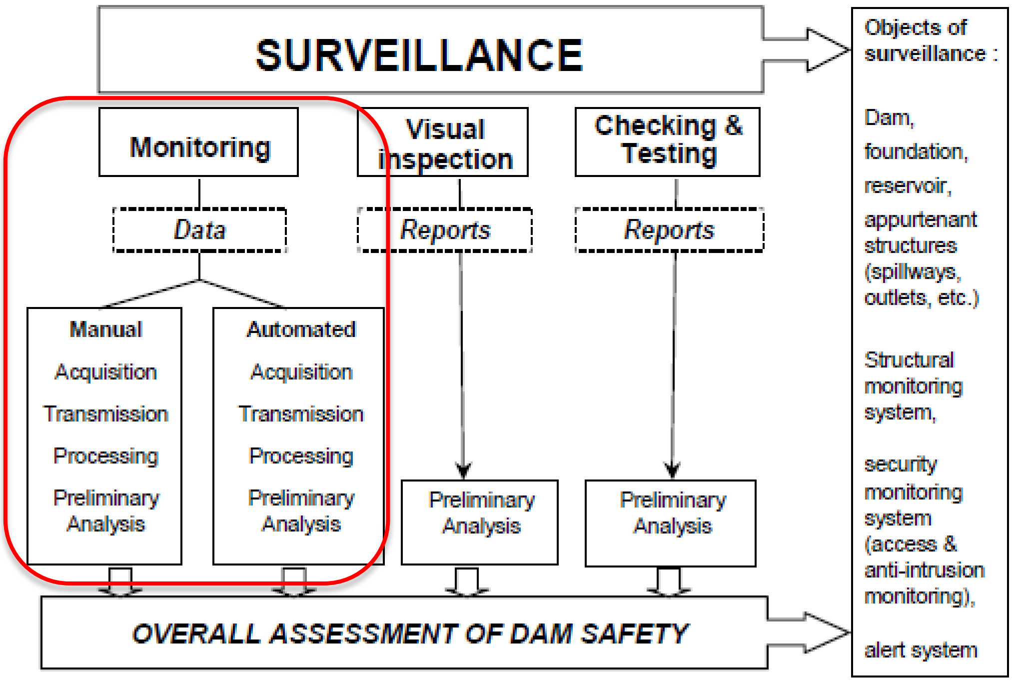


*Figure 3: concepts included within dam surveillance, highlighting dam monitoring as one important part.[9]*

Instrumentation is only a small component of dam surveillance programs, however technologies for it are fast developing, allowing it to provide in-depth knowledge and statistics that visual investigations or on-site assessments cannot (see Figure 2 and Figure 3). This includes not only the acquisition of data, but also its assessment and evaluation. The objective of dam surveillance is to provide a dam safety assessment, establishing an understanding of the dams' stability for present conditions and the future. It is important to note that while instrumentation is an important tool, it is not the only factor that can contribute to dam safety and is in face best used in combination with other methods to establish a monitoring program.

It is unreasonable to believe that all monitoring instruments can be clearly linked directly to dam safety. The limitations of the different types of instrumentation and processed data are discussed in more detail in Chapter 6. In common practice, a dam engineer identifies anomalies from ordinary monitoring instruments. If the (combination of) anomalies gives the dam engineer the impression that dam stability is in an unfavourable condition or with any doubts, the engineer should investigate further and conduct more tests to confirm their understanding and interpretation of the data.

Thus, a robust dam surveillance program must include the following factors besides a simple instrumentation system:

- A competent engineer who properly understands the dam
- Thorough inspections
- Proper checks and calibration of the surveillance and monitoring instrumentation system

Crucially, data from instrumentation must contribute to an engineer's understanding and judgement of any given situation for a dam surveillance program to be successful. This applies even to the most modern and advanced instrumentation techniques. Figure 4 shows how one weak link can undermine an entire dam surveillance program.

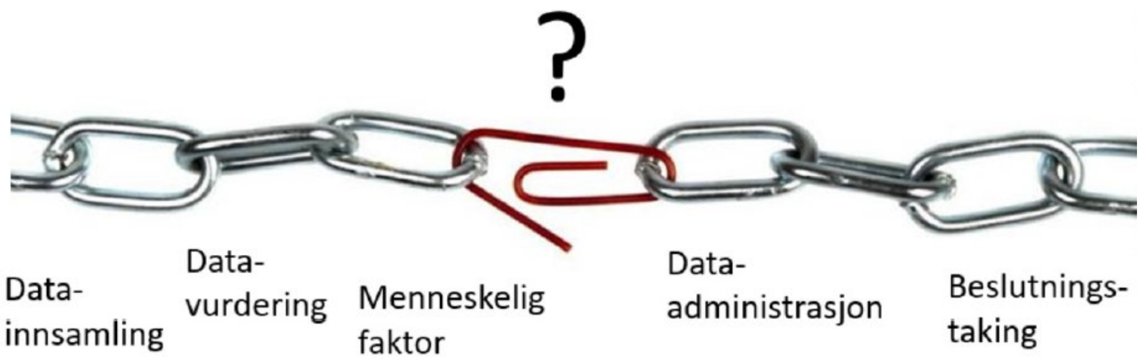


*Figure 4: Dam surveillance requires that all components of the system (here data collection, interpretation, human factors, administration, and decision making) are of the required quality. One weakness can cause the entire system to fail.*

## 3.3 Norwegian regulations and practice

The current section summarises some of the Norwegian dam safety regulations. Regulations differ internationally, especially when it comes to specifics about dam monitoring and surveillance. The report describes the authors understanding of international best practice, but dam owners should take into account how this aligns with the relevant regulations in their country.

Dam safety in Norway is codified in law by *Damsikkerhetsforskriften (DSF)* ("the law on dam safety") [3], under the water resources act (*vannressursloven*) administered by the regulator NVE on behalf of the Ministry of Petroleum and Energy. NVE has also released a number of guiding documents to assist dam designers and owners with the design and operation of dams and associated hydraulic structures.

Norwegian dams are classified according to their potential failure consequence from 0 – 4 (consequence class 4 dams carry the greatest consequences with failure).

DSF and guidelines contains provisions on dam monitoring that are in line with international best-practice. Periodic inspections are required at least once per year, with detailed inspections every 5 -7 years, extraordinary inspections during and after abnormal events (i.e. large floods), and a thorough dam safety assessment every 15 – 20 years. Dams in the lowest consequence class (0) do not require any inspections.

The guidelines for monitoring and inspecting dams and other hydraulic facilities have been recently updated and are now compiled in Guidelines nr. 3/2019 *Overvåking av vassdragsanlegg (monitoring of hydraulic structures)* [17]. Table 7-2.2 of the DSF and the previously mentioned guidelines is shown in Table 1.

*Table 1 Minimum requirements for the monitoring of Norwegian dams, by consequence class, dam type, and foundation (after table 7-2.2. of Norwegian Dam Safety Law).*

| *Dam type* | *Consequence class* | *Water level* | *Leakage* | *Deformation* | *Pore pressure* |
|---|---|---|---|---|---|
| *Embankment dam with foundation on good quality rock* | 2,3,4 | x | x | x | |
| *Embankment dam with foundation on soil or rock of low quality/rock cut by pronounced weakness zones* | 2,3,4 | x | x | x | x |
| *Concrete and masonry dams with foundation on good quality rock* | 3,4 | x | x | x | |
| | 2 | x | x | | |
| *Concrete and masonry dams with foundation on soil or rock of low quality/rock cut by pronounced weakness zones* | 3,4 | x | x | x | x |
| | 2 | x | x | | x |

The above requirements are the **minimum requirements** that apply to all dams in classes 1 - 4. For dams that are in poor condition, where the situation is not well understood, or where the situation requires it, the dam engineer should use additional techniques to obtain a better understanding of the dam's behaviour. It is the dam engineer/owner who is responsible for the safety of the facility, not instrumentation. Instrumentation is merely a tool that the dam engineers can use to help them maintain the dam.

# 4 Monitoring

## 4.1 General

Monitoring instruments provide data and information on the state of the dam. The current chapter deals with the data acquisition and transmission parts of a surveillance system (Figure 3). As discussed in Chapter 1, monitoring instrumentation is not the main focus of this report, as this has been dealt with in detail in earlier DSHP studies [5][6]. Relevant instrumentation schemes are briefly summarised in section 4.2 to provide context for the current report. This chapters' focus is on supporting instrumentation; in particular its definition, role, benefits, and the hardware needed to gather useful data.

## 4.2 Instrumentations

An overview of the typical continuous remote surveillance instrumentation schemes for concrete, concrete face rockfill, and earthfill dams is summarised by the instrumentation supplier RST [18] in Figure 5, Figure 6, and Figure 7.

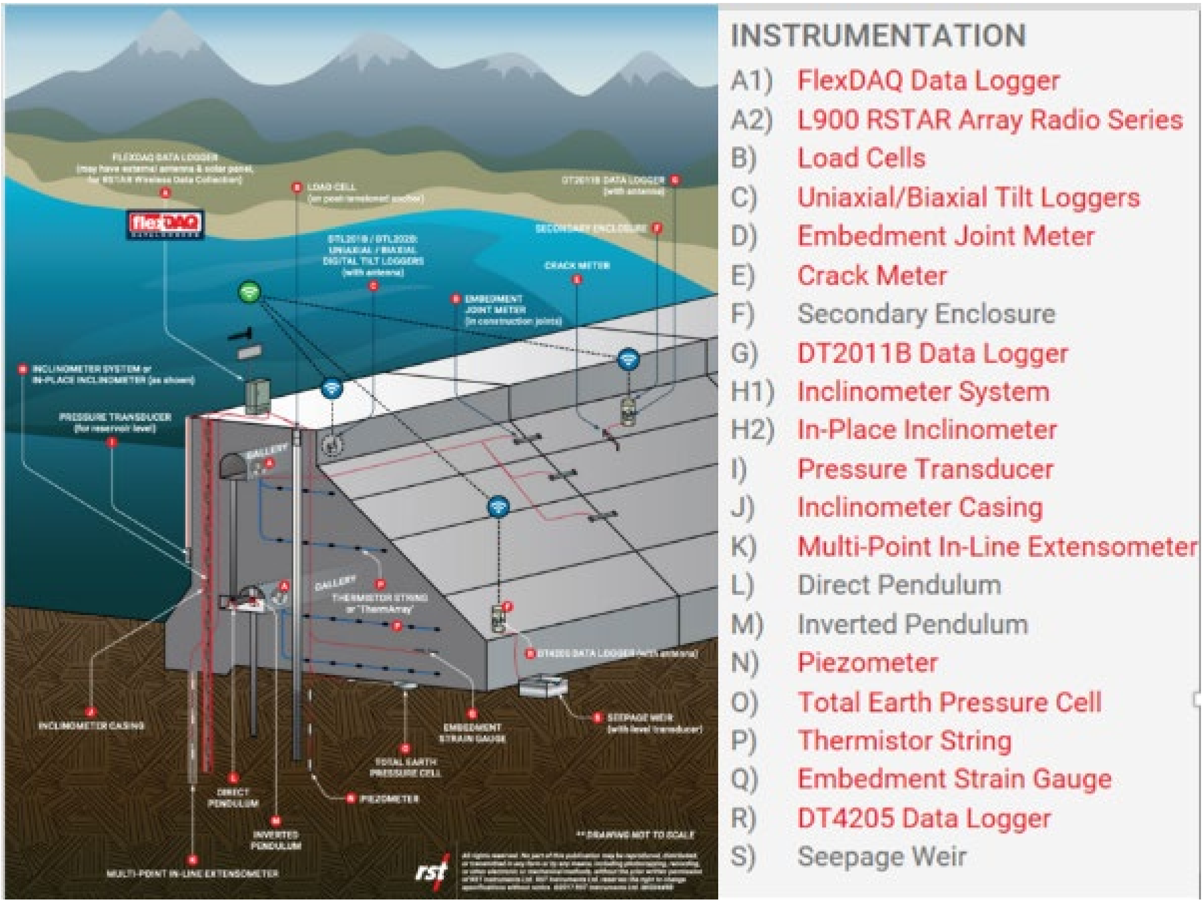


*Figure 5: A typical overview of the in-situ dam monitoring systems for a concrete gravity dam [18].*

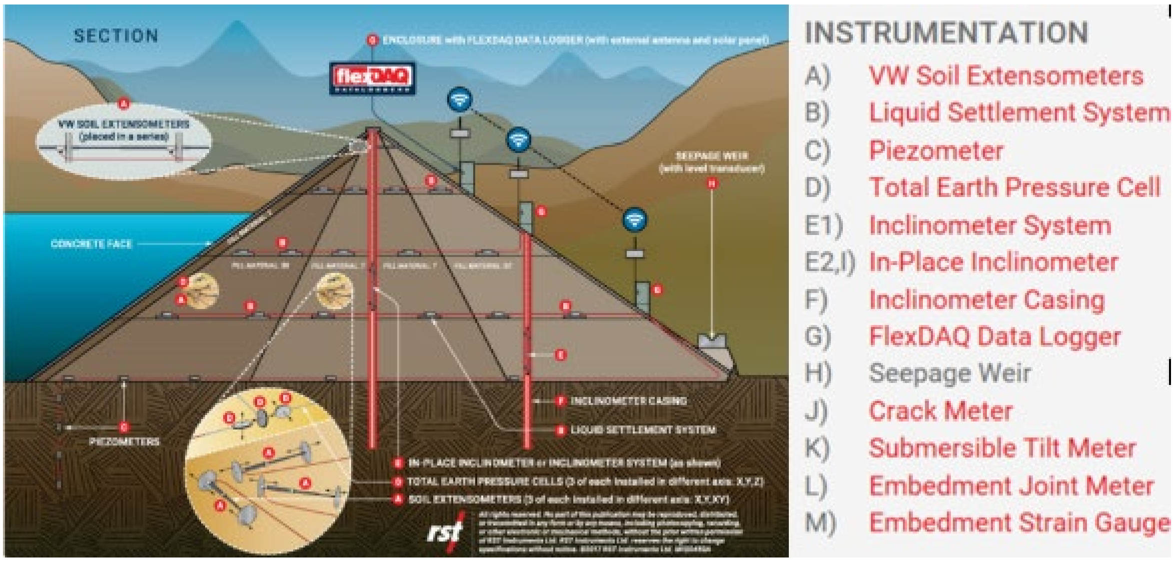


*Figure 6 A typical overview of the in-situ dam monitoring systems for a concrete face rockfill dam [18].*

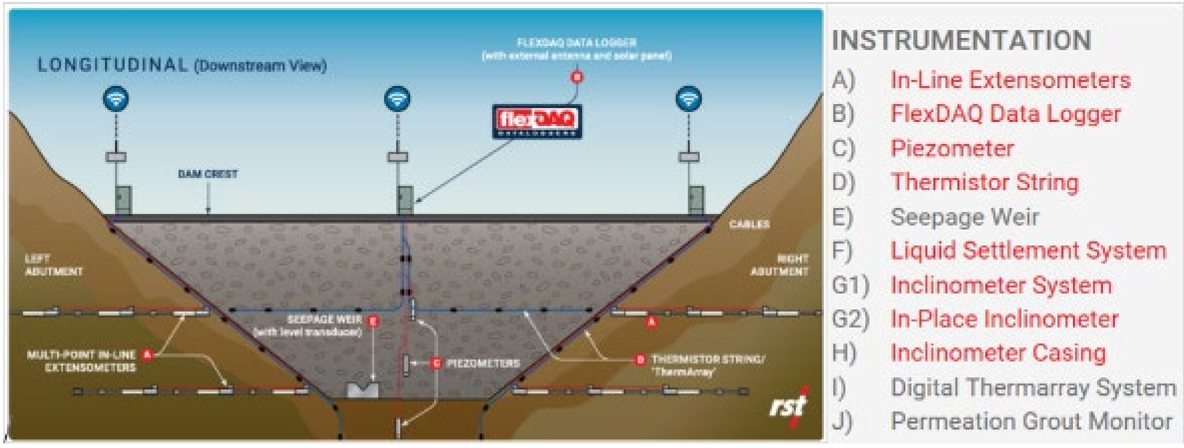


*Figure 7 A typical overview of the in-situ dam monitoring schemes for an earthfill dam [18].*

It should be mentioned that in-situ instrumentation and monitoring in the above figures covers all four categories (water level, leakage, deformation and pore pressure) required by Norwegian dam safety law [3]. All the instruments can be read remotely and continuously, which is equal and in excess of NVE's recommendations about measurement reading frequencies [17]. Moreover, the stress measuring instruments (such as load cells, earth pressure cells and extensometers) and supporting instruments (such as thermistor strings, weather stations, and CCTV) can be read remotely and continuously.

RST's summary of automatic remote monitoring instrumentation represents the cutting edge of instrumentation systems commercially available. These systems are most applicable for large dams. For many small dams, manual reading or standalone data logging still has its advantages. The advantages and disadvantages of different data collection methods are summarised in below in Table 2 by USSD [13] :

*Table 2: Summary of data collection methods, advances and disadvantages* [13].

| Data Collection Method | Advantages | Disadvantages |
|---|---|---|
| ***Manual Readings*** | • Generally simple to perform and do not require high level of expertise<br>• Personnel are already on site for regular visual observations<br>• Data quality can be evaluated as it is collected | • Labor intensive for data collection and reduction<br>• Not practical to collect frequent data<br>• Potential for errors in transposing data from field sheets into data management/ presentation tools<br>• May be impractical for remote sites where personnel are not frequently on site |
| ***Stand alone Dataloggers*** | • Frequent and event-driven data collection<br>• Consistent data collection and electronic data handling<br>• Equipment is fairly inexpensive and simple to set up | • Requires some expertise to configure dataloggers<br>• Data quality cannot be evaluated until it is collected from the field<br>• Potential for lightning strikes<br>• Power source needs to be considered |
| ***Real-time Monitoring Networks*** | • Frequent and event-driven data collection<br>• Consistent data collection and electronic data handling<br>• Real-time display and notification (24/7)<br>• Reduces labor effort for data collection and processing<br>• Can remotely change the monitoring frequencies and data collection configurations as needed<br>• Allows for rapid evaluation of monitoring results | • Automation may encourage complacency if overall monitoring program is not well defined or understood<br>• Requires a higher level of expertise to install and maintain<br>• Higher cost of installation and periodic maintenance<br>• The importance of frequent routine visual inspections may be overlooked or discounted somewhat due to the real-time presentation of automated instrument readings<br>• Potential for lightning strikes<br>• Power source needs to be considered |

## 4.3 Supporting instrumentation

This section aims to review existing technology concerning those elements that serve as support, or complementary to, the instrumentation installed in a dam for monitoring and continual surveillance of its structural behaviour. In other words; these measurements are not directly related to, but can assist in interpreting, a dam's stability. Note that in this context measuring the reservoir water level is defined as supplementary (non-structural) monitoring!

### 4.3.1 *External variables*

The behaviour of a dam is mainly conditioned by external factors that affect the structure, and the land on which it sits. These variables are:

- Environmental conditions
- The hydrostatic load generated by the water level in the reservoir
- Waves and ice effects
- Water temperature
- Debris (clogging of spillways)

- Landslides (waves, debris source)

In the following subsections we will explain the most commonly used methods and techniques for measuring these variables.

#### *4.3.1.1 Environmental conditions*

Some dams are equipped with meteorological stations, automated or not, that provide information regarding the environmental conditions that affect both the dam and the reservoir. The main variables measured by a typical meteorological station at a reservoir are:

- Precipitation
- Evaporation
- Wind speed and direction
- Solar radiation
- Relative humidity of the air
- Air temperature

These variables can be critical to the interpretation of monitoring data. When no weather station is present, *senorge.no* has a large dataset with interpolated Norwegian climate data. The reliability of this dataset changes from location to location and from parameter to parameter, but in the absence of local meteorological stations it can be a useful addition to other monitoring data.

#### *4.3.1.2 Reservoir level – Hydrostatic load*

The upstream water level can be continuously monitored with instruments based on the following three principles:

- Direct measurement of a hydrostatic load with a pressure sensor.
- Indirect measurement of hydrostatic pressure by use of pneumatic (bubbling) systems
- Measuring the distance between the water surface and a fixed point on the dam (range meters).

**Pressure sensor**
Hydrostatic measuring systems are mainly used in concrete dams where they can be placed directly on a structure at depth in the reservoir (below the interference caused by wave action, flow, and fluctuations in reservoir level). A typical example is shown in Figure 8.

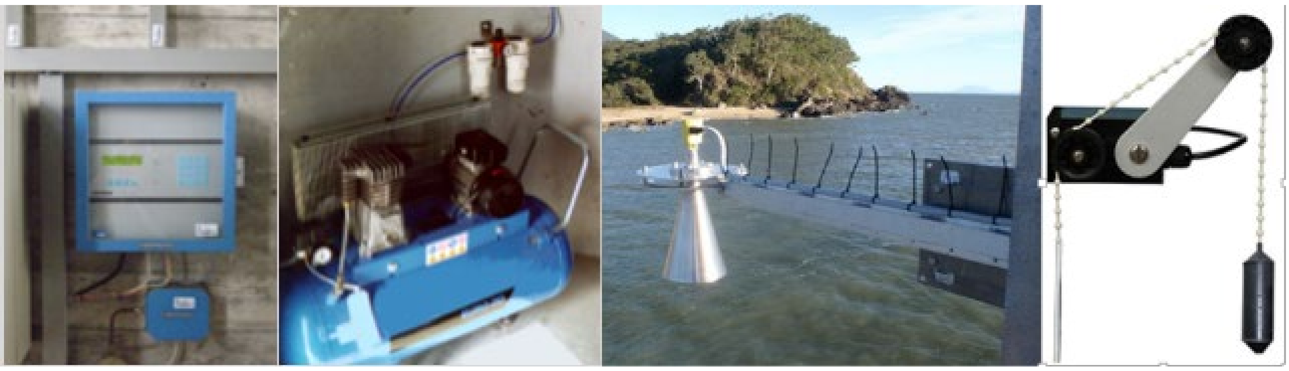

*Figure 8: systems for measure the upstream water level: hydrostatic sensor (left); Pneumatic system (middle left); range meter, auscultation (middle right); range meter, float sensor (right).*

**Pneumatic Systems**

In a pneumatic, or bubbler, system, a compressor pumps air into a well through a pipe, and the backpressure is measured. Pneumatic systems do not need to be installed below water (only the pipes extend into the reservoir, the compressor and sensors can be installed elsewhere, or on or near the dam) and are the most used system in embankment dams. A typical Pneumatic system is shown in Figure 8.

It should be noted that corrections for atmospheric pressure must be taken into account for both hydrostatic and pneumatic systems.

**Range meters**

The distance between the water surface and a fixed point in the dam can be directly measured by a range meter. Range meters can be sub-divided into the auscultation type (ultrasonic sensor and microwave radar) and float sensors. These are shown in Figure 8. Range meters are the most common method for measuring water levels in small concrete dams, channels, tailing dams, and gauging stations.

Limitations on the use of auscultation range meters are as follows:

- Large water level ranges are not expected.
- There is a direct line of sight between the reference point and the water surface.
- There is no wave action or turbulence on the water surface.
- There are no floating objects on the water surface that can interfere with the measurements
- Adverse weather conditions (heavy rainfall or dense fog), are not expected.

Among the different systems that exist for measuring distances between two points, the most commonly used in the field of dam auscultation are ultrasonic sensors and microwave radar equipment. Floating range meters are not as sensitive to turbulence and can be used to give reliable readings during inclement weather.

Water level measurements based on floating sensors are widely used in dams and facilities where no large fluctuations in reservoir level are expected. Their dependence on mechanical moving parts is offset by their precision and long-term stability.

The range of ultrasonic and microwave radar range meters is approximately between 10 m - 30 m, respectively. Radar range readers have a measurement accuracy of 0.1%.

**Measuring waves**

No examples of instruments specifically for the measurement of waves on dam reservoirs were found. Visual assessment of wave height against a reference mark on a dam is the most common method of determining wave size.

### 4.3.2 *Water temperature*

In some cases, it can be useful to measure the water temperature in a reservoir for controlling the thermal impact on the upstream side of a dam or estimating the probability of ice formation. There are multiple measurement methods, but one of the most common temperature sensors is the PT-100 sensor, which provides excellent stability over time.

In concrete dams that are under construction, these can be embedded inside the upstream face. In existing dams, they are installed on the upstream face of the dam or the intake structure and should be properly fixed and connected. Depending on expected reservoir level fluctuations, several sensors can be installed at different elevations.

In addition, reservoir temperature can also prove useful in understanding the source of leakage water if temperature measurements of the leakage water are available. Water temperature can also impact results from deformation measurements.

### 4.3.3 *Debris and blockages*

Visual assessment of debris on a reservoir or blocking a spillway is required as no measuring instruments were found. Water level measurements both upstream and downstream from the dam are a good secondary indicator, a good analogy is a head-loss measurement over a thrash-rack. However, this is intended to be used in addition to, not as a direct replacement for, any systems to register a spillway opening.

## 4.4 Data loggers and Communication Systems

Critical to the success of a continuous monitoring program of the structural behaviour of a dam is a Data Acquisition System (DAS), which is responsible for collecting and transmitting all information provided by installed instrumentation to a control room.

Almost all modern dam monitoring systems are equipped to allow automatic reading.
Automatic Auscultation Systems (AAS) can be sub-divided into two categories:

- Centralised system
- Distributed system

#### *4.4.1.1 Centralised systems*

In a centralised system solution, all signals from the sensors are transmitted to the data logger, using a metallic pair cable. The signals are collected by a DAS integrated in the data logger.

Centralised automatic monitoring systems are commonly composed of the following elements:

- A network of sensors and transducers that provide, through the necessary wiring, the electrical signals that the data logger registers.
- A manual reading box (CLM) collects the signals provided by the sensor network and allows users to read them through portable terminals.
- A Data acquisition cabinet ("data logger") that registers data from the CLM, processes and stores data where required, and eventually transmits acquired data to a control centre.
- Optionally, a dam´s computer that operates as SCADA can be incorporated from the control centre for presentation of data and reports.

The elements composing a centralised system are shown in Figure 9. The advantage of a centralised system is its overall simplicity. Other advantages include:

- Less equipment and lower costs
- More reliable for simple monitoring
- Low maintenance for simple monitoring

A centralised system is therefore most suitable in the following conditions:

- Real-time data transmission is not required
- Relatively few measuring instruments, and they are of a simple nature
- Measuring instruments are not very far (< 500 m) from the control centre

It should be noted that the signals are transmitted via metal cables. The system's sensitivity to induced electrical oscillations (surges) increases significantly with distance. Furthermore, it is common practice to install a UPS system that guarantees the supply of power to the device in the event of failure.

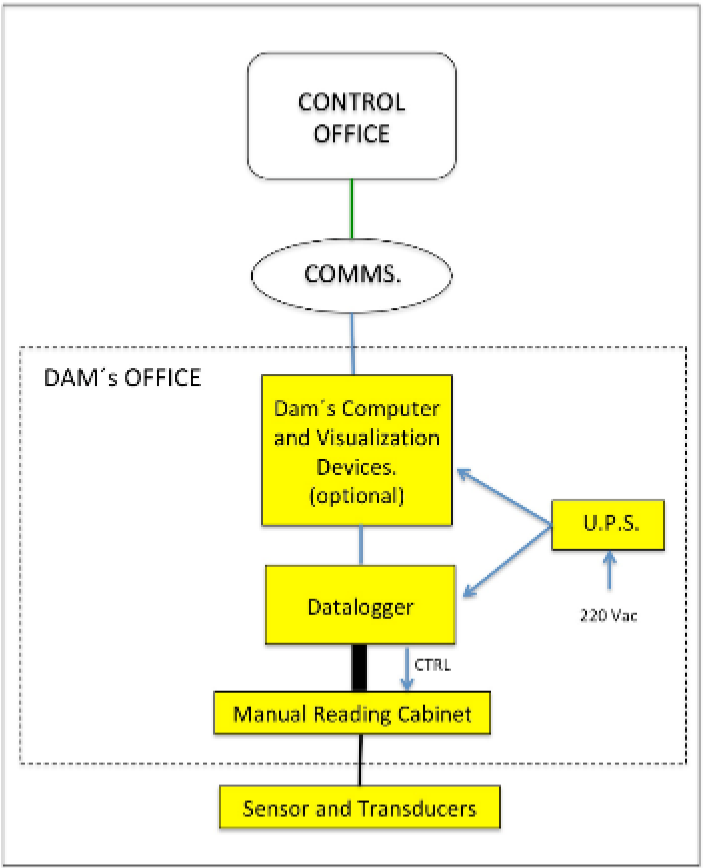


*Figure 9: elements composing a centralised monitoring system*

#### *4.4.1.2 Distributed systems*

Distributed systems are the most common system type used to collect monitoring data on large dams. They are most relevant when the distance between sensors and control room is large. Elements that compose a distributed system are shown in Figure 10 and are described as follows:

- A network of sensors and transducers that are distributed in the dam structure.
- Manual reading boxes (CLM) installed at the sensor locations.
- Control cabinets. These obtain data from CLM boxes and transmit processed data to the control centre.
- A local communication network between the control cabinets and the control centre.
- Optionally, a dam´s computer that operates as SCADA can be incorporated from the control centre for presentation of data and reports.

As indicated above, distributed systems are the most common solution for the automation of monitoring of the large dams.

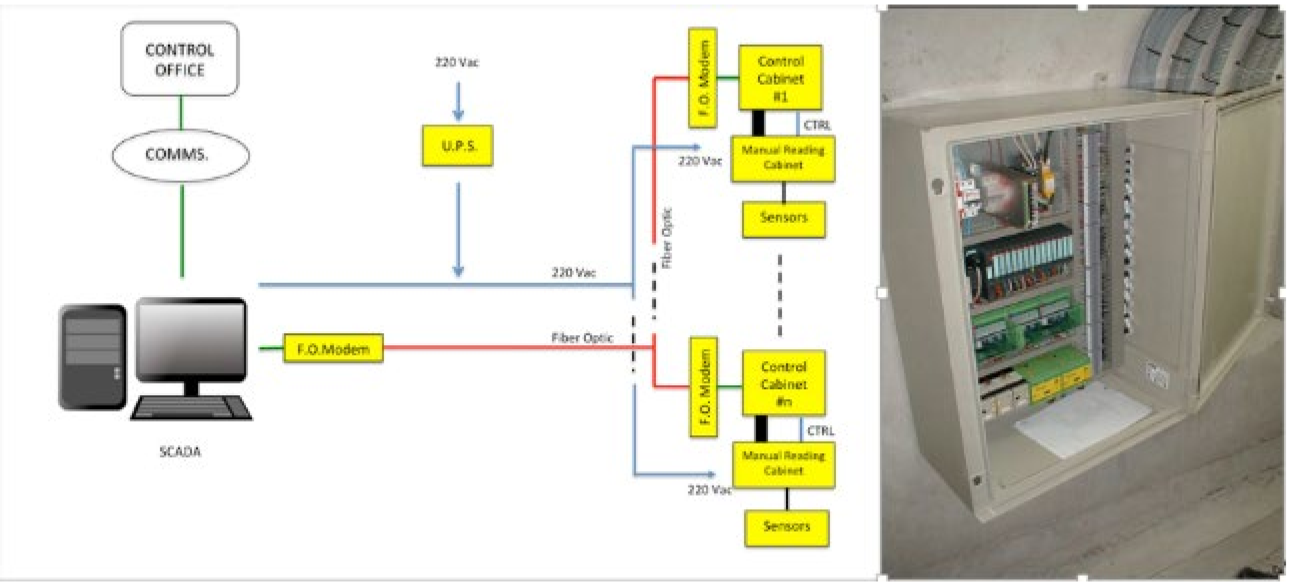


*Figure 10: Elements composing a distributed system (left), example of a control cabinet (right)*

The main advantages of distributed systems are as follows:

- Significantly reduces the costs and complexity by reducing electrical wiring and cable conduits between the sensors and the DAS.
- Improves reliability by limiting signal losses, reducing noise ratio, and providing protection against the induced surges
- Better control of data quality.
- Simplified maintenance for complicated monitoring schemes.

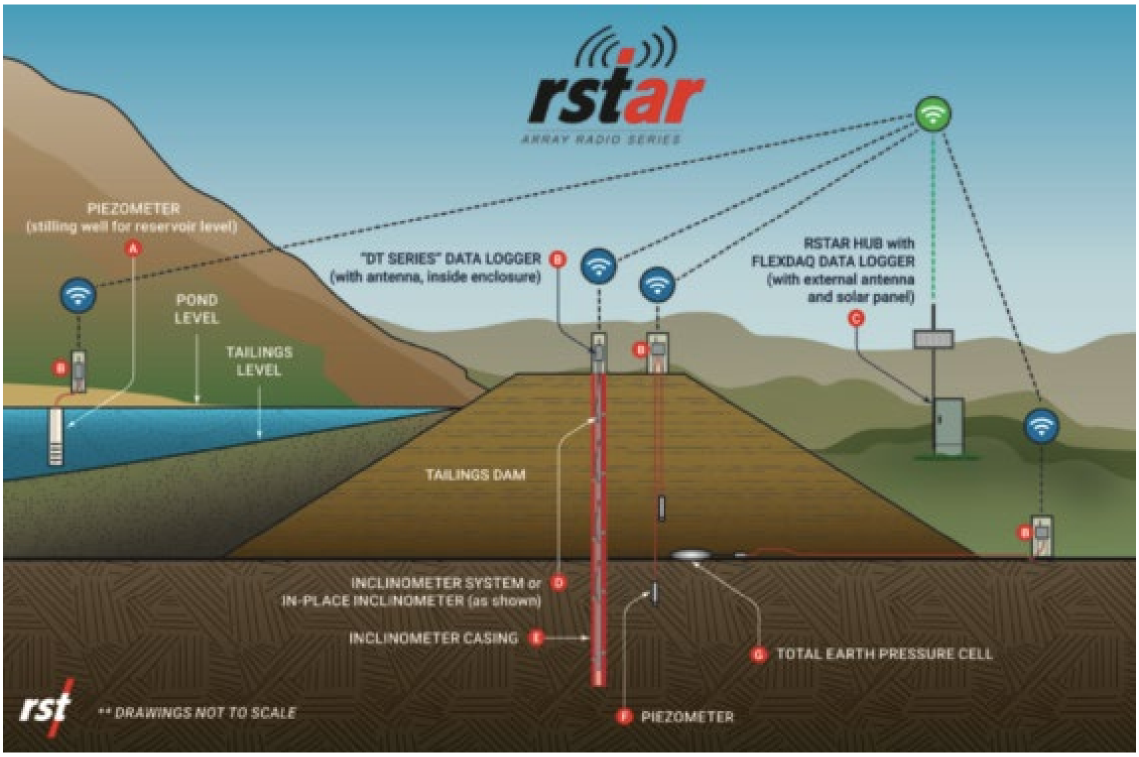


*Figure 11: A typical distributed communication system according to RST.A D, E, F and G are different types of sensors. B is the control cabinet. C is the control cabinet with DAS that connects with the control centre by wireless method (powered solar panel).*

Usually, the local network of a distributed system consists of fibre optic wiring that allows for the covering of long distances without increasing the risk related to overvoltage induced by atmospheric discharges. Other alternatives are wireless networks based on Wi-Fi, Bluetooth, ZigBee, or LoRa technologies. With the wireless network, different network topologies like point-to-point, star, or mesh, can be built.

A common solution is for the DAS to be connected to the control centre via a local communication network at the dam site (wireless or fibre optic) (Figure 11). It is also practical to install an Uninterruptible Power Supply System that guarantees the supply of power to the control centre. This way, the DAS will maintain normal operations even when there is a temporary loss of the service in the electric network.

### 4.4.2 *Reliability*

The protection of equipment and devices against water or dust is classified according to guidelines from the International Electro-technical Commission (IEC) called the Ingress Protection Code (IP code), shown in Figure 12. The IP code consists the two letters (IP) and two additional digits. The first digit ranges from 0 to 6 and indicates the degree of protection against the solid particles, typically dust. The second digit ranges from 0 to 8 and indicates the degree of protection against the water.

The electronic components of an Automatic Monitoring System must be protected by an enclosure with at least an IP-66 or greater when located outdoors or in e.g. a tunnel, crawlspace, or unheated area. This level of protection will guarantee the isolation and insulation of the electronic components.

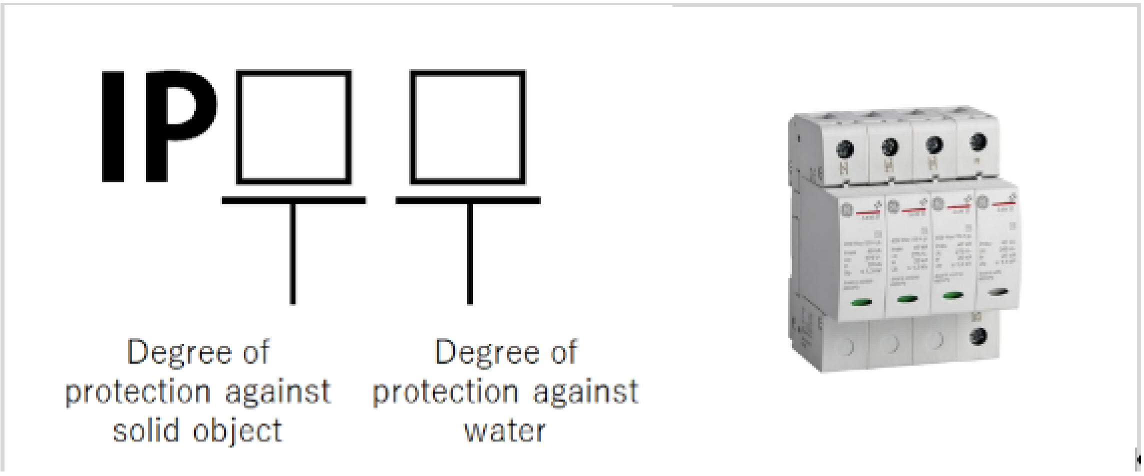


*Figure 12: Ingress Protection Code (IP code) (left) and galvanic isolation elements (right)*

### 4.4.3 *Environmental conditions*

The most important environmental condition is the working temperature for the electronical devices, or the temperature range within which they will operate as intended. In Norway, outdoor air temperature can be as low as -50°C in winter. In summer, the temperature can be over 50°C for metal equipment that is directly exposed to the sun. It should be noted that devices buried underground, within a structure, or submerged under water are unlikely to be exposed to such extreme variations in temperature.

The operating temperature for common commercial equipment used for automatic dam monitoring systems ranges from 0-70 ° C. It is recommended to check the specified working temperature of a given device against the Nordic climate. For some equipment placed outdoors, such as meteorological stations, dataloggers, antennae and so on, a wider range of operating temperatures (-40 to +85 ° C), may be required.

## 4.5 Qualification requirements for technical staff

Dam owners should be aware that special knowledge and skills can be required to operate and maintain a dam monitoring system. As chapter 3 discussed, systems based on manual readings are in general easier to maintain than automated systems.

Operators should be able to make manual readings of sensors, retrieve data from automated systems, and have a basic understanding of how to interpret the data. Knowledge for making basic preventive maintenance works is helpful so as not to be dependent upon external contractors, as these are not always readily available. More complicated maintenance work is often conducted by external companies or manufacturers.

An electrician or electrical technician is required for regular maintenance. Even for systems that are not automatic, many sensors are electrical and protected behind cabinets. The technician should be able to review and repair cablings, junction boxes, and power supply. The repair of an electrical sensor should be conducted by the manufacturer.

Installation and maintenance of the devices and communication networks for an automated system requires more specialised knowledge. Some automated systems are closed systems that can only be maintained by the manufacturer. An open system can be repaired by a trained electrician or expert belonging to the maintenance team of the dam owner, or a specialised contractor. The ability to program data loggers can be useful, but as it is only required on very rare occasions this is mainly done by external contractors and is therefore unnecessary expertise for a dam operator to have “in house”.

The engineer that interprets the monitoring data should have a good understanding of the overall dam behaviour and stability. Moreover, they should have basic knowledge of the facility in order to distinguish between anomalous data and dam behaviour.

# 5 Data Acquisition and Management

## 5.1 General

The digitalization of private life and industry has progressed rapidly during the last decade. Within industry, Asset Management is a common way of describing the management of facilities during operation. In the case of dams, this does not only include maintenance and operation, but, due to the potentially very high risk associated with them, dam safety management and surveillance.

As stated in chapter 3, monitoring is an important part of dam surveillance and plays a key role in the framework of dam safety. Dam surveillance is a key risk mitigation tool, providing a means of early identification to reduce the probability of events that could lead to dam failure occurring (ICOLD, 2008). Due to aging dams worldwide, population expansion, and a growing demand for transparency, there is a need for increasingly intensive monitoring systems. This may include automation, telemetry, and information technologies solutions. As a response, operators tend to reduce their non-specialised onsite staff and centralise their technical knowledge.

Nevertheless, a perfectly working monitoring system will not necessarily reduce risks if the data is not evaluated periodically and used to improve dam safety. It is therefore essential to connect data acquisition, evaluation, and decision making as efficiently as possible (Figure 13). The aim is to transform raw monitoring data into valuable information, providing the operator with clear a picture of the dam’s behaviour and the state of the monitoring system.

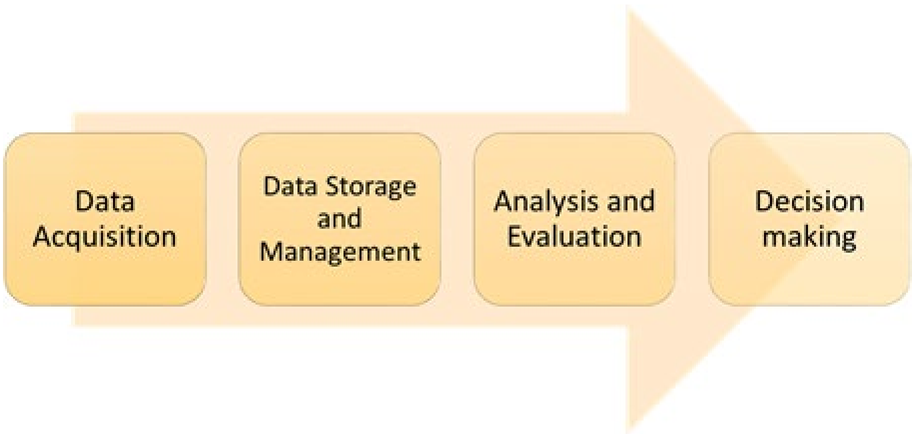


*Figure 13: Monitoring tasks, from data acquisition to decision making*

Many dam operators rely on ad-hoc solutions for data analysis, such as spreadsheets with manual data entry. However, a centralised database with specific dam surveillance features can help streamline these tasks, especially in large dam portfolios equipped with telemetry systems, where large amounts of data can make manual analysis inefficient and time-consuming. It can also allow analysis tasks for geographically dispersed portfolios to be centralised in a single technical office. The advances of information technology during the last decade offer completely new possibilities for the management of monitoring data.

Functionalities that make dam monitoring data management systems useful to support decision-making include:

- Direct communication with telemetry systems, streamlining the acquisition process and maintaining real-time features
- Keeping data up-to-date and readily available for all stakeholders within a potential database

- Built-in tools for periodic data validation and quarantine, allowing the monitoring system's condition to be verified
- Built-in tools for analysing large volumes of data, with a focus on cross-referencing, correlation analysis and early detection of failure mode events

For example, the implementation of an integrated monitoring system by a Spanish dam owner helped to improve dam safety and reporting considerably for more than 50 dams. At present, more than 100 engineers, technicians and other personnel involved in the owner's dam safety program have access to the data. During the last 6 years, more than 300 annual, and 50 extraordinary reports, were prepared using the software in a more efficient and detailed way than previously.

Additionally, after a seismic event, both the dam owner and external experts had immediate and easy access to updated data of all affected dams and could quickly make informed decisions about the measures that had to be taken. The same day, any anomalous data that exceeded threshold values detected through the automatic data acquisition system could be reviewed from any computer with internet access. The following day, technicians made extraordinary manual readings and uploaded data in the morning. At the same time, updated charts of all monitoring data from the dams were available for the elaboration of a detailed extraordinary report on time.

## 5.2 The decision-making process and system integration for the dam owner

### 5.2.1 *Decision making*

As mentioned above, the scope of a monitoring tool can be very broad. The greater the level of integration within other systems and the more functionalities available, the greater the benefit of monitoring data. Nevertheless, systems that are too complex can also be counterproductive if they are not working properly and cause unnecessary costs and effort to all stakeholders.

As for the dam owner, the key factors to consider in the design and implementation of monitoring systems can be classified in to Policy, Technical, Process, and People (Figure 14).

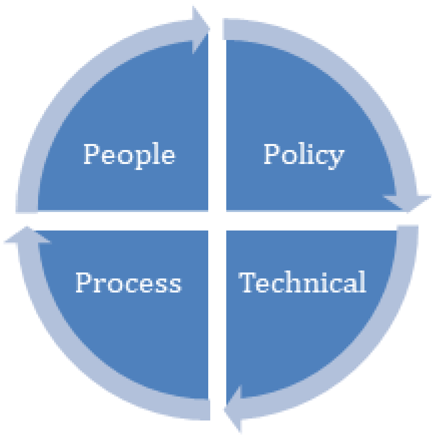


*Figure 14: Key aspects to be considered in the design and implementation of monitoring systems can be grouped in to four categories.*

**Policy** refers to legal regulations and guidelines. The applicable dam safety legislation should be considered in order to identify the legal obligations of the dam owner regarding dam monitoring.

**Technical** refers to the technical requirements of the monitoring management tool. These are not only the requirements of the end-user for data processing and evaluation, but also IT-requirements on security and protocols. The number of dams and other monitored structures, as well as the type of existing monitoring and automated data acquisition systems, affects the necessary characteristics of the system.

**Process** describes the working processes and information flow that should be covered by the monitoring system. How far the established working procedures shall be covered, controlled, or substituted by an automated tool.

**People** refers to the personal requirements for each user, taking into account responsibilities, skills and field of work. This is a key aspect for the successful implementation of a monitoring system.

Moreover, the available budget might be the decisive factor for specifying the requirements of a dam monitoring data management tool. Simple spreadsheets are often used due to budget constraints and their simplicity. While this may be sufficient for small dams, when handling a large amount of data (a large number of sensors or longer time series), this becomes inefficient. This is especially true when data interpretation is made periodically and charts must be updated manually for every report.

### 5.2.2 *Integration within other software*

As discussed above, dam monitoring and data management should be integrated within the Dam Safety Management framework of the dam owner. However, the scope of dam monitoring software usually varies due to the requirements of individual owners. These depend on established working procedures and other software and databases that the owners have already implemented. In Section 5.4 a number of features that can either form part of the monitoring system or of other software packages are explained.

The monitoring tools can be partially or completely integrated with the data management software tool. It is important that each software developer clarifies the data formats that their software requires, so that the data obtained from the monitoring tools can be seamlessly integrated with the data management software.

Regarding the type of data, automated data of the reservoir level or meteorological data is sometimes already available in other databases that are maintained for management of hydropower production or flood forecasting. This information is important and should be integrated if it is not available through other means.

Some dam owners have an emergency system for different kinds of incidents and alarms. In these cases, it is helpful to integrate with the existing infrastructure to transfer alarm triggering from monitoring sensors to the centralised system.

Some countries require the installation of a Control Centre for Emergency Action Plans that uses its own software. As monitoring data is an important indicator for detecting Emergency Situations, information regarding alarm triggering should be shared between systems.

In some companies, there is an Asset Management tool for the management of maintenance works and other associated tasks regarding their infrastructure. Integration of monitoring data and the Asset Management tool can also be required. This should be carefully considered so as to ensure that none of the systems become overloaded.

## 5.3 Process for establishment of a data management tool

The implementation of a data management tool is more than just the purchase of a software license. As it involves many stakeholders it should be well planned and carefully considered (Figure 15). Especially in large companies with strict internal policies and regulations, the implementation of new software has to be well thought-out as many different proceedings and areas of responsibility must be taken into account.

There should a collaboration between IT-experts and dam monitoring experts, as they each have different expectations and responsibilities. However, the most important aspect for a successful implementation process is the software's acceptance by the end user.

Therefore, the users should be involved during the entire implementation process. This process can be broken down into the following phases:

- Development and Procurement
- Configuration
- Start of Operation

***A perfectly working software that is not user friendly, or that does not support the needs of technicians and engineers, will not be used.***

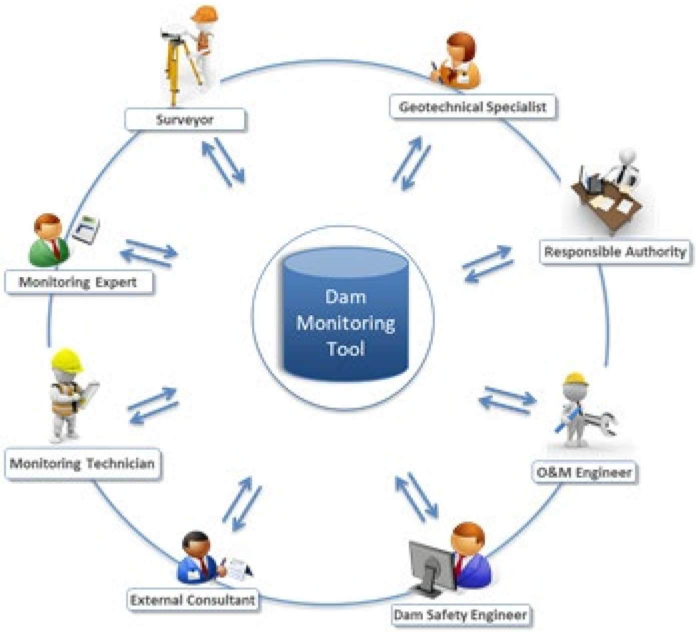


*Figure 15: Stakeholders involved in dam monitoring*

Gradual rollout of a new software tool should also be considered. This can be done by incorporating only the basic features of the tool in the beginning so that users can start working and gain familiarity with them and not be shocked by too many changes and new functionalities.

For dam owners that operate a large number of dams, it is recommended to start with a few structures and gradually expand the program to include the remainder. In this way, the system can be tested on a small group of users, ideally those that are more open and welcoming regarding changes. The lessons learnt help to optimize implementation for the rest of the dams.

In the following sections, the impact of the below aspects on the successful implementation of a monitoring system is considered:

- Involving all stakeholders, including engineers, technicians and IT-experts
- Defining "must have" and "nice to have" requirements. Don't focus solely on flashy features, but also on how they can be used for data processing, dam safety, and reporting.

- Compiling updated information about the installed monitoring system
- Correct configuration of the software systems also requires knowledge and expertise in dam safety
- Considering training and adaption time during the implementation process

### 5.3.1 *Development and Procurement*

The development, procurement, and installation of a dam monitoring management tool is mainly the "computer science" part of the implementation process. Nevertheless, this phase should not be managed exclusively by IT-experts. The experience and input of both Dam Safety and Dam Monitoring experts is essential for a successful project. This applies both to the dam owner, and to the provider/developer of the software tool. Therefore, it is important to include specific knowledge in Dam Surveillance (not only structural monitoring), instrumentation, automation systems, data analysis, and dam safety in early phases of the implementation project.

A dam owner can choose to either buy or self-develop a software. Now that the commercial market is more mature and had time to develop, it is recommended to purchase an existing commercial software with the required features and functionality to avoid the risks associated with software development.

When purchasing existing software, the dam owner saves a lot of time and knows exactly what they are getting for their money. This is particularly true in cases where the software has already been successfully used for other dam projects. In addition, it is a good strategy to establish a small pilot project to ensure the quality of the investment.

Software can be installed on a *cloud server*, on a *central server* and/or directly on to a *user's computer*. Installation on a central server operated by the dam owner should not be underestimated, as the compatibility with existing system software must be guaranteed and security requirements, installation proceedings, and access policy for external companies must be taken into account.

Installation on a cloud server is easier and offers more flexibility, not only during the installation process but also during maintenance and operation. Nevertheless, the cloud server has to fulfil the dam owner´s requirements, especially regarding performance and security.

In the following table (Table 3), a selection of different available software solutions is shown. Some of these may only be used with certain types of sensors or manufacturers. Many are designed for monitoring in general, while others are focused on specific dam monitoring requirements.

*Table 3: Examples of available software and their developers.*

| Software | Developer |
|---|---|
| ARGUS | Soil Instruments, UK |
| ATLAS | Slope Indicator Co, Mukilteo, WA, USA |
| AvaNet | AVA Monitoring AB, Göteborg, Sweden |
| Cautus Web | Cautus Geo, 3400 Lier, Norway |
| Conwide | Conwide AB, Fagerhult, Sweden |
| DamData | Ofiteco, Spain |
| DamSmart | AECOM |
| GEOSCOPE | Sixense-Soldata, France |
| GeoViewer | RST Instruments, Coquitlam, BC, Canada |
| GKS Pro | GGB, Germany |
| HoleBASE | Keynetix Ltd., Redditch, UK |
| HYDSTRA | Kisters AG, Germany |

| | |
|---|---|
| Intellidam | GlobVision Inc, Canada |
| iSiteCentral | Geocomp Corporation, Acton, MA, USA |
| ISY JobTech | Norconsult, Norway |
| Konect GDS | Campbell Scientific |
| MissionOS | Maxwell Geosystems, Hong Kong |
| MLSuite | Canary Systems Inc., New London, NH, USA |
| SDC | Glötzl, Germany |
| TerrWeb | Encardio Rite, India |
| Trimble 4D | Trimble, USA |
| Vista Data Vision | Vista Engineering, Reykjavik, Iceland |
| WebDavis | Solexperts |
| WMS | Sisgeo, Italy |

Due to the variety of available software tools and the fact that many are constantly undergoing updates and development, this report does not include a comparison of the available solutions. It is often only the developer who knows the whole potential of their product and information in commercial material may be misleading.

### 5.3.2 *Configuration*

As soon as the software is developed or purchased, it must be configured according to the individual dam and its installed monitoring system (Figure 16).

Configuration includes a summary of the installed monitoring system including the setup of all sensors with their corresponding identification codes. Further configuration depends mainly on the available features of the selected software tool. These can be the incorporation of formula for technical calculations, preconfiguration of templates for charts and graphs, uploading of historic monitoring data, and the definition of threshold values.

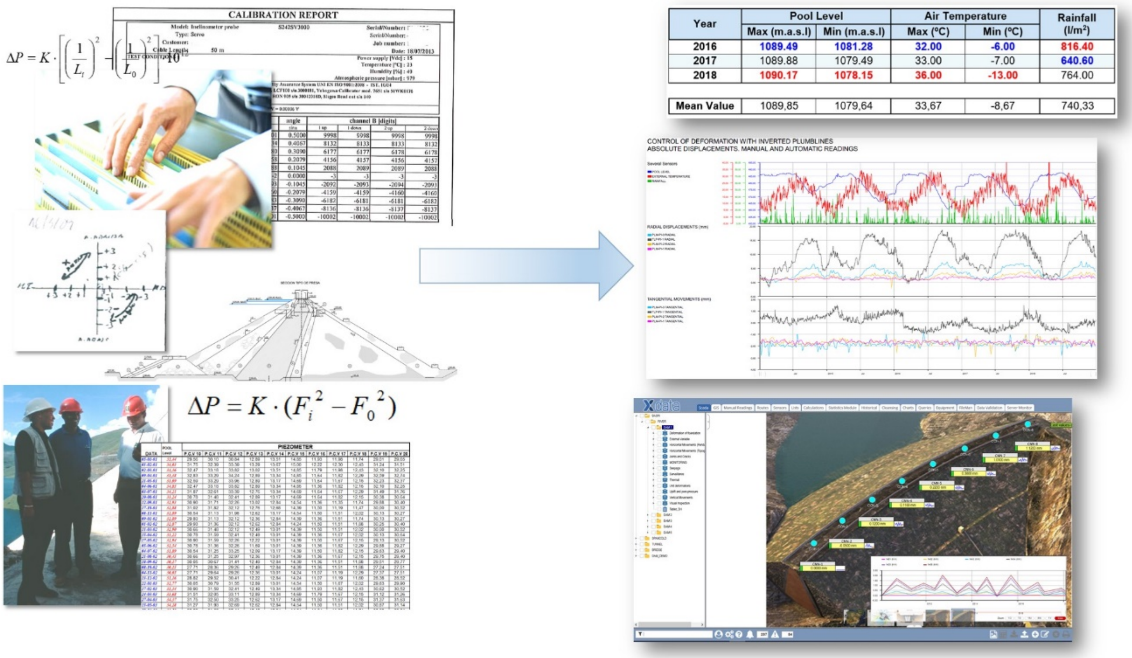


*Figure 16: Review of information for the configuration of formulas, historical data, drawings, tables etc.*

Configuration of the chosen software requires expertise in the field of dam monitoring; especially processing, review, calculation, and analysis of dam monitoring data. It is not just about configuring numbers, but about understanding how the available information will be used as well as processing and presenting data in a useful way in order to make it easy understandable for the end user (engineer, operations personnel, consultants, etc.).

Regarding the configuration technical values, especially in older dams with little or no documentation, this task often requires further investigation to determine the initial values, material properties, and parameters (for example, the height and material properties of the clay core in an old embankment dam).

Summing up, the configuration process is an important phase during the implementation of the dam data management tool and should not be underestimated. Even if it depends on the features of the software, in the end, it is the fine-tuning of the design of the software interface for interpreting data that is most important. Therefore, engineering knowledge in the field of dam safety and dam surveillance is indispensable for the configuration of the dam monitoring data management tool.

### 5.3.3 *Starting the system*

After finalising the configuration of the system, it can be set into use. This start-up stage differs from the general operations that form part of the implementation process and include the proper operation and maintenance of the system.

Training sessions for personnel that are going to be using the software is a key aspect for a successful implementation of the dam monitoring management tool. Only if the user understands the different features of the software and can apply them efficiently, will they use it to the best of its abilities. *A perfectly working software that is not used correctly by the different stakeholders is a failure*.

The implementation of a new software tool always necessitates a change in working habits and learning. Human resistance to changes should not be underestimated. To counteract this, training should not only an explanation of the new software features, but also an element of motivation to encourage their use. Advantages of using the tool and the benefit of dam surveillance should be highlighted.

After successfully implementing the software, the operation and maintenance phase begins. The scope of O&M works depends on each software tool and the method of installation, for example via a cloud server or installed a local server of the dam owner. If the provider has remote access permission to the software, periodic update and maintenance works can be conducted more easily.

## 5.4 Features

There is a wide range of features that are already offered by existing software tools and many more possible additional features that can technically be incorporated in the future. Dam owners should define their priorities and distinguish between “nice to have” and “must have” features.

In this chapter, the most important features are described. The report distinguishes between the following types of features that are dealt with in the subsequent sections:

- General features
- Data presentation
- Additional features

### 5.4.1 *General features*

#### *5.4.1.1 Databases and Hardware*

The selected database capacity should be sufficient for handling the expected amounts of data and all automated processes. With modern computer technology, this is rarely a significant issue, but should be considered when handling very long time series of data, large number of sensors, and several dams. This also applies to the required hardware.

#### *5.4.1.2 Sensors*

Dams usually are installed with instrumentation from different manufacturers with different types of signals, such as frequency, voltage, resistance or current that are converted into a digital format for reading. All read data values are associated with a timestamp. Measuring frequencies can differ greatly. While most sensors have 1 reading per month, others take readings once per week or day, and in some cases every hour or 15 minutes. Most dams have between 20 and 100 sensors, but some have more than 1000.

The dam monitoring data management tool should therefore satisfy the following feature requirements:

- Ability to process signals from various sensor types
- Simple to reconfigure existing sensors and new sensors when needed
- Possible to store additional sensor information

#### *5.4.1.3 Calculation*

It must be possible to distinguish between raw data provided by the sensor, and calculated values needed for the interpretation of dam behaviour. The monitoring tool software should make the calculations necessary to obtain these engineering values. Even if calculations can be made before data is uploaded to the database (most automated data acquisition systems (ADAS) calculate values and can transfer them to the monitoring tool, or convert hand read data from a technician in the field), it is highly recommended to store both raw data and calculated values in the database in order to be able to revise calculations. Users should be able to review the formulas and parameters used in the calculations.

Taking into account a possible upgrade or repair of the monitoring system in the future, the user should be able to modify existing formulas or set up new calculations.

#### *5.4.1.4 User profiles*

As earlier stated, many users with different backgrounds and needs are expected to work with a dam monitoring data management tool. These differences in each users' endgoals should be reflected in their user profiles.

For example, a monitoring technician takes manual readings on site and uploads the data to the tool. The monitoring engineer reviews and interprets the data. The system should be built to allow multiple users simultaneous access to streamline the workflow.

#### *5.4.1.5 Data acquisition*

Acquisition of monitoring data for dams can be done manually automatically if an automatic data acquisition system (ADAS) is installed. A software tool should be configured to receive data in both ways in order to cope with situations such as the automatic system check, maintenance downtime, or system failure. Additionally, most dams monitor control variables where data cannot be acquired automatically, such as geodetic control points or inclinometers.

Manual data acquisition can be done by way of a user interface in the application where data can be typed in by hand or through the upload of files or data sheets.

The use of portable measuring devices equipped with data storage, that allow the direct feed of measurement records to an archive, or the use of portable devices (laptop type) allowing recording, immediate validation of the measured (by a manual measuring device) data, and the direct feeding of these records to the archive makes manual operations easier and more reliable [9].

In addition to portable devices used for collecting data from sensors, some manufacturers offer their own software for manual data acquisition that can be installed on devices such as mobile phones or tablets. This software is synchronized with the software tool database and allows the upload of data in real-time via web connections. It can also provide additional information included in the central database, such as limit values or historic data, for personnel on site.

If an ADAS is installed, this data can be directly imported to the dam monitoring data management system. Therefore, a communication link between the different dataloggers and the software is required. If the software server is located on site, an FO or wireless connection to the dataloggers is usually required. If the software is installed on a central or cloud server, internet connection will be necessary. In both cases, established protocol for safe data transfer must be established.

#### *5.4.1.6 Data export*

Even if the monitoring tool incorporates (nearly) all necessary features, it is useful to be able to export data to other databases for post processing. In some cases, monitoring data is required by other experts that do/should not have regular access to the system. Many users prefer to make additional calculations within other programs, such as Microsoft Excel.

The monitoring tool should therefore allow for exporting to common data formats like *.csv or *.xls.

#### *5.4.1.7 Data review, validation and editing*

Users should be able to review all data that has been uploaded to the monitoring tool. Before evaluating the data, an experienced engineer should verify manual and automated data. This should be done both on raw data and on calculated technical values. Errors in the data are sometimes easier to identify in raw data.

Information should be registered in the system even if it has not been validated.

In a custom solution, workflows specific to each individual client (dam owner), involving several levels of responsibility and data approval, can be incorporated before final data validation.

Apart from reviewing and validating data, the user should be able to modify or delete data. Especially in manual readings, certain errors are obvious and can be corrected. In any case, these changes should be registered in the system.

#### *5.4.1.8 Alarm triggering*

Thresholds for monitoring data can be defined in many different ways, depending on the characteristics of each variable. The easiest and most common ways are maximum and minimum values. More advanced threshold values are dynamic and depend on for example other variables, such as temperature and reservoir level, or the rate of change of a variable. Dynamic thresholds can make alarm triggering more precise and therefore the software tool should offer the flexibility to incorporate them.

In some cases, it might be necessary to assign several threshold values to one sensor in order to consider different alarm levels. A first level can be informative, and the following level generate an alert or alarm.

As threshold values can vary due to sensor recalibration or just through an update using more historical data for a statistic model, it is important that the user can define and modify the threshold values that are configured in the system.

New readings, both of manual and automatic data, should be automatically compared to the specified thresholds for triggering the corresponding alerts and/or notifications. Users should be informed by the system about every threshold value that has been exceeded. This can be done through the interface by showing information about the corresponding sensors in a clear and visual way, usually with different coloured rankings or traffic lights. Email or SMS notifications can be a possibility too in some programs.

Depending on the responsibilities within a company, it might be necessary to validate notifications and alarms in order to register that the person in charge has checked them.

Different types of threshold values and how to set them is further expanded upon in Chapter 6.

#### *5.4.1.9 Reports*

A dam monitoring management tool should *not* automatically generate a complete dam safety report. Production of these reports requires detailed analysis of the available data by an experienced dam safety and monitoring expert. Nevertheless, the tool should assist them as much as possible by processing and generating the information that is needed for evaluation. The tool should cover especially repetitive and time-consuming work. The minimum requirements to be included in a monitoring report depend on local guidelines and, in some companies, on specific internal guidelines and regulations.

The most commonly included information is are charts or tables summarising data values. More detailed information such are drawings combined with monitoring data or reports on alarm triggering and threshold values, can also be included. To best incorporate this data into a monitoring report, it should be easy to export images via jpeg or pdf formats from the software.

In the following section “Data presentation”, examples of charts and tables that can be part of a monitoring report are shown.

### 5.4.2 *Data presentation*

Good presentation of data is essential for facilitating its use to interpret dam behaviour. It is the key for turning sensor data into useful information. Most software tools offer a wide variety of charts and diagrams. The right data presentation depends on the sensors and external variables that influence the control variables.

The presentation should help to identify these external effects, compare different sensors to each other, detect anomalous behaviour or erroneous data, and help to understand dam behaviour.

As already mentioned in section 5.3, a powerful software that has not been correctly configured is not very useful. Therefore, an expert in dam monitoring should advise on the best way of presenting the data.

In this chapter, the most common ways for presenting monitoring data are shown.

#### *5.4.2.1 General properties of charts*

Some software tools are limited to a simple graphical visualization of times series without the possibility of modification. This can be helpful for a quick review of selected sensors, because the user does not have to configure all chart details before viewing the data. The software automatically applies scales, colour bars and other properties to the chart.

Nevertheless, if users wish to visualise particular aspects of the evolution of one or more variables, manually configuring or modifying charts is necessary. For example, variations in a few values can significantly change the graph's scale or axes, meaning that more important variables can no longer be meaningfully assessed. In this case, manually modifying the scale is essential for a detailed analysis of dam behaviour.

Graphical tools for monitoring data offer many possibilities for the individual configuring of charts and diagrams but also have their limitations. Microsoft Excel graphs include a number of features and a high degree of flexibility that many users take for granted. Most visualization tools included in monitoring software do not offer this degree of flexibility. An example is shown in Figure 17 (following page).

The most common options for manually reconfiguring charts are:

- Colour, type and thickness of lines
- Mark reading values with dots to accurately show exact values
- Adapting variable descriptions presented in a legend
- Minimum/maximum values along axes
- Adding comments and reference lines

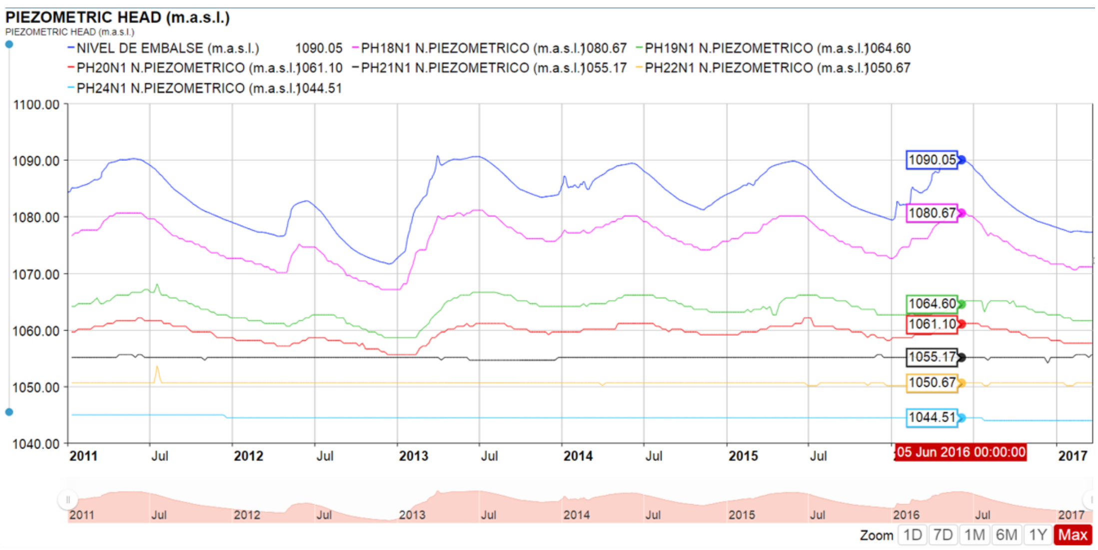


*Figure 17: Chart showing the level of 5 piezometers dependent on time with exact reading value.*

#### *5.4.2.2 Dependent on time*

The most common and easiest way to graphically present data are time graphs that depict the changes in variables over time. Time is plotted on the horizontal axis and the values of the control variable on the vertical axis.

Graphs should be able to combine several sensors in order to easily compare them. If different types of variables with different units are to be compared, the tool should offer the option of including a secondary or tertiary vertical axis. Several scales can also be necessary if the same units are used but the order of magnitude varies significantly between sensors. An example is shown in Figure 18.

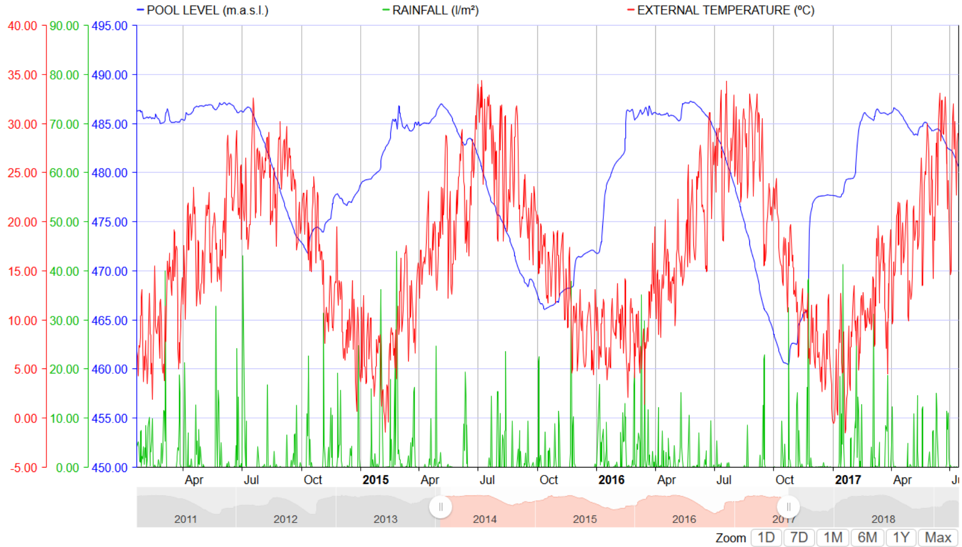


*Figure 18: Chart dependent on time showing three scales for external variables: reservoir level (masl), precipitation (l/m$^2$) and temperature (°C).*

If monitoring data is available over a long time period, it might be helpful to include the same chart twice in an annual report: the first covers the whole period in order to show long-term trends, and the second chart only shows the last 1-3 years in order to support a more detailed analysis of the recent behaviour.

This type of diagram is useful for almost all kinds of sensors and is necessary for most basic data interpretation. Other chart types that can help to analyse dam behaviour in a more detailed way are explained in the following sections, below.

#### 5.4.2.3 Dependent on space

Monitoring data can be visualised as a function of space, showing monitoring data of several sensors taken during one measurement period. In this way, differential behaviour between certain areas along a dam crest or gallery can be easily identified.

A typical example is the visualization of deformations obtained from a topographic survey of all control points along a dam crest. Other examples include the comparison of piezometric levels, or joint displacements within a dam gallery (example Figure 19).

This type of chart is usually made for sensors that have longer time periods between readings, but can also be made using selected data measurements from sensors that conduct measurements more often.

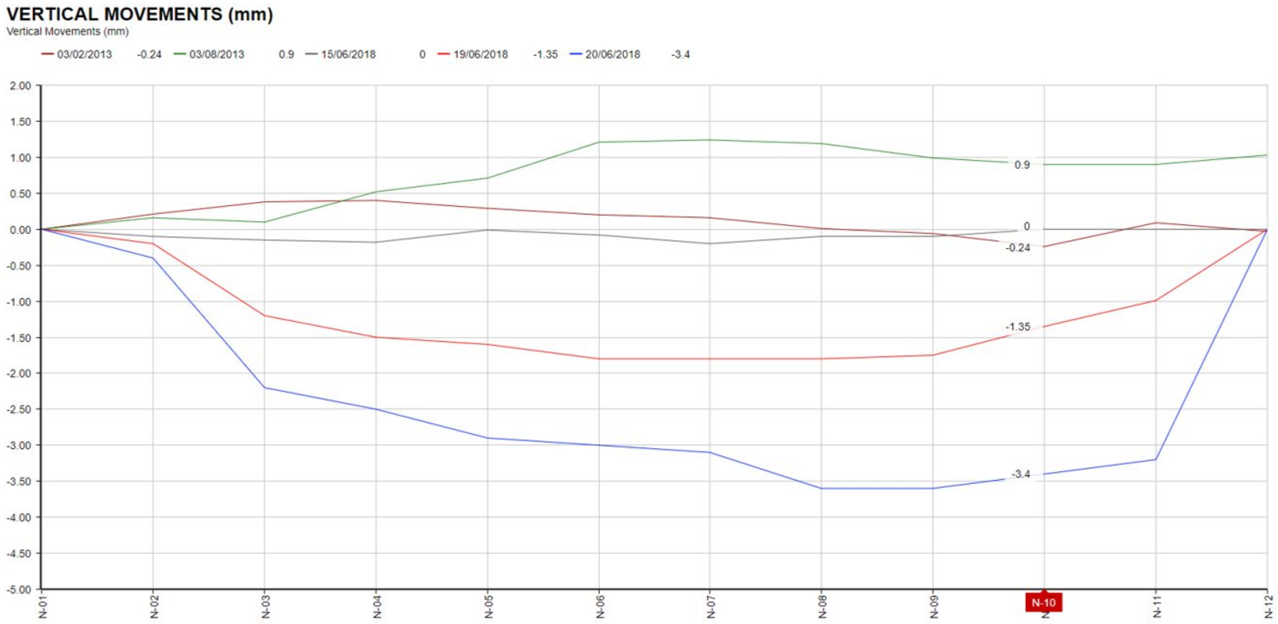


*Figure 19: Chart showing vertical movement along a dam crest.*

Measurements from inclinometers in particular are best shown on graphs as a function of space. Due to their installation, it is more descriptive to use vertical charts in order to show deformation of the measurement points as a function of installation depth (Figure 20).

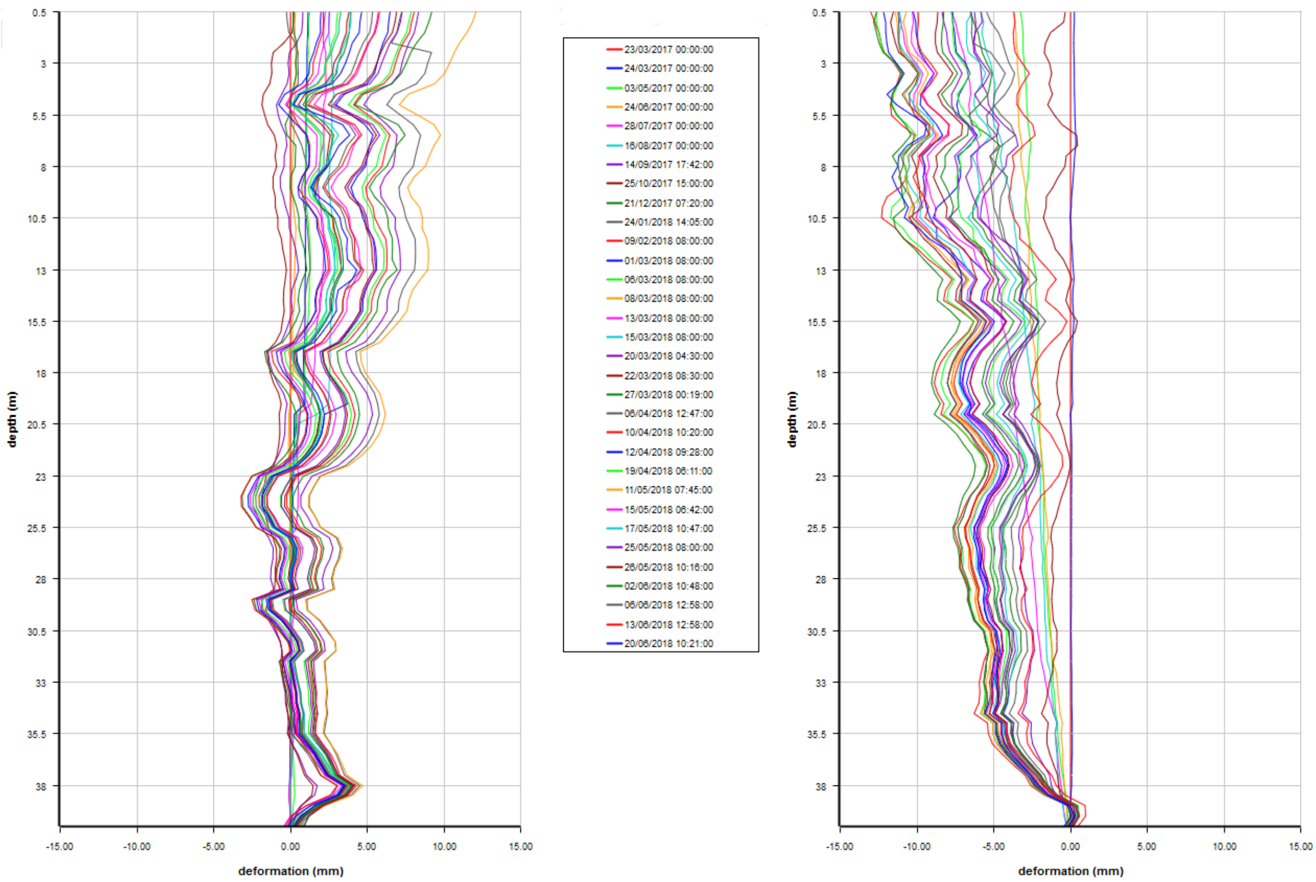


*Figure 20: Chart showing deformation of inclinometer in A and B directions along a borehole.*

#### *5.4.2.4 Dependent on other variables*

How control variables change with time is usually controlled by external factors, often reservoir level, air temperature, and or precipitation. Other controlled variables can also be used, such as concrete temperature or uplift pressure. In order to illustrate these relationships, correlation graphs are used. These graphs depict the relationship between a control variable whose value is plotted on the y-axis and an external variable, plotted on the x-axis.

In the following figure (Figure 21), the relationship between reservoir level and leakage is shown. Colours distinguish between different periods in order to show a possible evolution in time.

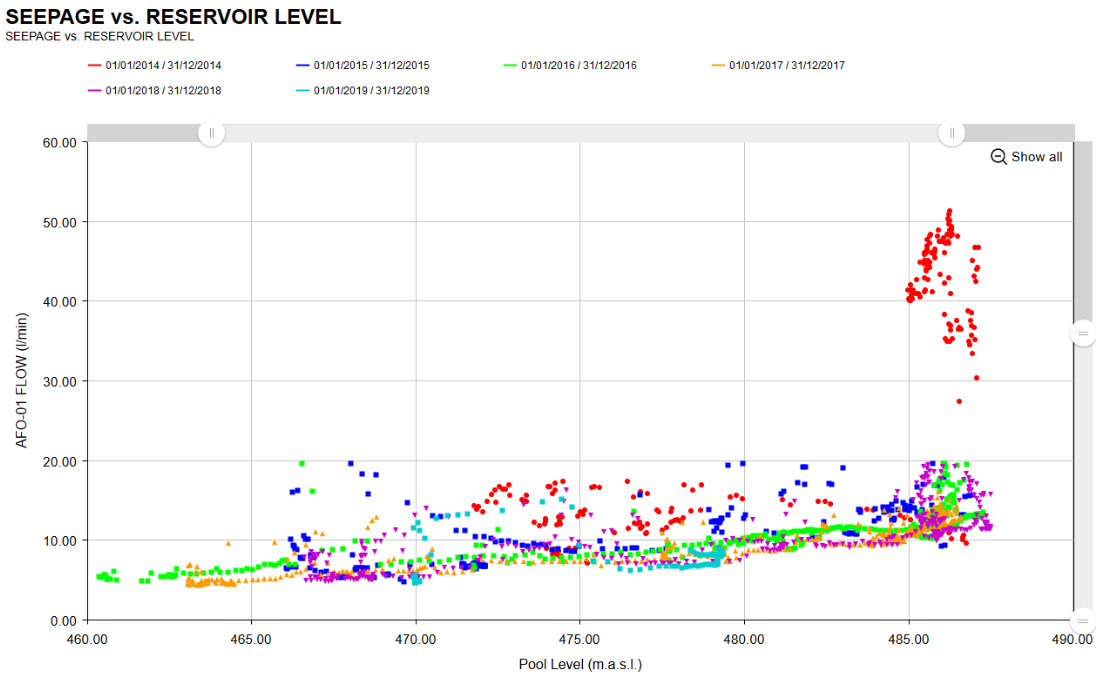


*Figure 21: Chart showing seepage vs reservoir level in different time periods.*

By connecting each value in chronological order, the evolution in time can be shown even more precisely as shown in Figure 22. However, can easily become confusing if too many variables are included.

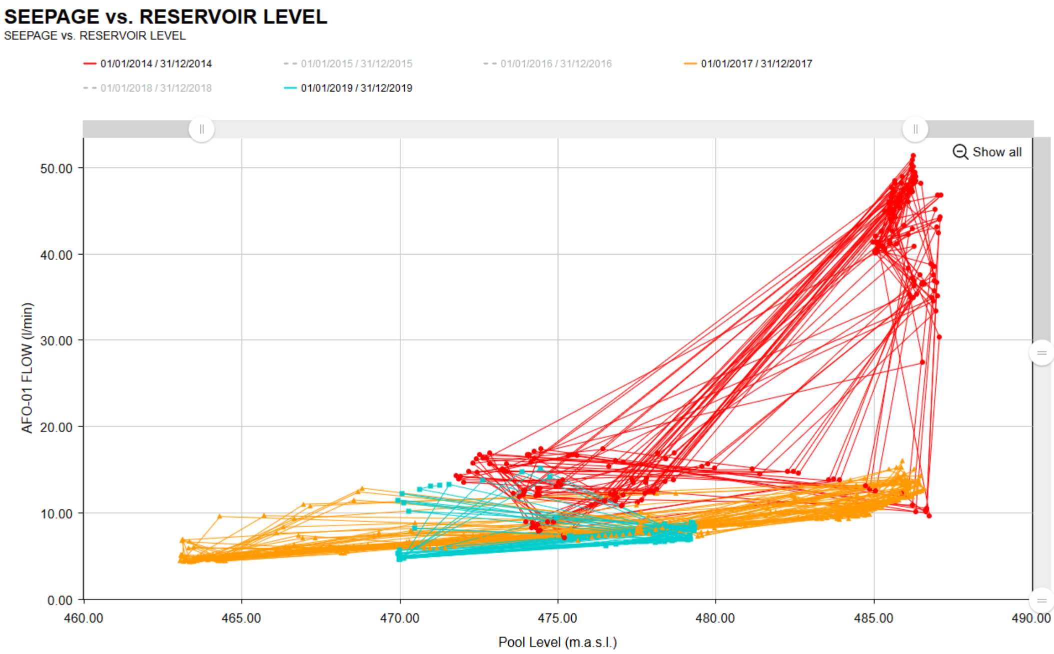


*Figure 22: Chart showing seepage vs reservoir level in chronological order through different time periods.*

Another example of a correlation chart is the comparison of different sensors within one global timeframe (Figure 23). In this case, different colours do not show several timeframes but different sensors. In this way the sensitivity of control variables to an external factor/variable can be determined.

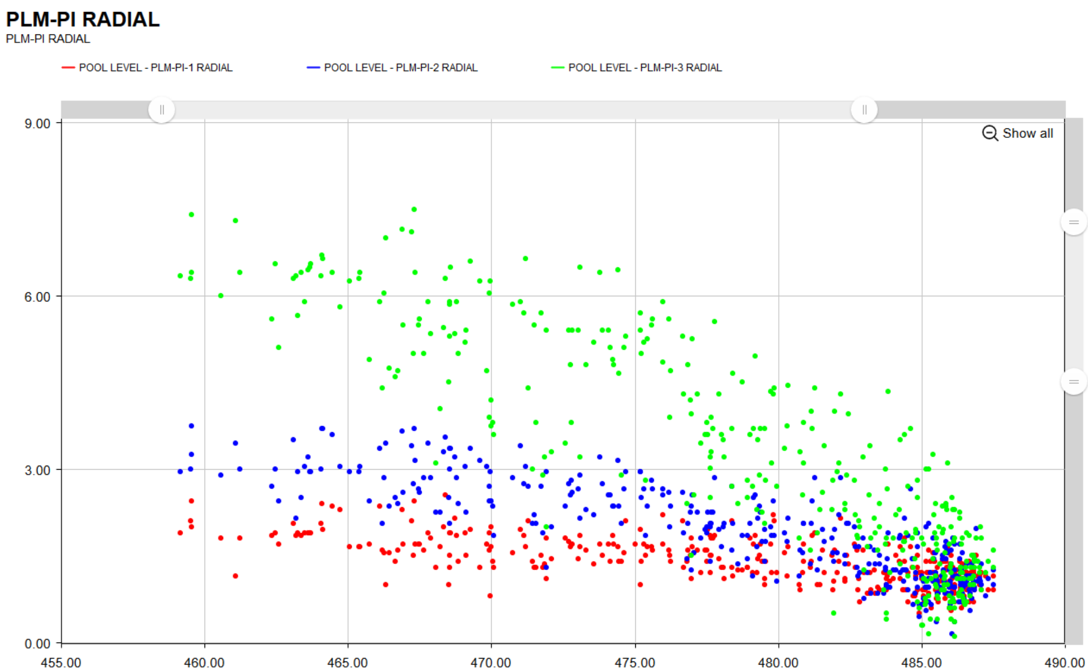


*Figure 23: Radial movements in plumb lines at three different control points vs reservoir level.*

Some sensors (such as plumb lines) measure several variables and can register displacements in two or more directions. This can be visualised in a descriptive way through correlation charts by using x and y axes for each direction (radial and tangential). An example is shown in Figure 24.

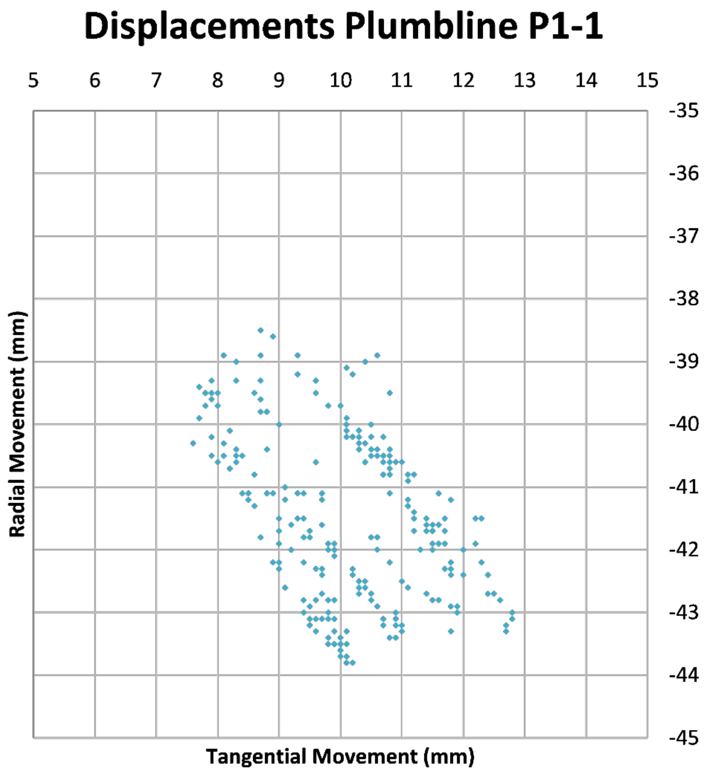


*Figure 24: Correlation of radial and tangential movements of a plumb line.*

#### *5.4.2.5 Combinations of graphs*

For data interpretation, it is important to have all necessary information presented in 1 view or on 1 page, especially if several sensors with different units or magnitudes have to be compared. In most cases, it is better to include about 3 charts with different sensors in one view instead of using one chart with all sensors. In this way, information can be better structured and interpretation becomes easier. In the following figure (Figure 25) an example for the interpretation of plumb line data is shown. It includes a combination of three charts using the same time scale in the horizontal direction. In the upper part, external variables including reservoir level, temperature, and precipitation are shown. Below, movements of a plumb line in 4 different control elevations are shown on two other charts, separating radial and tangential movements.

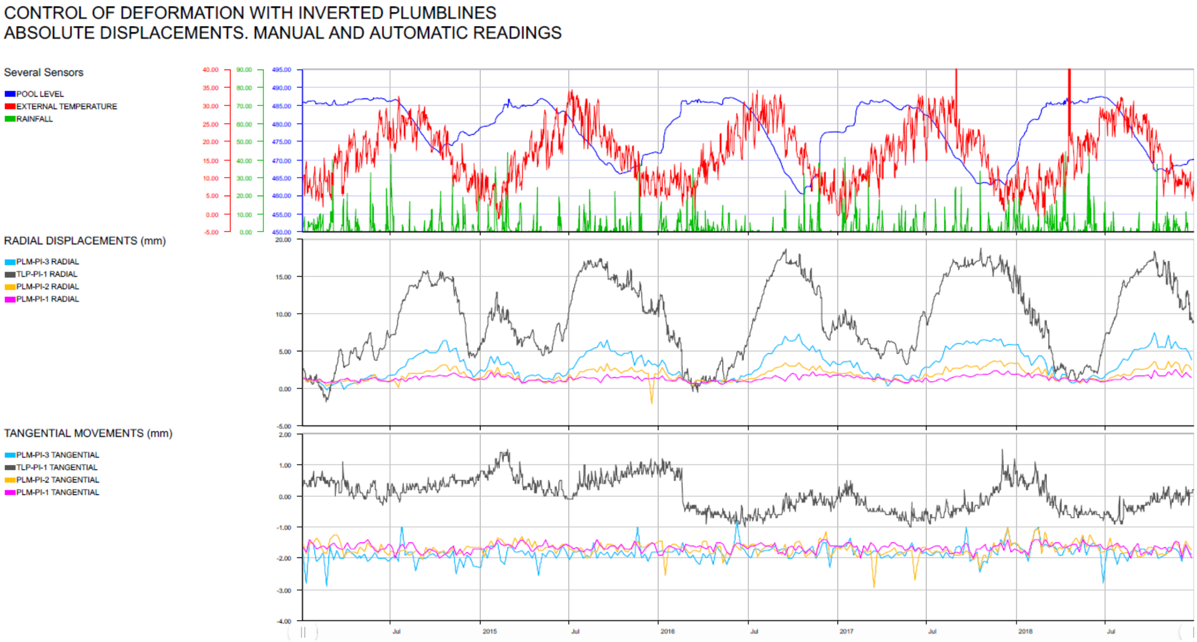


*Figure 25: Chart combining external variables and radial and horizontal displacements of a plumb line at different control elevations.*

#### *5.4.2.6 "Dashboard" Map Views - SCADA*

Many software packages include layout views similar to SCADA screens. These display readings from sensors superimposed on a drawing, image, or map. Dashboards are a type of graphical user interface which provides at-a-glance views of most important information provided by the monitoring system.

These views usually show data in real time, or the latest available data from each sensor. They are mainly used for quickly checking the current state of a dam, without beginning a detailed time series evaluation. They offer a high degree flexibility, are very descriptive, and are often used to show sensor locations. This is especially helpful for a user who does not know all the details of the monitoring system.

In Figure 26, following, different variables of one measurement point are shown. In this case, the current value of the different control directions of a three-dimensional joint meter.

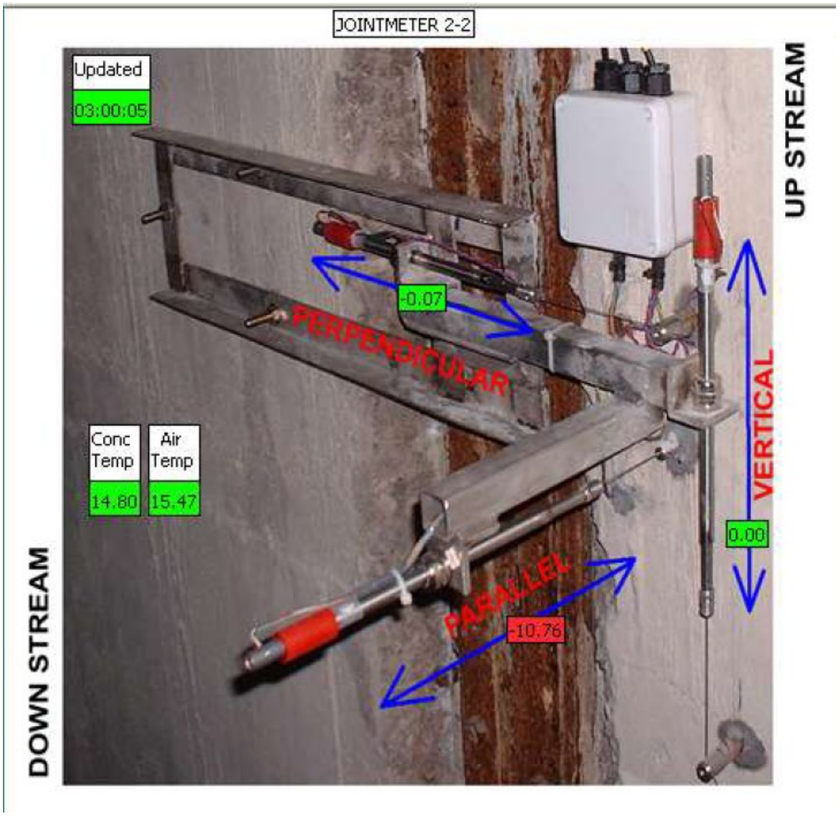


*Figure 26: Visualisation of real time values of a 3D-joint meter.*

Figure 27 shows the location of pendulums in a profile view. In addition to presenting the values, different colours are used to indicate whether the reading falls within specified thresholds.

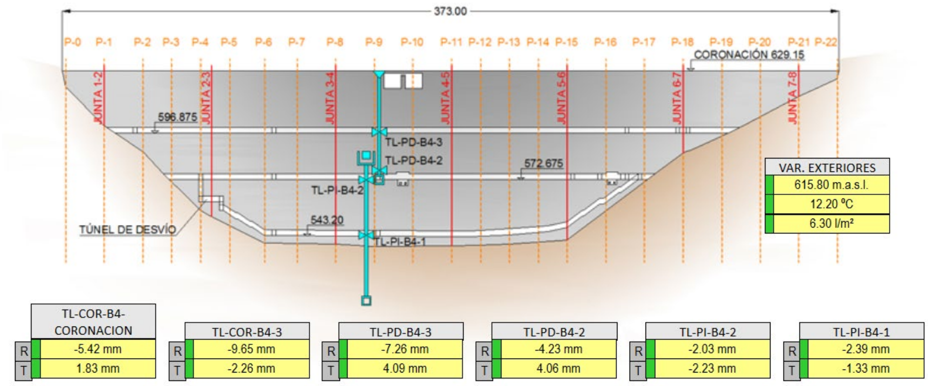


*Figure 27: Visualization of real time values and alarm levels over front view of the dam.*

Depending on the effort invested in the preparation of these figures, 3D models or photos can also be used (Figure 28).

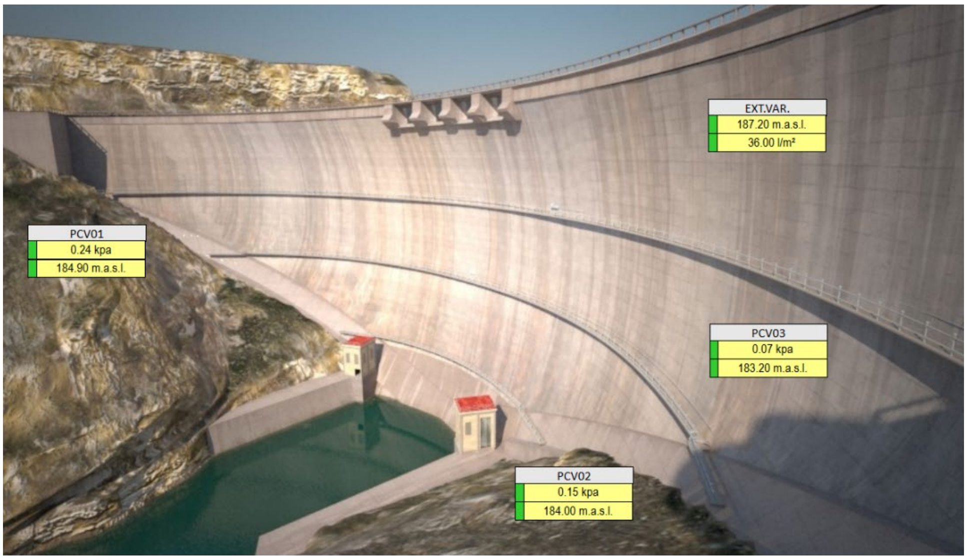


*Figure 28: Visualization of real time values and alarm levels over 3D model of a dam.*

Some systems offer the possibility of including values not only as digital numbers, but also by a gauge, column or bar chart. This allows showing of the present value within a range of custom values. It can then quickly be determined if values are below or close to threshold limits (Figure 29).

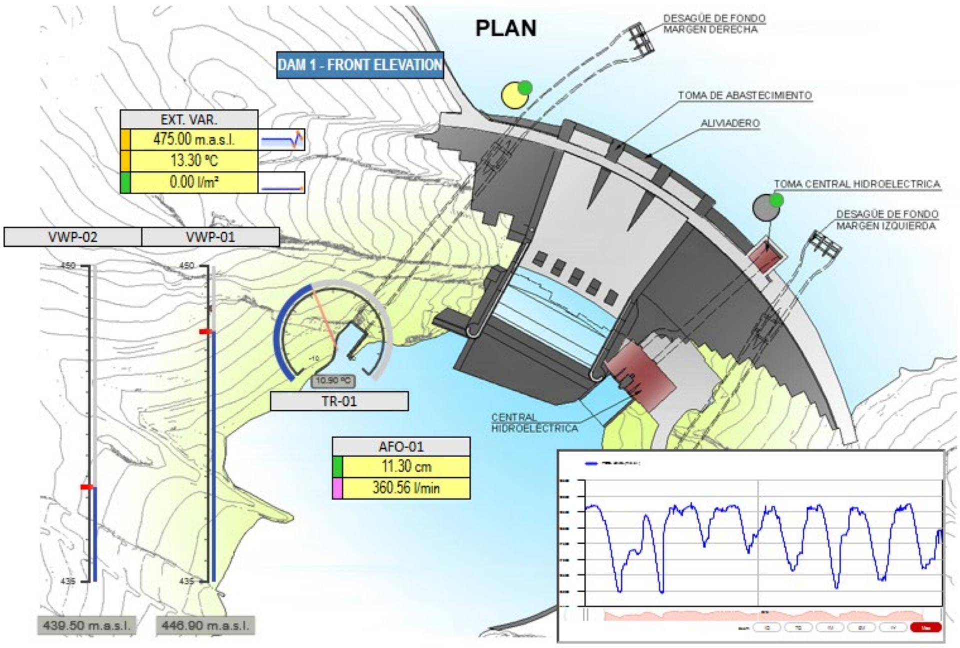


*Figure 29: Visualization of real time values with gauges and a column chart over plan view.*

These figures can also be interactive and include tooltips for additional data, or buttons to have direct access to other information related to that sensor (Figure 30).

These capabilities make these ways of visualising data a powerful tool for reviewing all available data and obtaining a good picture of the current state of a dam. Nevertheless, for a detailed interpretation, the various charts mentioned in the preceding sections are essential.


*Figure 30: Visualization of a 3D dam view in combination with tooltips and popup charts.*

#### *5.4.2.7 Tables*

Even if graphs and figures are the easiest way to visualise data for interpretation, in some cases it can be useful to present selected data in tables.

It is not usually necessary to print out a list of all measured data, as this information will likely be overwhelming for the reader. If an exact numerical value must be reviewed, it is sufficient in most cases to do this directly in the database.

However, a summary of selected data provides can provide additional value to a data interpretation, especially when a basic statistical evaluation is included. The most relevant information is annual maximum and minimum values, annual oscillation, and mean values. An example of combining different information into a table is shown in Table 4.

*Table 4: Monthly maximum and minimum value of external variables, maximum and minimum annual values (red and blue colour) and annual mean value.*

| Year 2018 | Pool Level | | Air Temperature | | Rainfall (l/m²) |
|---|---|---|---|---|---|
| | Max (m.a.s.l) | Min (m.a.s.l) | Max (ºC) | Min (ºC) | |
| January | 1082.70 | 1079.42 | 18.00 | -4.00 | **145.40** |
| February | 1085.30 | 1082.14 | **14.00** | **-13.00** | 135.60 |
| March | 1087.46 | 1084.24 | 15.00 | -5.00 | 76.70 |
| April | 1089.47 | 1087.63 | 15.00 | -4.00 | 138.50 |
| May | **1090.17** | **1089.54** | 23.00 | -2.00 | 54.20 |
| June | 1090.10 | 1088.72 | 29.00 | 2.00 | 23.50 |
| July | 1088.60 | 1085.84 | 32.00 | **6.00** | 8.50 |
| August | 1085.73 | 1083.46 | 33.00 | 5.00 | **6.80** |
| September | 1083.39 | 1081.54 | **36.00** | 3.00 | 14.10 |
| October | 1081.47 | 1080.00 | 24.00 | -1.00 | 19.70 |
| November | 1079.96 | 1078.97 | 23.00 | -3.00 | 130.60 |
| December | **1078.94** | **1078.15** | 17.00 | -5.00 | 10.40 |
| | | | | | |
| Mean Value | 1085,27 | 1083,3 | 23,25 | -1,75 | 63,67 |

### 5.4.3 ***Additional Features***

In this section some additional features are explained that are, or can be, incorporated in monitoring tools. Most of them provide additional information and added value for the analysis of dam behaviour or an optimization of working procedures. As already mentioned in section 5.2.2, integration within other software, these additional features can either form part of the monitoring tool or of another software.

#### ***5.4.3.1 Geographical Information Systems (GIS)***

In section 5.4.2.6 Dashboard/Map Views, the visualization of monitoring data in combination with images and maps was described. In contrast to these static images, Geographical Information Systems (GIS) offer a more dynamic way of visualising data. By assigning geographic coordinates to each sensor, its location can be seen with a GIS viewer on maps and satellite images. GIS tools allow the user to view larger areas and zoom to the area of interest.

This is especially helpful for handling several dams through one interface, or a net of hydro-meteorological stations in a river basin. The ability to pan and to change the level of zoom can also be helpful for particularly long dams. An example is shown on the next page (Figure 31).

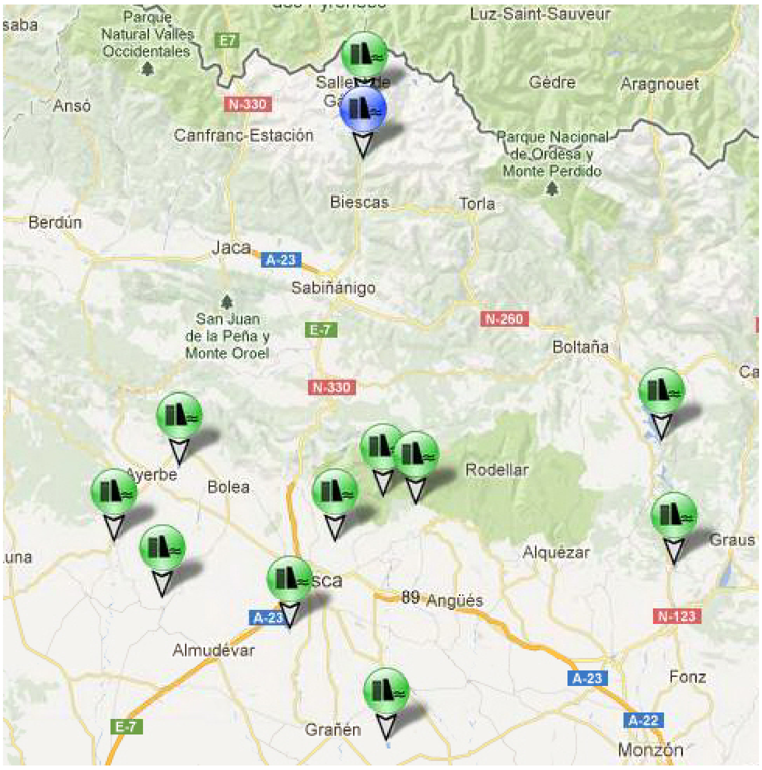


*Figure 31: Location of several dams shown in map view.*

GIS tools are not limited to a geographical visualization but also offer many features for showing additional information and linking to other databases. This can be done through tooltips or through the incorporation of different background layers (Figure 32).


*Figure 32: Location of monitoring pegs on a dam crest showing alarm levels.*

Nevertheless, in most cases a 2D plan view is often not sufficient for showing all monitoring data, especially if sensors are distributed along several galleries, or installed in the same location at different elevations. In this case, a traditional SCADA view allows a better presentation. A more sophisticated approach would be a 3D-GIS or BIM solution as mentioned in the following section.

#### *5.4.3.2 Building Information Modelling (BIM)*

Building Information Modelling (BIM) creates added value and synergy by linking different kinds of data to 3D models. The models include valuable information about facilities and infrastructure during design, construction, and operation. It is a digital representation of the physical and functional characteristics of a facility.

BIM also offers many possibilities for the handling of monitoring data. The first step is the visualisation of the installed monitoring system in a 3D model. This helps the user get a better understanding of the location of each element, the geometry, and emplacement within the structure. A navigation menu allows the user to turn the model in any direction, "walk" along the galleries and zoom to the different elements that were included in the model. Taking into account that the 3D model is digital, alternative points of view that are not available in 2D drawings can be established. In addition, even more information such as geology or construction details can be incorporated.

BIM, however, is not just a simple 3D visualization of information. By linking monitoring data and other information for dam safety management and operation, added value can be achieved. These can be observations from visual inspections or maintenance works. Figure 33 show an example of combining monitoring data with a 3D model.

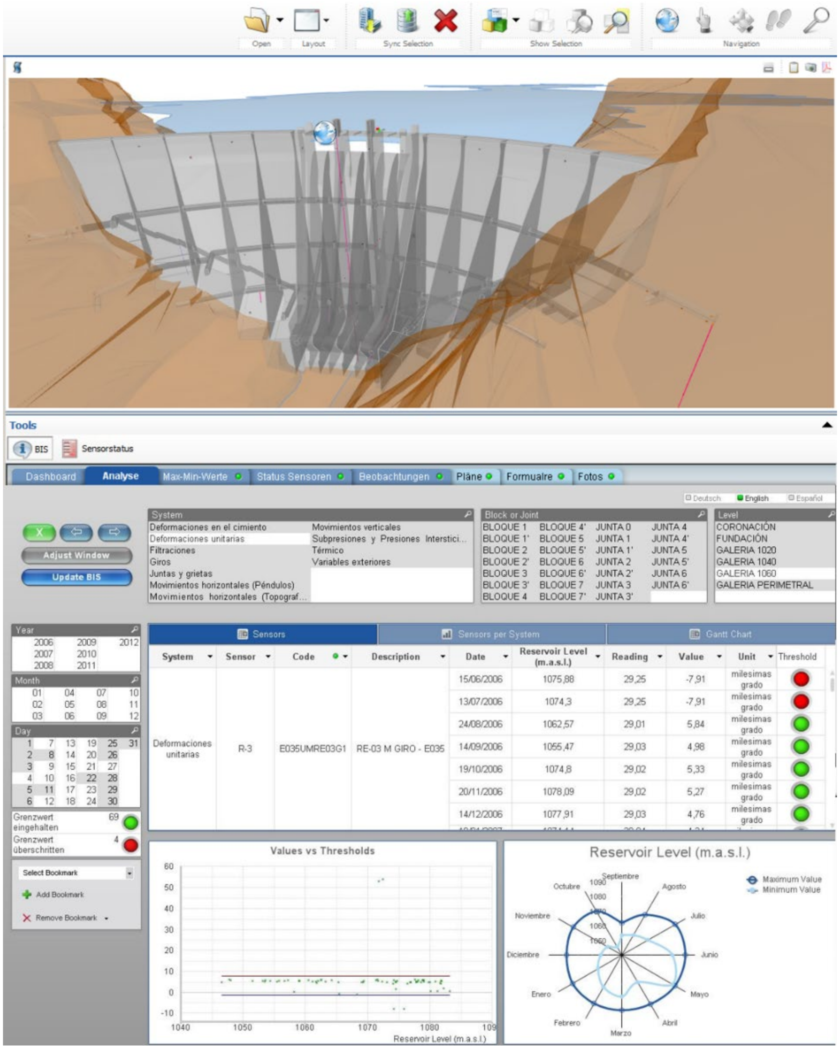


*Figure 33: Combination of monitoring data with 3D model.*

The possible applications of such a solution go further than just managing monitoring data, and could even be used as an Asset Management tool.

### *5.4.3.3 Statistical models*

For a more detailed analysis of historic time series, a statistical evaluation model can be used (Figure 34). If a general statistical evaluation tool is used, data must be transferred manually or automatically through an interface from the monitoring tool. This is avoided if the statistical model is already incorporated in the dam monitoring management tool and the same database is used.

The aim of a statistical model is to determine a regression curve that describes the evolution of a monitoring variable as precisely as possible. The influence of main external effects such as reservoir level, temperature, and rainfall or irreversible effects during time can be considered.

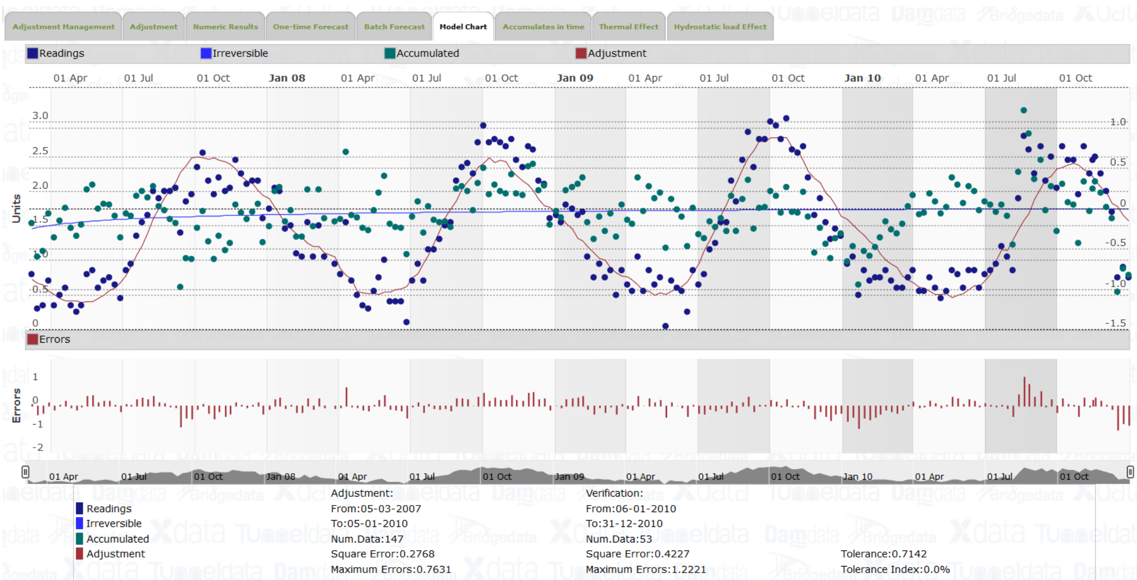


*Figure 34: Statistical evaluation of monitoring data.*

By isolating the effects of each of these components, their impact on the behaviour of the control variable can be quantified (Figure 35). This is also a very powerful tool for detecting irreversible effects, such as the increase of piezometric pressure or deformation of the dam structure in time by isolating other external effects.

The obtained information can be used for the definition of threshold or expected values for control variables with predefined boundary conditions using a combination of time, temperature, and reservoir level.

Apart from statistical models, neuronal networks (analysed via an algorithm to determine patterns) and machine learning methods can provide additional information. The dam owner should be aware that trained experts are still required for handling and interpreting these models.

Finally, it must be emphasized that statistical models require representative data over a time period to return results with the required precision.

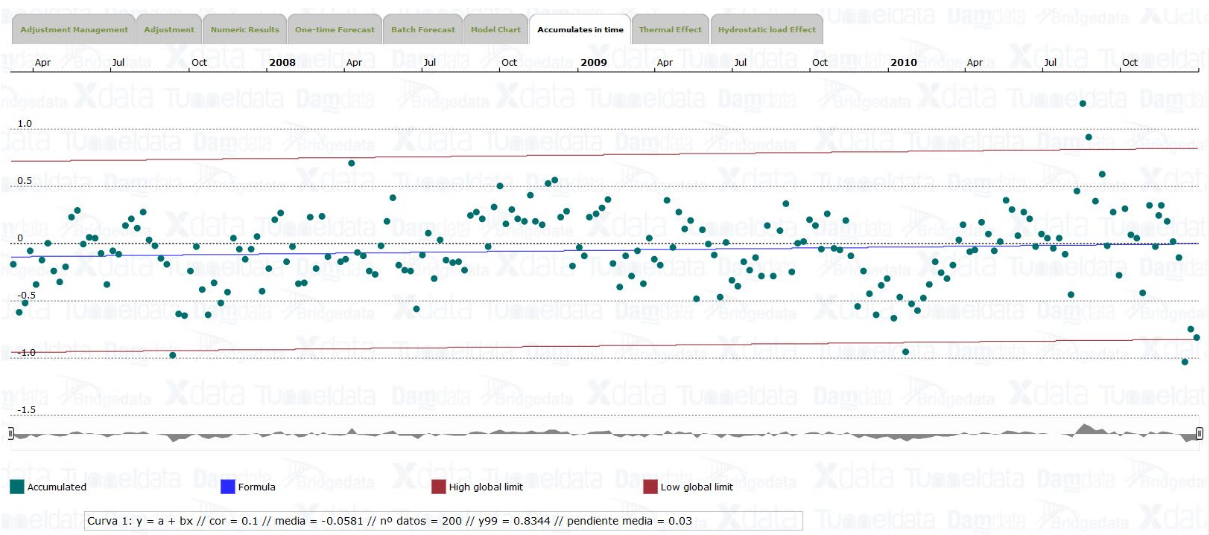


*Figure 35: Evaluation of irreversible effects over time.*

# 6 Data Interpretation

## 6.1 General

Dam monitoring is one part of a surveillance program that should also include tasks such as visual inspections and testing (see also Figure 3). The combination of all dam surveillance tasks is one of the most important pillars of dam safety assessment during construction and operation. An increased amount of real time data and improved software solutions allow for opportunities in automating some of the data interpretation tasks. However, exclusively relying on triggering values based on monitoring data, without any further interpretation, is insufficient for obtaining a complete and reliable view of the safety of a dam. *Therefore, a detailed analysis made by an experienced engineer is still essential and cannot be replaced by automated data evaluation*. Information provided by software tools for the management of monitoring data can effectively help in this decision-making process.

The current chapter discusses the relationship between monitoring data and dam safety. Monitoring data needs to be processed and interpreted to provide meaningful information about the state of a dam. Commercial monitoring data software as introduced in Chapter 5 is a powerful tool that can aid in this process. Relating monitoring data with potential dam failure modes helps the engineer (either external consultant or employee of the dam owner) to interpret data efficiently in a goal-oriented way and allows an early detection of anomalous behaviour. Through some selected examples, it is shown how a combination of monitoring data, visual inspections, and investigations can be related to potential dam failure scenarios. The chapter is organised as follows:

- Typical potential failure modes for international and Norwegian dams (section 6.2). The section shows what kind of situations monitoring data should detect.
- Selected dam monitoring data and its basic characteristics (section 6.3). The section explains the most common monitoring data available to engineers in Norway and how this data can be used to assess the safety situation of a dam.
- Vision for dam stability: combining hazard/failure modes and monitoring measurements pattern, and typical examples in practice (section 6.4).
- Recommendations on threshold values and reliability (section 6.5)

The chapter is based on an intensive desk study. This focused primarily on ICOLD documents [7][8][10][15] and earlier research from the USA [12][13], UK [11], and Australia [14].

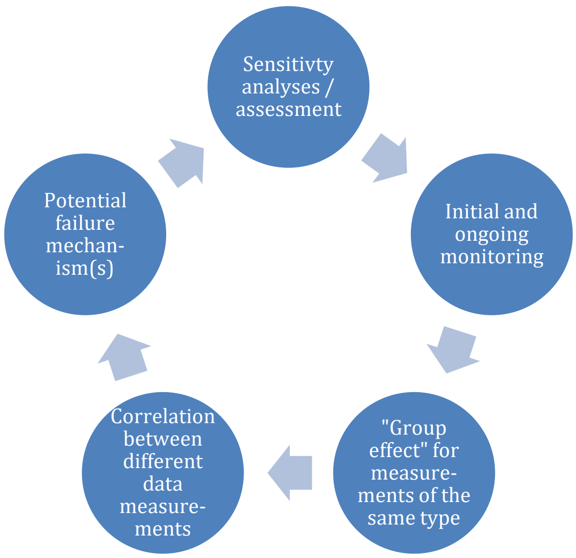


*Figure 36: Monitoring strategy - the relationship and iteration process between different types of data.*

## 6.2 Typical potential failure modes for Norwegian dams

### 6.2.1 *General*

A detailed list of common dam failure modes is presented in the Defra report [11], 12 failure modes and 46 hazard modes have been summarised. In the report, a failure is defined as a "major uncontrolled and unintended releasing of water", and a hazard as "unwanted human injury or property damage to the dam". One or more hazards in combination can develop into a failure if no remedial actions are taken. Therefore, surveillance should focus on the early detection of failure and hazard modes that could lead to later dam failure.

### 6.2.2 *Summary of the failure and hazard modes*

The 12 failure and 46 hazard modes identified in the Defra report [11] are grouped and summarised in Table 5:

*Table 5: Summarised failure and hazard modes according to the Defra report.*

| No. | Summarised Defra failure or hazard modes | Comments based on Norwegian practice |
|---|---|---|
| 1 | Catastrophic overtopping due to the dam settlement or inadequate flood design capacity. | Relevant to Norwegian dams |
| 2 | Deterioration of the embankment dam core caused by various type of leakage and internal erosion. | Relevant to Norwegian dams |
| 3 | Deterioration of the ungrouted/grouted dam foundation caused by leakage or internal erosion. | Relevant but rare in Norway. Norwegian dams are generally required to be founded on competent bedrock, and bedrock in Norway is generally shallow and competent. |
| 4 | Hazard related with hydraulic structures, such as overflow, blockage of the spillway, inadequate energy dissipation, out-of-channel flow etc. | Relevant to Norwegian dams |
| 5 | Structural instability of the concrete dam | Relevant but rarely leading to total failure due stringent dam inspection requirements in Norway |
| 6 | Ice & wave actions including local tsunami waves caused by large landslides | Relevant, but rarely leads to failure except in the (very rare) case of tsunami waves caused by large landslides |
| 7 | Deterioration of the core, concrete, foundation, membrane, etc. by corrosion or other chemical effects. | Relevant, but rarely leads to failure due to stringent dam inspection requirements in Norway |
| 8 | Deterioration caused by animal, vegetation, and/or human activity. | Generally less relevant to Norwegian dams because (1) most embankment dams in Norway are rockfill dams; (2) strict riprap requirements; (3) stringent inspection protocols |
| 9 | Seismic events/loading | Generally less relevant due to low earthquake acceleration in Norway |

It should be noted that over 95% of dam failures are due to overtopping and internal erosion according to ICOLD [19]. This corresponds to points 1-4 in Table 5, and are the most relevant failure modes for Norwegian dams.

## 6.3 Selected dam monitoring data and its basic characteristics

In this section, the most common control variables, such as deformation, leakage, and pore-pressure are discussed.

### 6.3.1 *Deformation measurements*

Deformation can be measured with different sensors along the dam crest, upstream and downstream faces, and inside the dam body (along the top of the core for embankment dams, otherwise within galleries). One can distinguish between absolute and relative displacements and deformation.

From an analytical view, it is very difficult to establish a threshold value for deformation that has a level of accuracy which is representative for dam stability. The reason is that dams are generally designed under the limited equivalent method with simplified load conditions and additional safety margins, but in practice, deformation will be driven by a combination of many complex effects such as temperature variation, chemical reaction, consolidation, and creep. Threshold values can therefore only be easily applied to a statistical model where representative data is available.

Moreover, different dam types have different levels of tolerance to deformation. Embankment dams usually undergo significantly higher deformation over their lifetime than concrete dams.

The following list highlights some considerations for interpreting deformation data for Norwegian dams:

- The correctness and representativeness of the dataset and sensor calibration must be verified in order to avoid confusing anomalous or erroneous data with anomalous behaviour.
- Instrument accuracy must be considered before interpreting the data.
- Sign convention must be clearly defined: the user should know the orientation of the sensor and direction of each movement (upstream - downstream, left abutment – right abutment) and, in the case of absolute values, the coordinate system. In Figure 37 the direction of horizontal movements observed with 4 plumb lines in a dam crest are visualized in plan view.
- Deformation rates can provide additional information and should be analysed alongside absolute values. Examples of typical deformation patterns that can be identified, such as accelerated towards failure and flatten-out type are presented in Figure 38 and Figure 39.
- A typical settlement pattern along the crest of an embankment dam is shown in Figure 40. Anomalies should be well studied with other dam surveillance tools to form a picture about overall the dam stability.
- A typical pattern of vertical movements along the crest of a gravity dam due to the influence of seasonal air temperature is shown in
- Figure 41. The effect of expansive behaviour of concrete with time can also be observed.

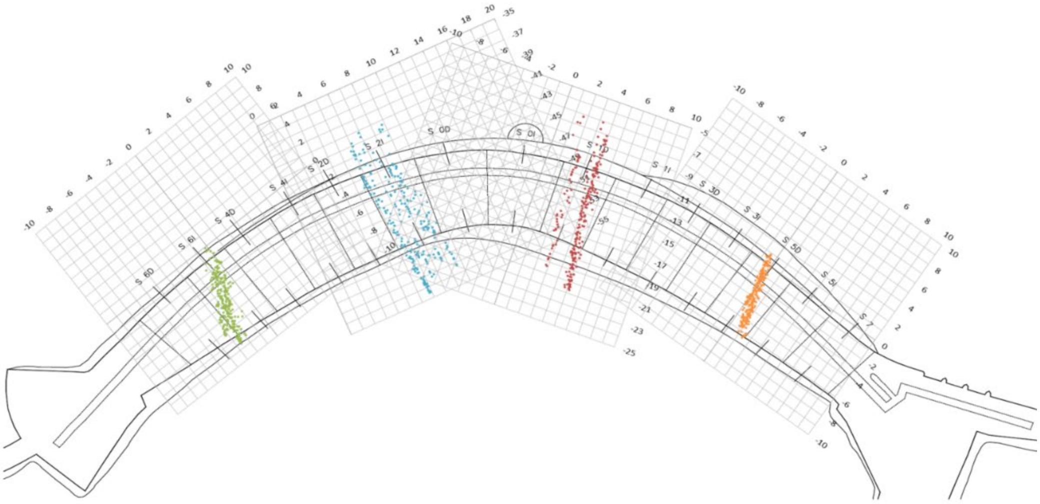

*Figure 37: Horizontal movements observed with 4 plumb lines in a dam crest.*

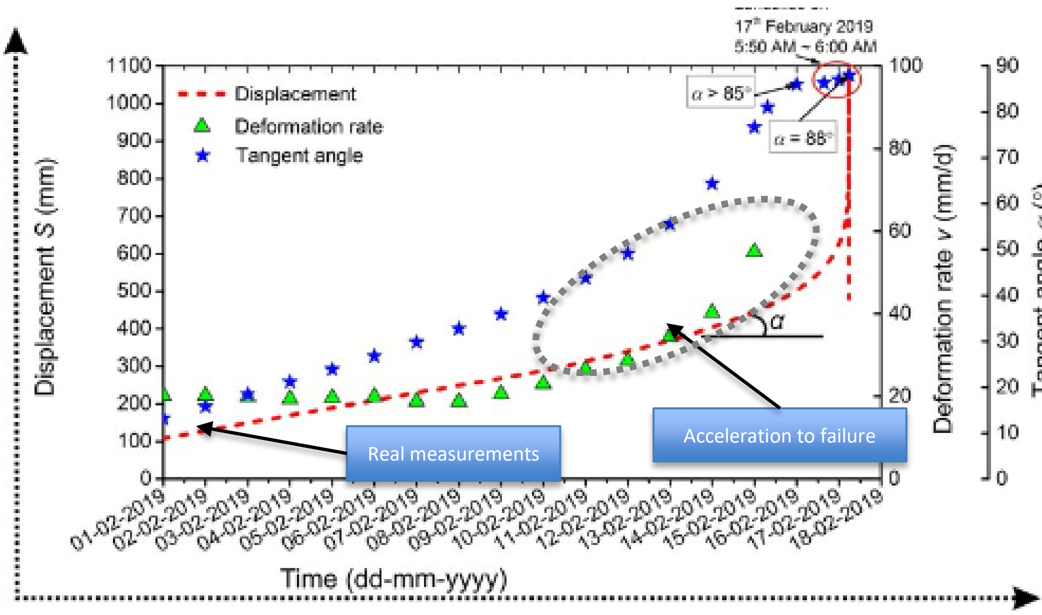


*Figure 38: example of typical "acceleration towards failure" deformation.*

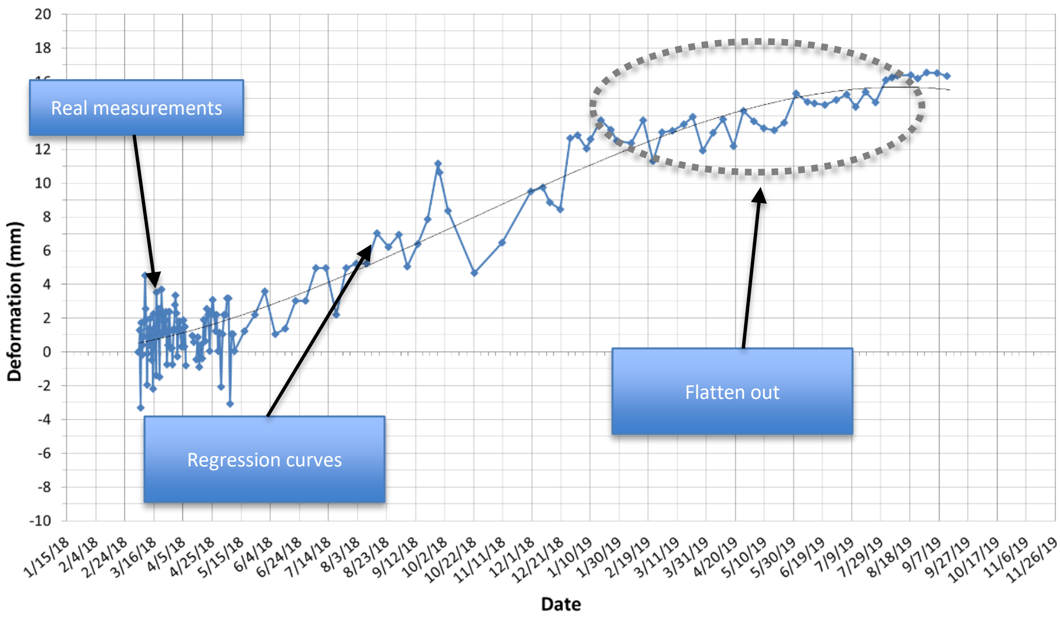


*Figure 39: an example of typical flatten-out type deformation.*

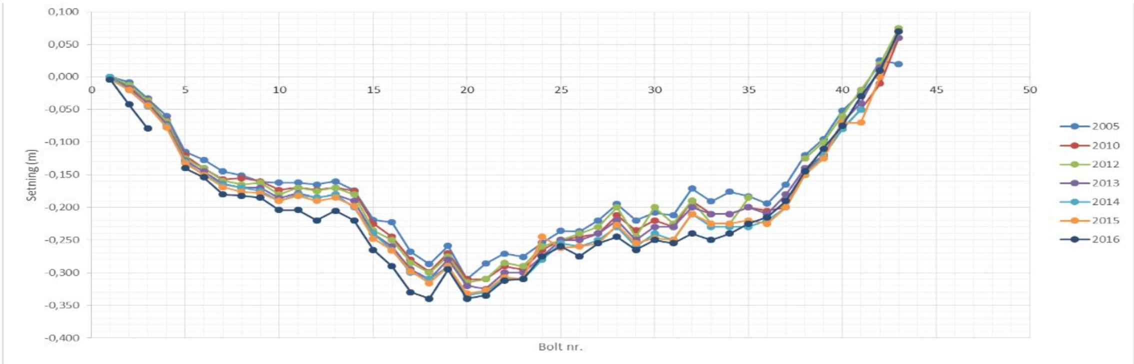


*Figure 40: Typical settlement along the crest of an embankment dam.*

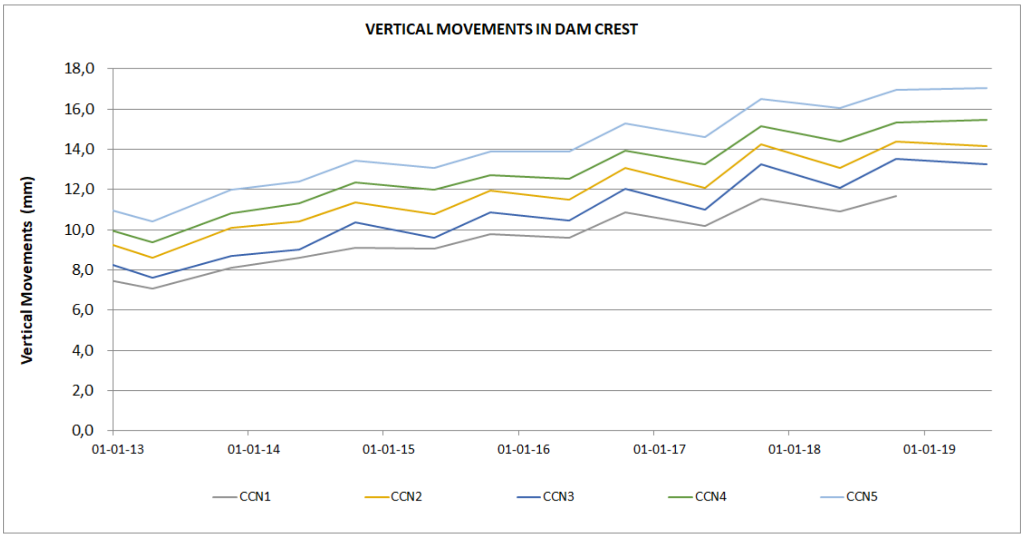


*Figure 41: Vertical movements along the crest of a gravity dam as a function of time – allows the observation of the influence of seasonal air temperature on the expansion of concrete.*

As mentioned above, unusual deformation measurements should be assessed together with other observations in the entire dam surveillance program to obtain a proper overall picture of the stability of the dam. Redundancy with different monitoring systems can verify the accuracy of the data. Special attention should be payed to irreversible deformation or accelerating displacements rates (Figure 38 and Figure 39). This could indicate the development of instabilities within the dam.

### 6.3.2 *Leakage measurements*

Leakage measurement through V-notch weirs is the most common monitoring instrumentation used in Norwegian embankment dams. However, just like with deformation measurements, it is difficult to establish an accurate threshold value with deterministic models, as leakage volume is largely related to uncertainty in the permeability of the dam material and foundation. Statistical models can therefore provide a better means of establishing threshold values.

Permeability (either laboratory or in-situ) test results are usually accurate to within one order of magnitude. Errors in leakage calculations are also approximately one order of magnitude. Flow at higher leakage rates behaves according to turbulent flow principles (vs laminated flow), making Darcy’s law no longer applicable for the calculation of leakage. Most software assumes Laminar flow.

A typical leakage measurement time-series is shown in Figure 42 [6]. The following points should be considered during interpretation:

- Correctness and representativeness of the dataset and sensor calibration must be verified in order to avoid confusing anomalous or erroneous data with anomalous behaviour.
- Instrument accuracy must be considered before interpreting the data.
- Units must be clearly defined (l/s, l/min, $m^3$/min)
- It is important to look into the development of the leakage measurements, particularly increases of leakage over time. It is also useful to compare the leakage over the same period of previous years.
- Precipitation (see Figure 42 [6]) and reservoir level (Figure 43) are the most important external factors that affect leakage. Temperature can also have an effect.
- To detect signs of internal erosion, visual inspections of leakage water should be made, focusing on sediment and suspended particle content.

Leakage measurements provide important information about the condition of a dam. Leakage can not only threaten the stability of a dam, but the uncontrolled release of water from a reservoir also represents an economic loss in many cases. The increased leakage volumes of the dam shown in Figure 43 necessitated extensive rehabilitation works. The figure also shows the influence of reservoir level on leakage. Both automated and manual readings can be compared to confirm the accuracy of leakage measurements. After rehabilitation measures taken in 2015 a marked reduction in leakage through the dam was recorded.

In summary, leakage measurement should be viewed in combination with other observations and measurements as part of the entire dam surveillance program. It is particularly important to compare leakage measurements with upstream water level, precipitation, and temperature. Signs of potential internal erosion should be looked for.

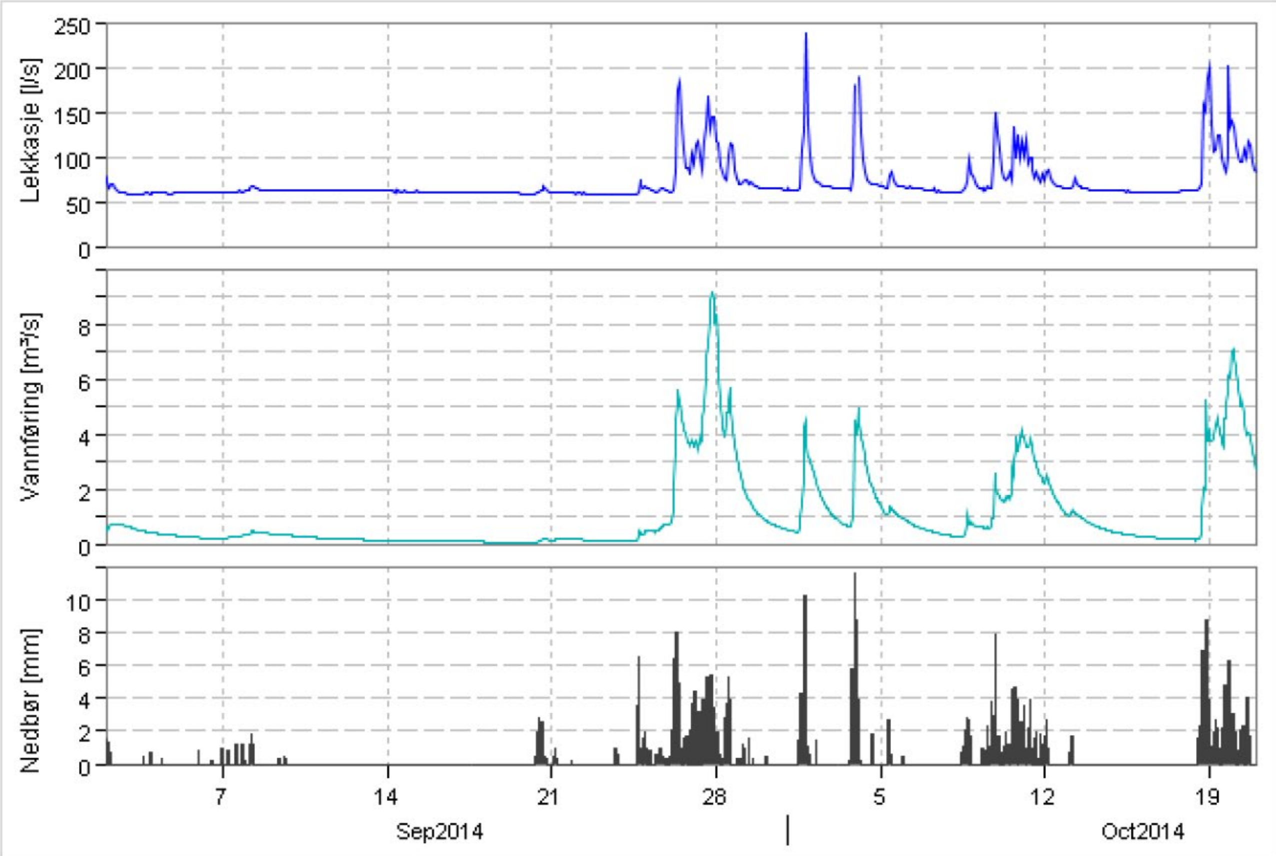


*Figure 42: Typical leakage measurements plotted together with inflow and precipitation, Svartavatnet dam in Haugsdalsvassdraget, Norway.* [6]

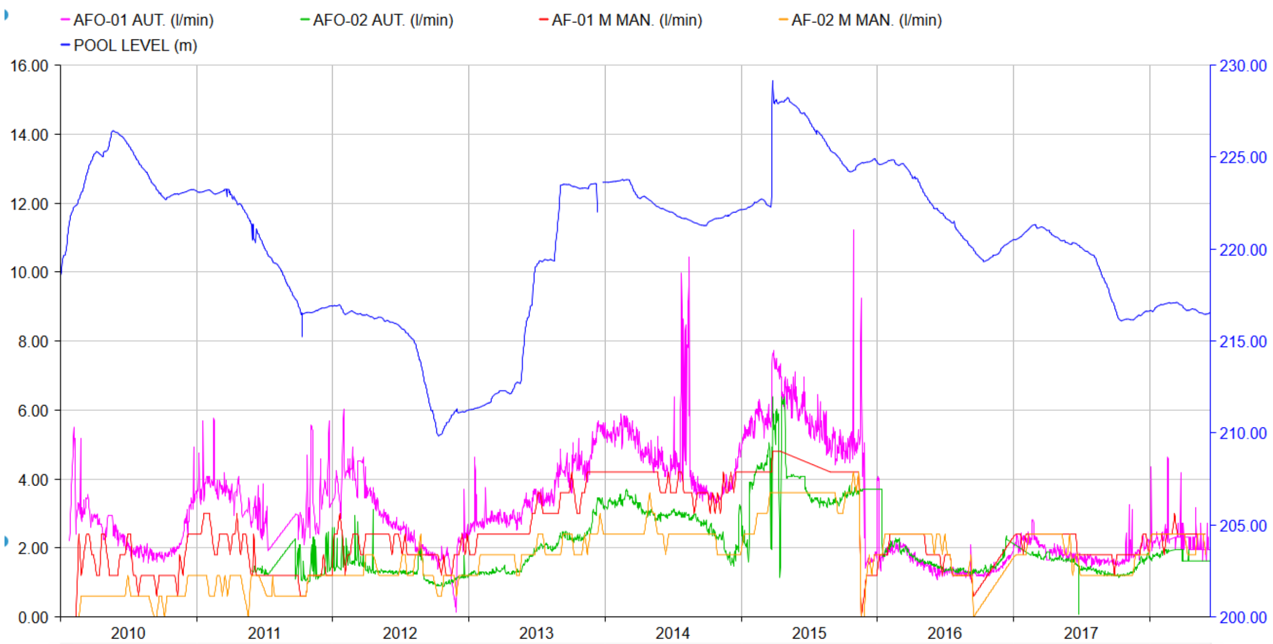


*Figure 43: Manual (orange and red), and automatic (pink and green) leakage measurements before and after rehabilitation measures. The blue line shows the reservoir level.*

### 6.3.3 *Measuring pore water pressure*

Measuring the pore water pressure is a direct method to monitor the uplift pressure in gravity dams, or the evolution of piezometric pressure levels in the dam body or foundation of embankment dams. Pore water pressure can also be directly correlated with dam stability, allowing relatively reliable threshold values to be established by an analytical method, compared with deformation monitoring measurements. This is detailed and discussed in section 6.5.

Installation of piezometers in the dam body is done preferably during construction but may also be completed afterwards. Installation inside the body of an existing embankment dam is more complicated and must be well planned in order to avoid damaging the core of the dam, filter layers, or drains. Piezometer installation is costly as it often requires drilling works which is usually more expensive than the piezometer itself. Maintenance of the piezometers can also be problematic.

Some considerations for the interpretation of pore water pressure data for Norwegian dams are:

- In order to compare pore pressure at different piezometers, piezometric head should be calculated and, in some cases, the hydraulic load, in %, related to the reservoir level. It is necessary to know the elevations of installed piezometers.
- Differences in pore pressure between adjacent piezometers give information about the hydraulic gradient.
- Uplift pressure in gravity dams and the proper performance of drainage layers can be verified with piezometers.

The below figure (Figure 44) shows changes in piezometric head with time inside a dam body. The dissipation of hydraulic potential from the upstream (PH18N1) to the downstream side (PH24N1), can be easily observed and confirms that all values are below the reservoir level.

In the following figure (Figure 44), the influence of the reservoir level on the evolution of piezometric head, is shown. Piezometers installed close to the upstream side (PH18N1, PH19N1, and PH20N1) show a more pronounced response to reservoir level than piezometers installed close to downstream side of the dam.

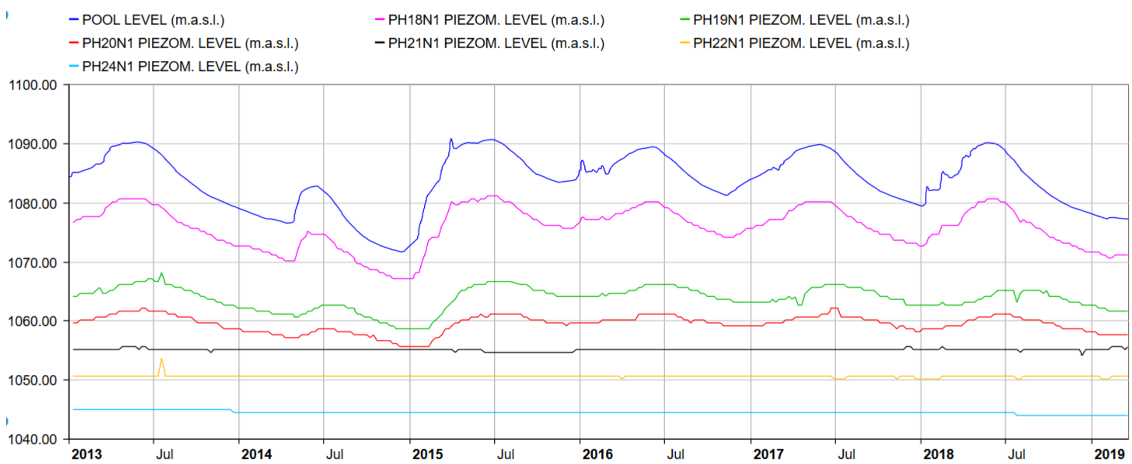


*Figure 44: Piezometric levels in a dam body as a function of time.*

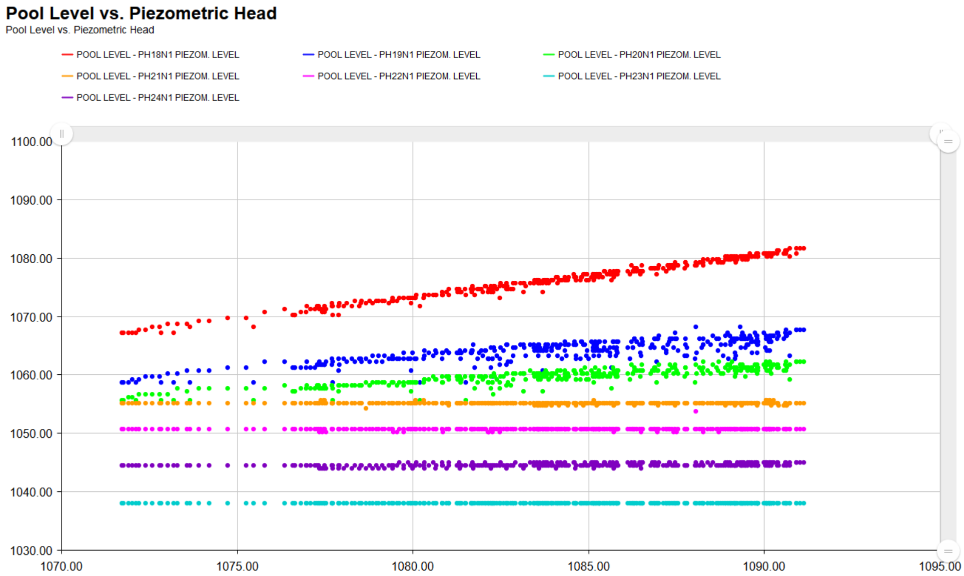


*Figure 45: Piezometric head (vertical axis) in dam body as a function of reservoir level (horizontal axis).*

## 6.4 Using monitoring data to obtain a clearer understanding of the condition of a dam

### 6.4.1 *General*

In this section, how to apply knowledge obtained from monitoring data to assessment of the typical failure modes of dams (section 6.2), is discussed. This includes both patterns that can indicate potential failure/hazard modes and those that exclude them. Some typical examples will be provided. It should be noted that the discussion of the potential failure modes is from the point of view of monitoring instrumentation. Other dam surveillance activities, such as visual in-situ inspections and laboratory testing of materials, are not the focus of this discussion.

### 6.4.2 *Patterns indicative of failure modes of hazard situations*

#### *6.4.2.1 Overtopping*

Overtopping of embankment dams can lead to failure much more easily than in concrete or masonry dams, as the crown material cannot easily withstand the erosive force of water. There are many reasons overtopping might occur, summarised as follows:

- Insufficient spillway capacity
- Under-estimation of floods
- No updated information available about the current water level or expected inflow
- Obsolete operating procedures
- Insufficient freeboard
- Malfunction of spillway gates or other outlets
- Settlement of the dam crest

Typical Norwegian embankment dams are rockfill dams with either a clay core, an asphalt core, or a concrete plate on the upstream face as the impermeable layer. Most Norwegian embankment dams are well founded on competent bedrock. Additionally, for recently redesigned or rehabilitated dams, compaction is well specified and controlled, particularly for high dams with high failure consequences. Norwegian embankment dams are therefore theoretically less susceptible to settlement failures.

Extreme floods, particularly those caused by climate change, is a very relevant threat to Norwegian dam safety. However, floods are generally regarded as a design and operation issue instead of a monitoring failure. The danger of damaging floods is primarily mitigated by regularly recalibrating the design flood magnitude and required spillway capacity. This is the main reason that Norwegian dam safety regulations require an updated flood evaluation by NVE once every 15 years. This, together with periodic inspections and comprehensive reviews (called *revurdering* in Norwegian) are important components of a monitoring program.

Despite these strict guidelines, the following phenomena which could lead to overtopping may be detected or controlled with the aid of monitoring instruments:

- Settlement of the dam body particularly dam crest
- Reservoir level measurements, in real time
- Installation of meteorological stations and hydrological stations upstream of the dam (this is not only dam monitoring but also supplies value and useful data to hydrologic calculations and forecasts)

#### *6.4.2.2 Internal erosion*

Internal erosion is another typical failure mode of a dam. It can occur in the body of embankment dams, dam foundations and abutments, and along supporting structures (e.g. bottom outlets). Internal erosion is a gradual process that starts with small features and can develop to total dam failure. In practice, monitoring instrumentation allows for the early detection of potentially hazardous behaviour, allowing risk reducing measures to be implemented.

The following phenomena which can indicate the presence of internal erosion may be observed via dam monitoring systems:

- V-Notch weir measurements that show irreversible, significant increases in leakage in time.
- Piezometers in the dam body or foundation show abnormal trends. These can be either increasing or decreasing pore pressure values. Hydraulic gradient between adjacent piezometers should be monitored.
- Unusual measurement trends in total pressure cells
- At advanced stages, internal erosion may cause local collapse of the dam core. This may lead to increased settlement or small rotational landslides that can be detected by deformation measurements through extensometers, settlement cells, or topographic/visual surveys.
- During inspection, leaks, discoloured leakage water, or muddy discharge could be observed along the downstream face of the dam. In more serious cases, sand boiling may be observed.

Storvatn Gausvik dam, a Norwegian embankment dam, is presented as an example. Leakage at the spillway canal was observed (Figure 46) during an inspection. High permeability of the dam foundation and high pore pressure in the dam's downstream toe were also observed during ground investigations and follow-up tests. Piezometers were subsequently installed. High pore pressure in the dam foundation showed a strong correlation with reservoir level (Figure 47). Leakage measurements and deformation measurements were normal. Internal erosion was therefore not expected to be the cause.

This is a typical example showing that pore pressure monitoring can contribute to a successful dam surveillance program, helping to identify potential failure modes in early phases before any failure becomes irreversible and the dam condition significantly worsens.

*Figure 46: Leakage and occasional discoloured discharge water were observed in the spillway channel (left). High pore pressure is observed in a borehole at the downstream dam toe (right).*

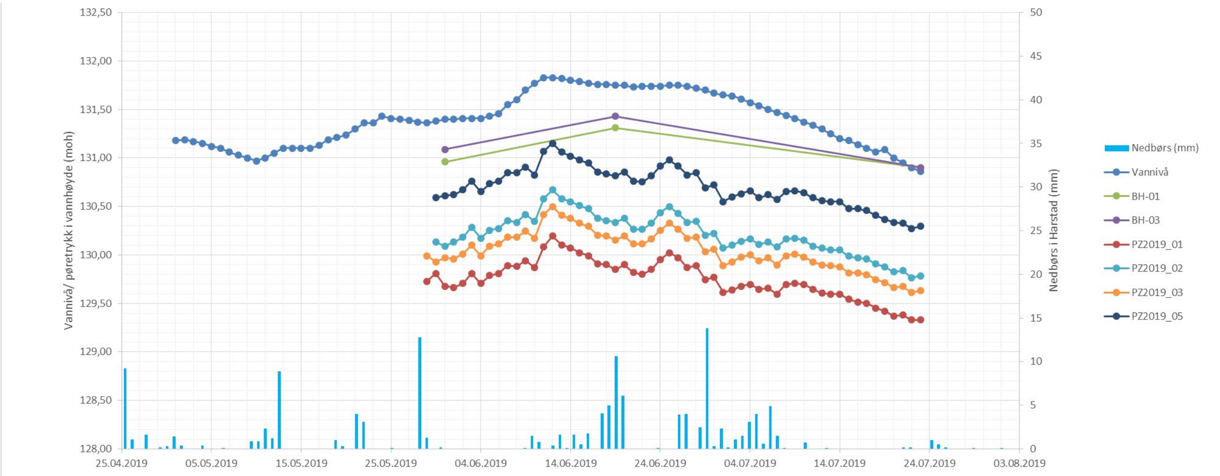


*Figure 47: High degrees of correlation between the upstream water level and piezometers installed in the dam centre and downstream toe.*

The collapse of Xe-Pian saddle dam D (Figure 48), the 23rd of July 2018 in, resulting in 40 fatalities with an additional 98 people missing is also presented as an example [20][21]. A panel of experts determined that the dam collapse was likely caused by internal erosion through the dam foundation [21]. Pore water pressures from piezometers measurements are high and reflect reservoir water level. Deformation in the dam is also controlled by water level in the reservoir (Figure 48Figure 49 and Figure 50).

It should be noted that, in the case of the Xe-Pian dam failure, the threshold value for settlement (30 cm) was exceeded on 18th July 2018. This did not trigger alarms or further investigation by the dam operator [21]. History has many examples of monitoring data that has been improperly interpreted, often with tragic consequences.

*Figure 48: Overview of the dam failure of Xe-Pian saddle dam D [21].*

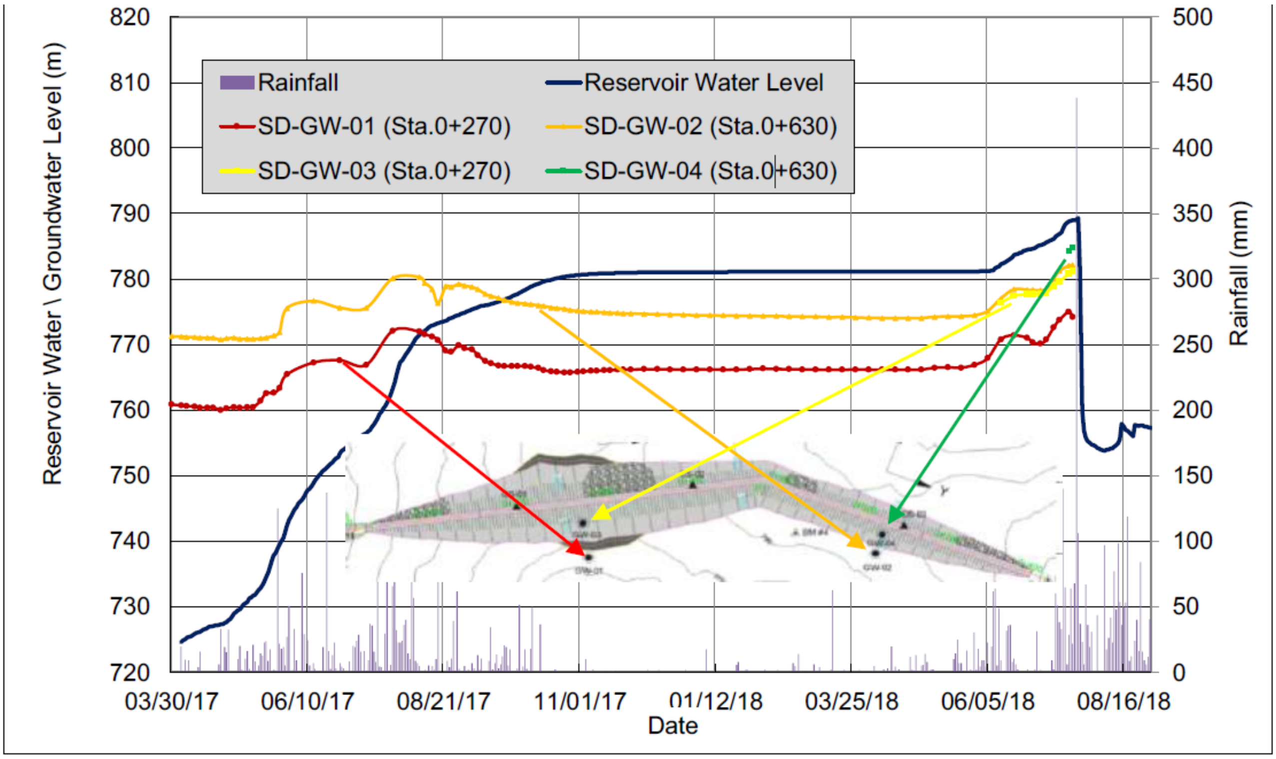


*Figure 49: High pore pressure in the dam, highlighting the correlation with the reservoir water level [21].*

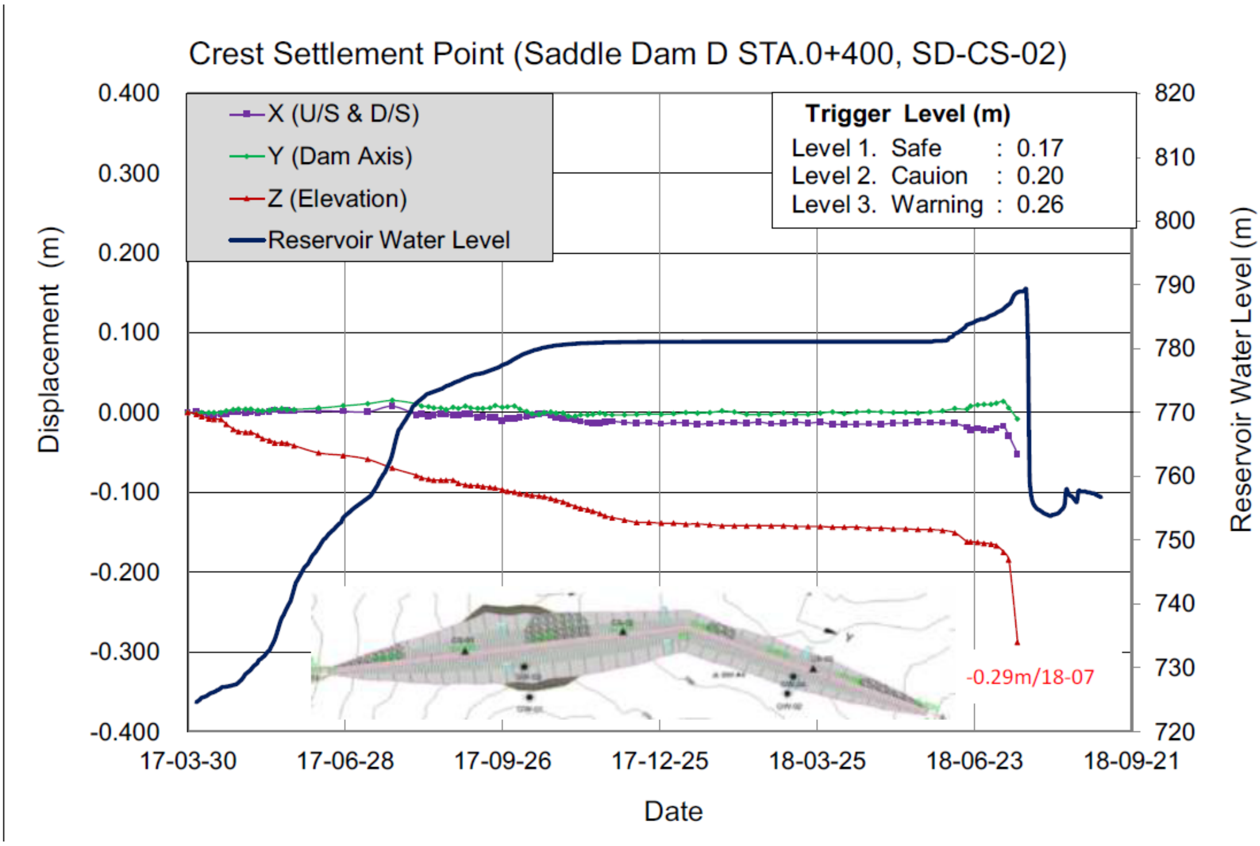


*Figure 50: Additional settlement is shown in the last two months of measurements, corresponding to an increase in reservoir water level.[21]*

#### *6.4.2.3 Hazard related with hydraulic structures*

The most common hazard related to hydraulic structures is the blockage of spillways leading to a reduction in the reservoir outflow capacity. However, this is often more a hydraulic or hydro-mechanical design issue, rather than an issue related to dam monitoring. The only practical recommendation is to establish a video camera for real-time monitoring of the spillway gate structure, particularly for remote dams with difficult access.

Another potential dam hazard related to hydraulic structures that can be observed by monitoring instruments is erosion/scour by outlet canals basins due to inadequate energy dissipation. This is shown in Figure 51 from the Defra report [11]

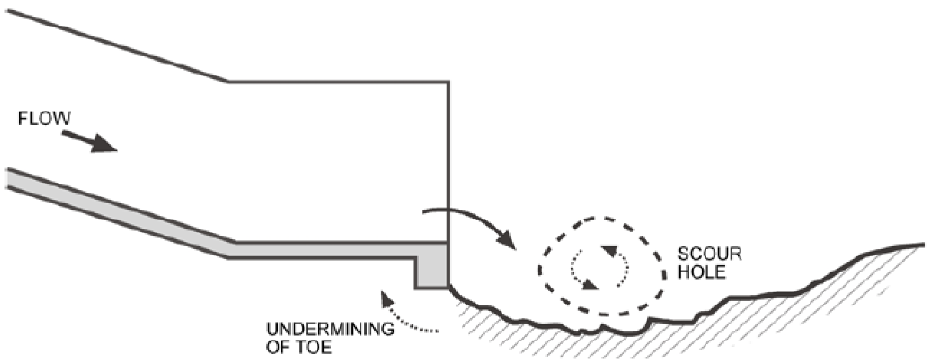


*Figure 51 Typical sketch of scour and undermining of the dam toe due to inadequate energy dissipation [11].*

Scour holes in the downstream channel can be imaged by bathymetric surveys (Figure 53). Settlement of the undermined dam/gate structure could be measured by deformation monitors in pillars (Figure 52). Increasing pore pressure (uplift pressure) caused by scour can also be monitored by piezometers installed in the dam foundation. The dams Isola Serfini in Italy and Kamuzu Barrage in Malawi are presented as typical examples.


*Figure 52: Isola Serfini dam in Italy on the left and Kamuzu Barrage in Malawi on the right.*

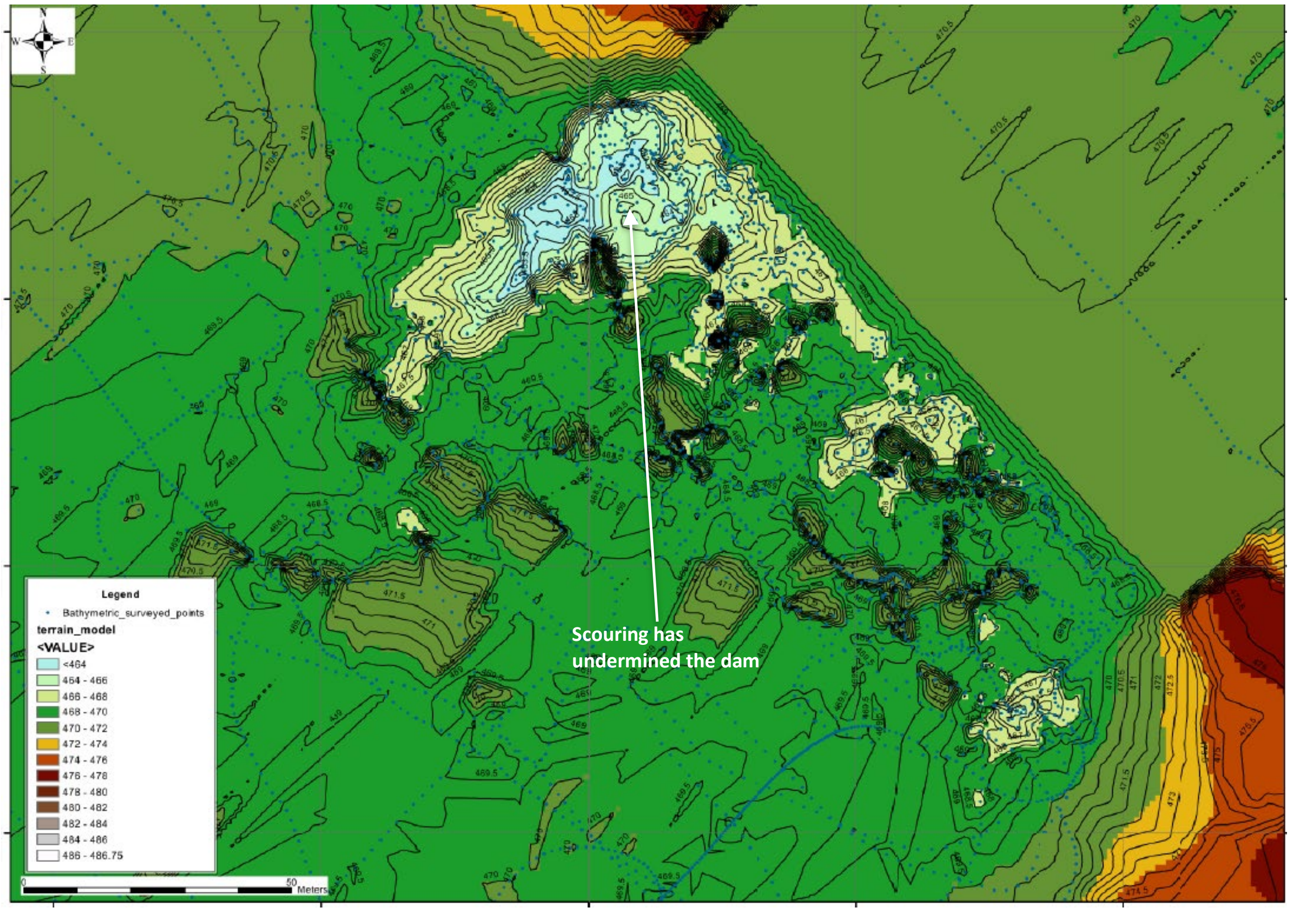


*Figure 53: Bathymetric survey showing scouring in downstream of Kamuzu Barrage*

#### *6.4.2.4 Structural instabilities of concrete dams*

Structural instabilities in concrete dams are relatively easy to monitor with deformation measurements. Crack development and propagation can be observed and measured through manually during visual inspections. Increases in leakage (through cracks) can controlled quantitatively during visual inspections in many cases. Increases in pore water pressure (uplift) can be detected by piezometers installed in the dam foundation.

It is important to conduct periodic inspections of concrete dams with installed post-tension anchors. In Norway, this is done by checking the tension at each Dam Safety Assessment (mandated at every 15 - 20 years), but it is also possible to install load-cells on tensioned anchors for continuous monitoring.

Different types of deformation measurements are used at different parts of concrete dam structures (galleries, crests, faces, joints). It is important to combine all of these different measurements to obtain a complete overview of a dam's stability.

#### *6.4.2.5 Ice & wave actions; including local tsunami waves generated by large landslides*

Ice and wave action can cause damage on dams and are a relevant hazard for Norwegian dams due to the cold climate. Neither is likely to lead to total failure of dam where a proper inspection program is implemented and followed, though they can still cause significant damages. Ice and wave actions are a good example where visual inspections provide essential information and monitoring data only plays a secondary role. The inspection program required by Norwegian dam safety law is in most cases sufficient in mitigating the hazard posed by these effects and further special built monitoring systems are not commonly used.

Large landslides, however, can cause dam failure. A well-known example is the failure of the Vajont dam in Italy. A 250 m high flood wave caused by a landslide into the reservoir overtopped the concrete dam and destroyed several villages downstream. Although the likelihood for large landslides into a reservoir is often low at Norwegian dams, it is a relevant risk, especially considering the potentially big consequences. Geological setting in other parts of the world might make this an even more important theme.

Banja dam in Albania is presented as a typical example for the successful monitoring of potential slope instabilities under the initial filling of the reservoir (seen as the most critical period). The left abutment slope of the dam and another slope in the reservoir were observed to exhibit continuous deformation during the construction period. An extensive monitoring program including inclinometers, piezometers, and surface monitoring markers, was undertaken during the initial reservoir filling, and with weekly stability reports during this period.

An example of the inclinometer and surface marker measurements are summarised in Figure 54. Determination of the movements obtained from an inclinometer are shown in Figure 55.

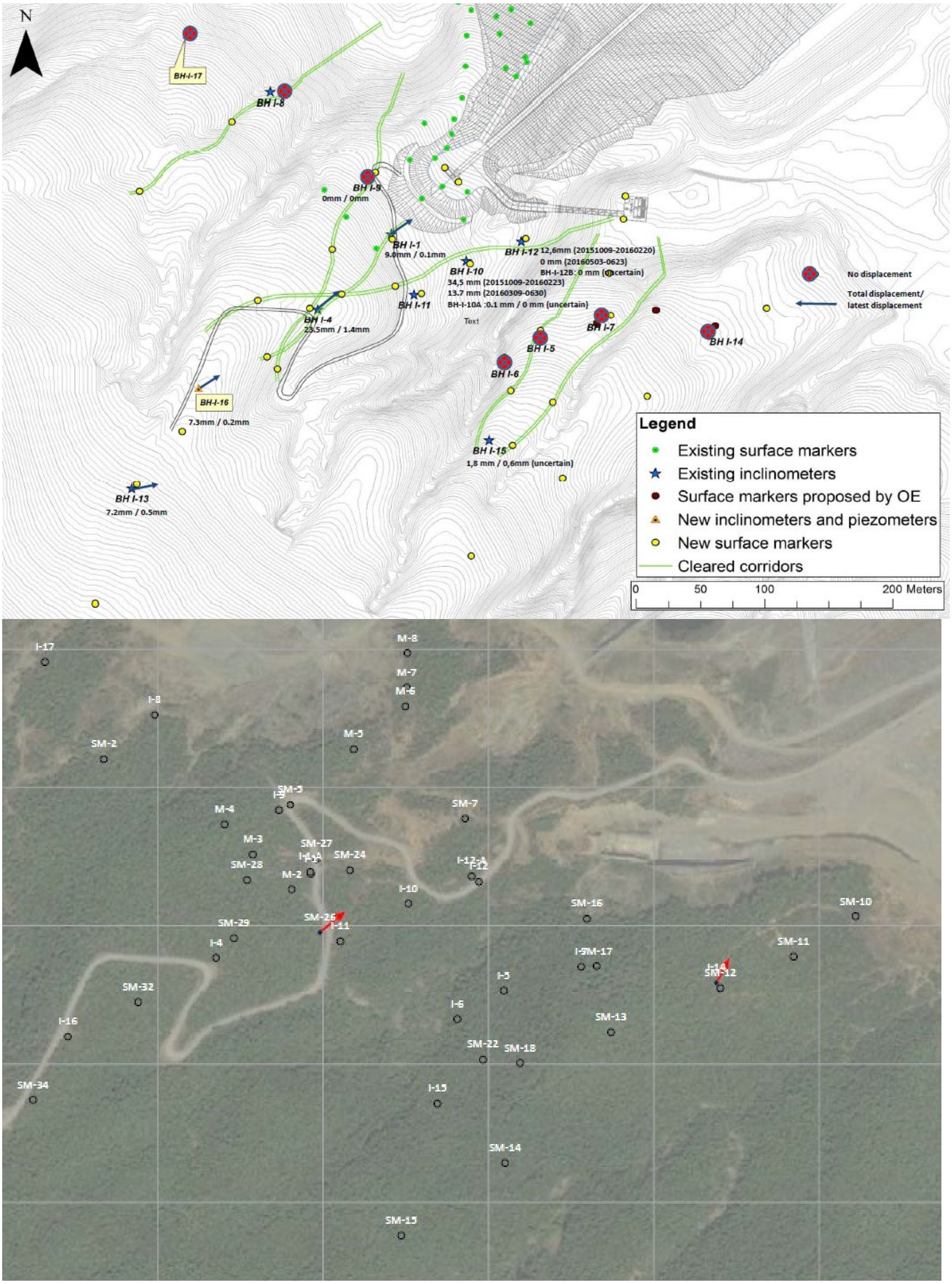


*Figure 54: Inclinometer (top) and surface maker (bottom) measurements on the dam left abutment.*

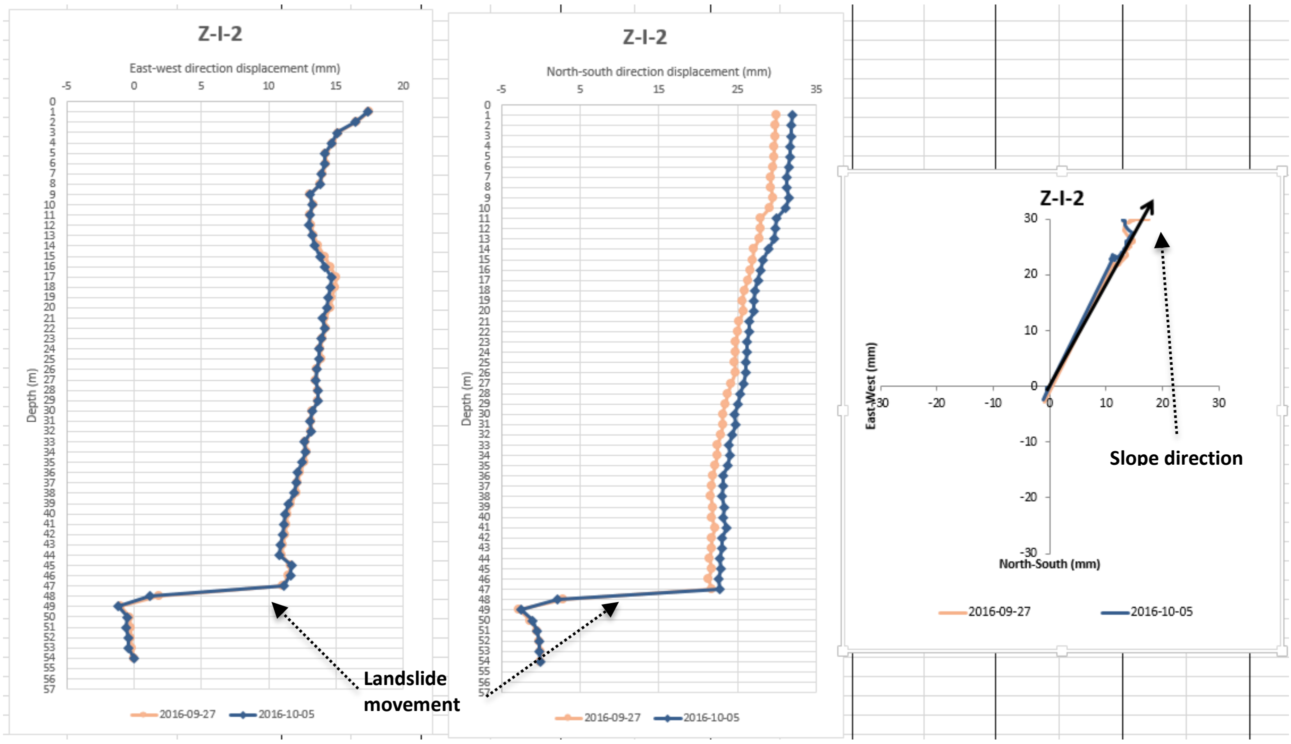


*Figure 55: Typical inclinometer measurements that indicate movement.*

## 6.5 Recommendations on threshold values and reliability

### 6.5.1 *Recommendations for to establish the threshold values*

Threshold values are usually defined through deterministic models or through a statistical evaluation of monitoring data. During construction and initial reservoir filling, no representative monitoring data is available, so deterministic models, or empirical values from similar structures, must therefore be used.

Statistical models can be used once a representative time series including different load scenarios is available.

The advantage of statistic models is that they are based on data sensors installed within the dam and can therefore take into account local conditions that cannot be defined in deterministic models. In addition, they are easier to develop, and can be calculated with traditional software.

In this chapter, details about the precision and difficulty of using elaborating deterministic models is presented.

Finally, it should be mentioned that deterministic models often provide more precise results when they are calibrated with real monitoring data.

#### *6.5.1.1 Deformation measurements*

As discussed in section 6.2, it can be difficult to establish a threshold value that directly relates to certain contingency or remedial actions. However, threshold values should be used to inform the dam engineer about any unexpected evolutions of monitoring data. This information will aid them in assessing a dam's condition and decide upon any further actions.

Referring to section 6.3.1, it is generally not recommended to establish threshold values by using complex analytical methods for deformation measurements. It is instead recommended to establish the threshold values by practical empirical, or statistical methods in combination with a good understanding of the dam's stability.

For example, for an embankment dam an empiric value of 0,5%-1% of the total dam height can be used as a first orientation for total long-term settlement of the dam crest.

- One should observe settlement to determine what is "normal" for each individual dam (also considering expected settlement rates estimated during construction). Before total settlement begins to detract from freeboard – which is often determined from hydraulic rather than geotechnical assumptions – it is the rate of settlement and any changes in this rate that are of interest, cf. Figure 38 and Figure 39. One should ask: is the settlement rate increasing or decreasing over time?
- Threshold values should be updated and adjusted gradually during operation by considering latest monitoring data.
- Initial actions undertaken when settlement first begins to approach threshold values could be to intensify monitoring and surveillance, for example conducting more frequent visual inspections of the dam or taking more frequent measurement readings
- Dam safety should always be looked at as part of a "big picture" and not isolated instances and measurements

#### *6.5.1.2 Leakage measurements*

As section 6.3.2 discussed, it is not recommended to establish leakage threshold values by using complex analytical methods. However, a threshold value should be used to inform the dam engineer about any unexpected changes in the monitoring data. This information will help them to assess the condition of the dam and decide if any further remedial actions are required. The following points should be considered when setting a threshold value:

- Threshold values should be updated and adjusted gradually during operation with the latest monitoring data. A practical example could be estimating a percentage of peak leakage from the previous few years, if the dam was stable over this time-period.
- In embankment dams, it should be noted that the total leakage is related to the permeability of the dam and foundation. These are usually estimated with an uncertainty approximately 10x. High accuracy in the threshold value should not be expected from deterministic models. Dam safety should always be looked at as part of a "big picture" and not isolated instances and measurements

#### *6.5.1.3 Pore pressure measurements*

As discussed in section 6.3.3, analytical methods can be used to determine threshold values for pore water pressure measurements with relative accuracy. Slope stability in embankment dams is extremely sensitive to pore water pressure.

A sensitivity analysis can be conducted by combining seepage and stability analysis together (as shown in Figure 56, following page). The seepage analysis provides an estimate of the pore pressure distributions throughout the dam and is used as input for the stability analysis. As the result, the relationship between the pore pressure and factor of safety can be established.

However, seepage analysis is not the only method to determine the pore pressure. Pore pressure can also be calculated by a drawn phreatic line or by using spatial distribution functions. An example of the pore pressure established by spatial distribution function is shown in Figure 57.

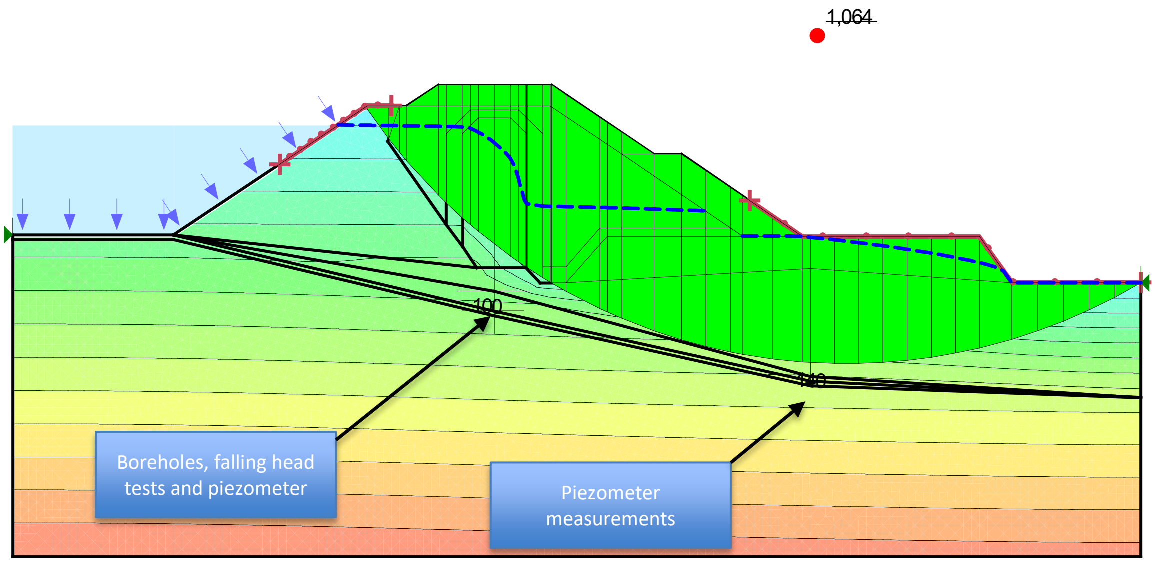


*Figure 56: Pore pressure condition established by seepage analysis.*

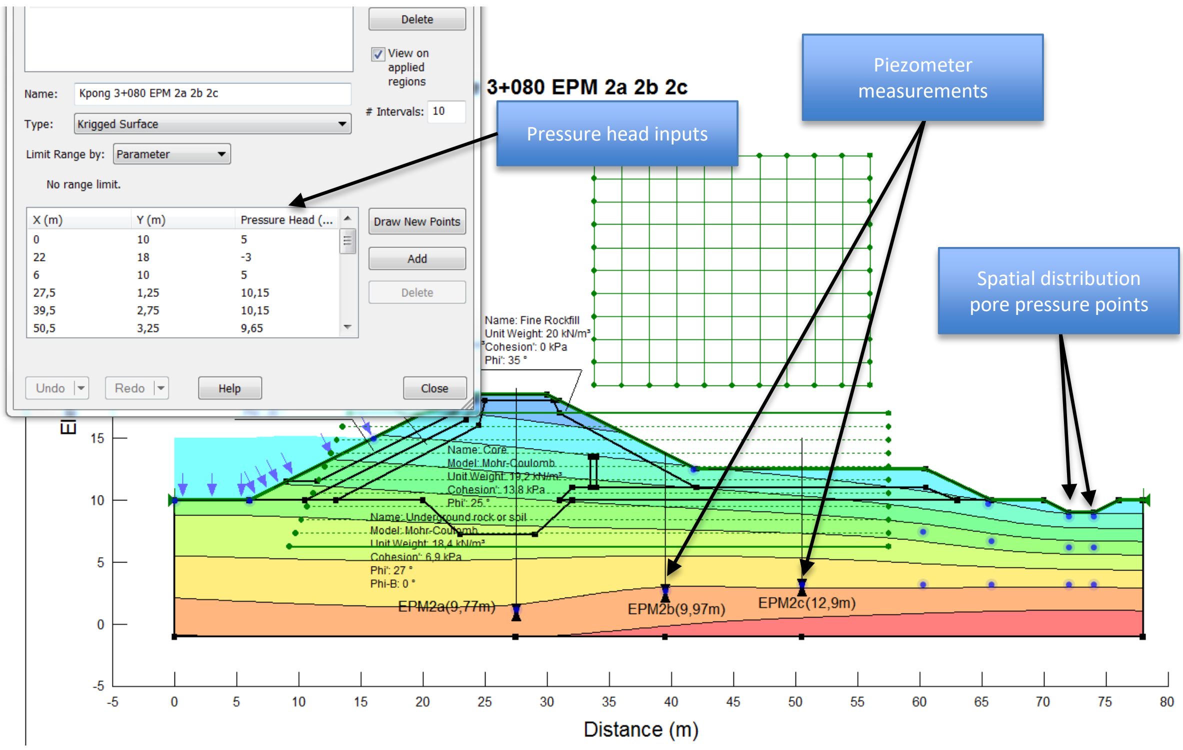


*Figure 57: Pore pressure established by the spatial distributed functions.*

Threshold values for piezometer measurements can be determined by analytical methods, but the following limitations must be considered:

- Analytical methods require the engineer to have sufficient geotechnical information, such as the ground investigation and field lab tests, and to properly interpret material parameters from this data.
- Dependence on changes in reservoir level and long response time in low permeability materials must be considered

Again, it is vital to emphasise that dam safety should always be looked at as part of a "big picture" and not as isolated instances and measurements with no relation to each other.

### 6.5.2 *Reliability*

It is important to establish a reliable overview and monitoring system for dam safety. All detected anomalies in the data should be well understood, even if they do not pose a threat to the safety of the dam. A misinterpretation of important threats due to distractions caused by anomalous data can therefore be avoided.

Many researchers are currently testing the ability to use machine learning tools to obtain information on dam stability, with the ultimate goal being the development of algorithms or artificial intelligence to assess dam safety. Some desk studies have been conducted with positive results, indicating that this technology might be a real possibility in the near future.

In Norwegian dams, some anomalies have been detected that, after investigation, were determined to be non-threatening to the dams:

- Reduction of leakage flow due to blockage, particular by ice during the winter (Figure 58).
- Sudden increasing in leakage caused by snow or frozen material melting within the dam body
- High pore pressure measurement due to high tailrace or ground water level

*Figure 58: Reduction of leakage volume due to ice blockage.*

A large release of leakage caused by snow/ice melting is a typical for some Norwegian dams. Sometimes, even higher leakage volumes can be caused by the breaching of an ice dam. The sudden increase in leakage measured at Aursjø dam on 17. September 2017 is an example of this (Figure 59).

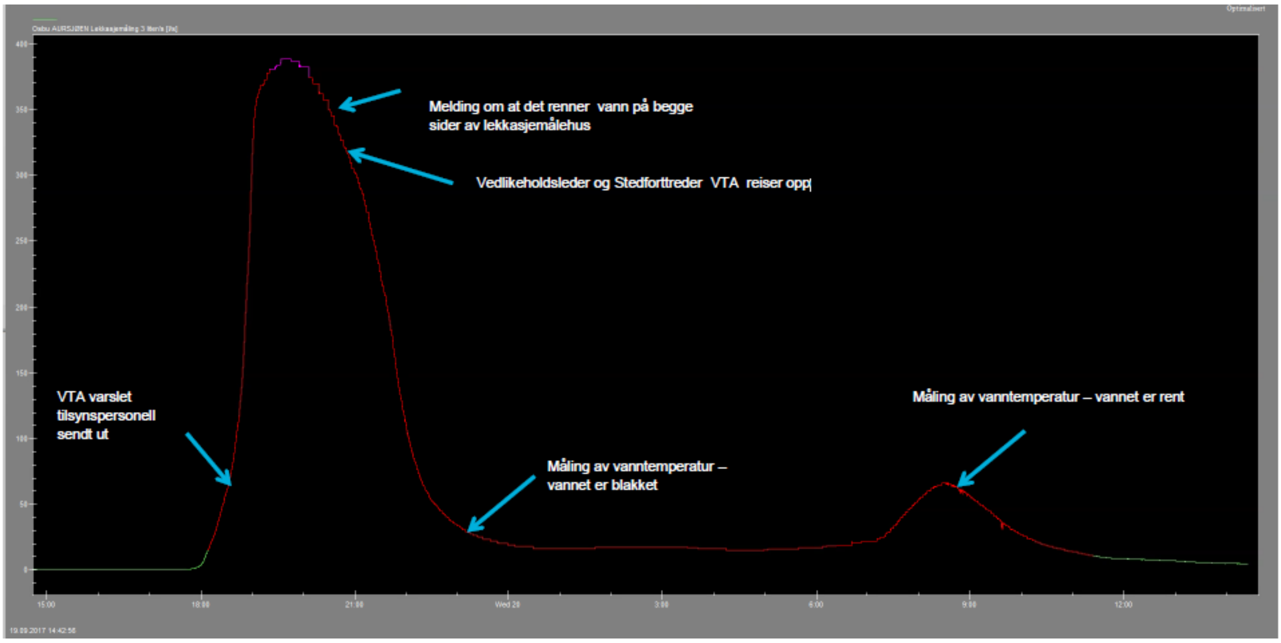


*Figure 59: Registered leakage volume with time during the event. The text indicates when an alarm was triggered (1st arrow), leakage water flowing on both sides of the measurement house (2nd), arrival of the supervising engineer onsite (3rd), temperature measurements of silty water (4th), and temperature measurements of clean water (5th).*

Aursjø dam is a 40m high embankment dam with a concrete upstream face. There is a road embankment in the downstream toe of the dam, and the leakage measurement house 3 is further downstream of the road embankment. The dam has a history of leakages and a new remote automatic leakage measurement system was installed from 2005-2007. During the leakage event of 17.09.2017, the threshold value 70 l/s was exceeded at 18:30. Personnel were notified and emergency inspections were conducted. At 21:00, the leakage reached peak volume of about 380 l/s. At 22:30, the total leakage fell rapidly to below 70 l/s and returned to normal levels in 24 hours. The total leakage volume is estimated at about 5000 m$^3$.

The causes of the event were later investigated. The leakage data was compared with the upstream water level, temperature, and snow depth (Figure 60) for the past few years. Personnel measured the temperature of the leakage water during the leakage event.

The spike in leakage volume was determined to have been caused by the thawing of frozen material in the road embankment, thereby suddenly releasing leakage water that had built up behind it. This event was determined to have not been caused by internal erosion or have negatively contributed to the dam's stability. The arguments to support this interpretation are as follows:

- The leakage volume returned to normal 24 hours after the event. Clean (not silty) water was observed.
- The leakage water had a temperature of around 0°C. The water in the reservoir was between 4°C - 8°C at the time.
- There is no correlation between the leakage and upstream water level, precipitation, snow depth, and temperature or deformation measurements (Figure 60).
- The road embankment is estimated to have sufficient pore space to store 5000 m$^3$ water.
- ROV inspections were conducted on the upstream face. No significant cracks in the concrete face were observed.
- The total precipitation of the catchment area for leakage measurement house 3 was plotted with the actual leakage measurements there (Figure 61). This shows that after higher than expected

leakage in 2008, lower than expected leakage was measured in 2009-2011, and then significant high leakage was again measured in 2012. This similar pattern is repeated in 2013-2017, indicating that high leakage in 2017 could be from water that had been dammed up since 2013.

- A similar incident occurred at Songa dam in 2010, in Norway.

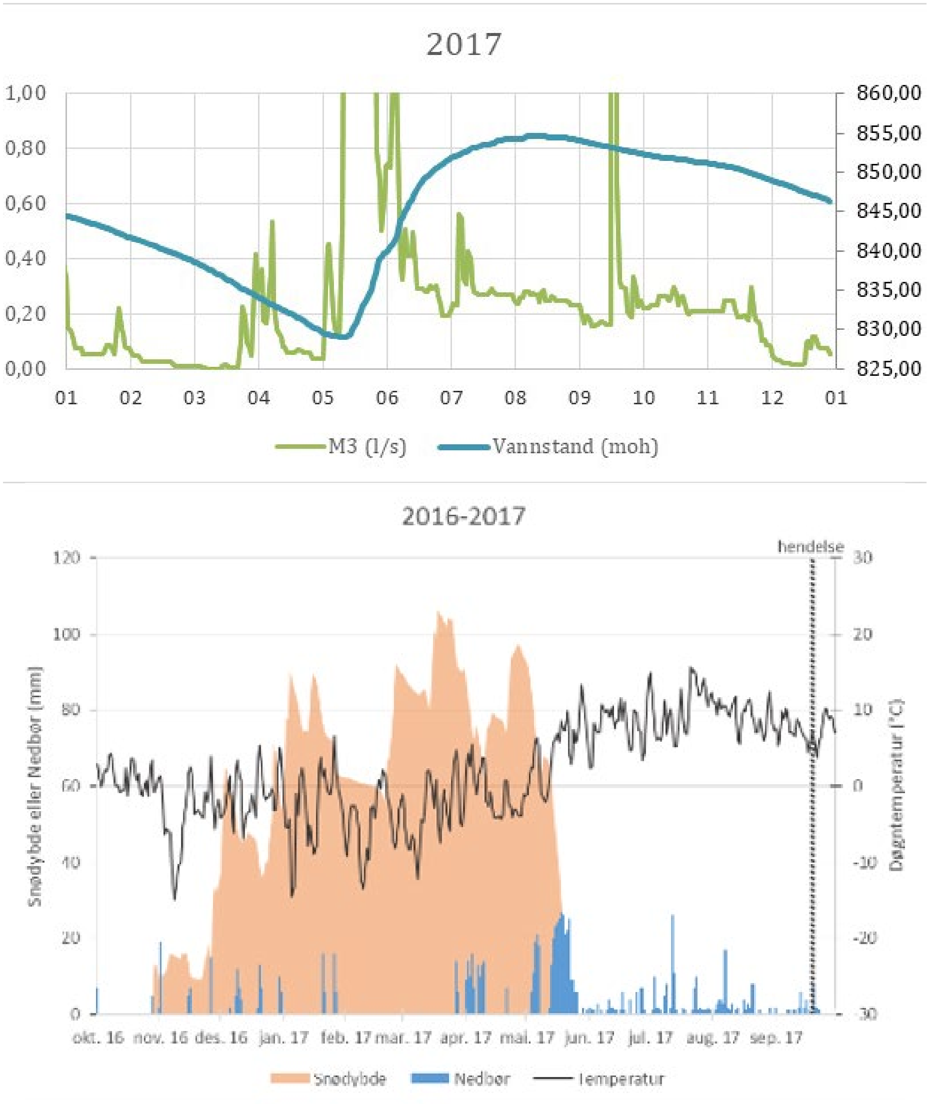


*Figure 60 Top: total leakage (green) plotted with upstream water level (blue). Bottom: snow depth (orange) plotted with precipitation (blue), and temperature (black).*

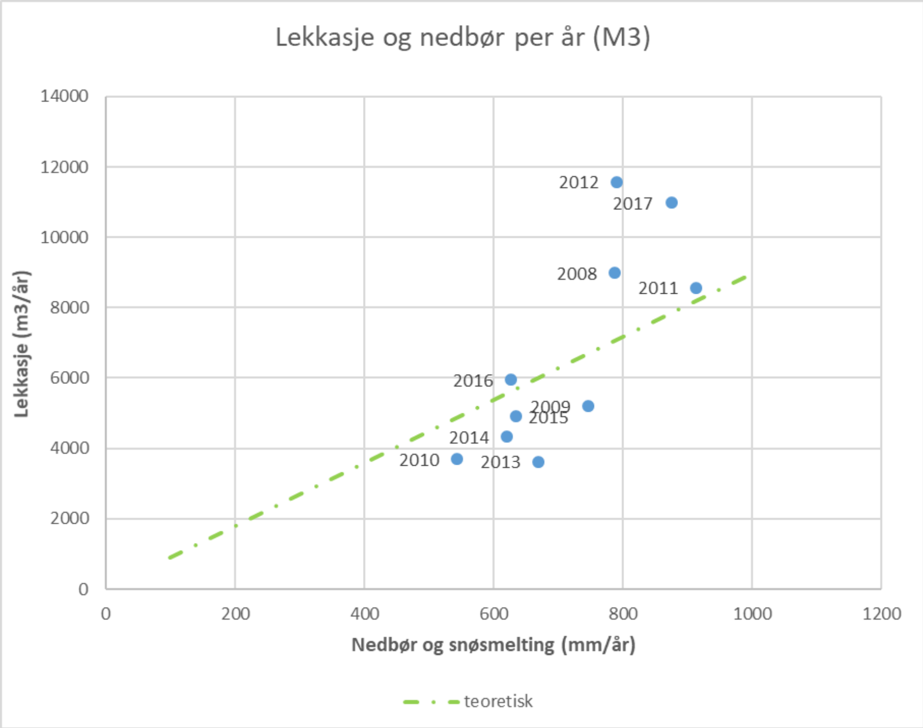


*Figure 61: Total yearly precipitation of the catchment area for leakage measurement house 3, plotted with the actual measured leakage.*

The following lessons can be learned from this example:

- Interpretation of monitoring data must be combined with other technical information and observations to get a complete overview of a dam's safety.
- It is extremely useful to use a tool that allows plotting different types of measurements together.
- Exceedance of the threshold value in this case is not related to dam safety. However, it is very useful to alert the dam engineer to anomalous behaviour, indicating that they should conduct more detailed investigations (often visual), which helps with later data interpretation and validation.

In summary, both the instrumentation available at the dam and the operators prompt actions, observations and analysis during the event, and follow-up, provided important data that could be used to determine the likely cause of the sudden increase in leakage water, and that it did not pose a threat to the dam's stability.

### 6.5.3 *Fixed vs. Dynamic threshold values*

Dynamic thresholds are defined as parameters that trigger a certain action, where the relevant triggering value varies according to external circumstances. These circumstances are in turn a set of measured parameters – including Boolean – in the case of dam safety related to reservoir level, meteorological conditions, or the environment, with associated timestamp.

A simple example would be measuring leakage through an embankment dam, where the alarm triggering value is also related to the upstream reservoir level. In previous sections it is shown that determining an "acceptable" relationship between leakage and water level is difficult from a theoretical basis; a practical approach adjusting the threshold value based on experience may be more applicable. Deviation from "normal" (i.e. earlier) behaviour can be used to set threshold values. This requires a thorough statistical analysis of available datasets.

It is often desirable to expand the set of parameters that control a dynamic threshold value – in the above example of an embankment dam, the threshold value is initially controlled by reservoir water level, however a larger set of variables to help detect the onset of internal erosion through a clay core could include:

- Rates of change or spatial variability in leakage measurements
- Whether the water level in the reservoir is rising or falling
- Piezometer measurements in the dam body (pore water pressure)
- Precipitation
- Turbidity measurements of leakage water
- Temperature (air, reservoir water, and leakage water)

All of these values must include a timestamp, and changes over time (trends) can be evaluated and used to determine threshold values. Different sensors of the same type can also be compared (i.e. how piezometers at different locations measure changes in reservoir level).

There are always conceivable cases where further information (measurements) would be of interest. Ultimately, the dam engineer must decide which parameters will be of relevance and governing, based on what is practically possible in terms of data collection, processing, and presentation. A good monitoring system will help with this, but the user's knowledge and understanding of the reservoir will be crucial in developing, operating, and understanding the monitoring system.

Fixed threshold values are in some cases both easier to determine, and interpret. An example could be for a concrete gravity dam founded on bedrock, where computations of the dam's stability depend only on the upstream reservoir level. If all other calculation parameters are unchanging (dam geometry, friction, shape of the uplift diagram, etc.) a given water level will correspond directly to a given factor of safety, and a fixed threshold value can be determined based off of this one parameter.

Nevertheless, even in this simple case can other, secondary, parameters that influence the factor of safety besides water level may be included, if measured. Measuring the uplift pressure (pore pressure) under the dam could improve the quality of the stability assessment. The relationship between pore pressure, reservoir water level, and factor of safety, could be mathematically determined and used to apply a dynamic threshold value. For existing dams, a statistical analysis of historical behaviour should be conducted to determine "normal" behaviour, and threshold values should be based on this. Changes in previous behavioural trends will indicate that "something" is happening to the dam, and it is then the job of the dam engineer to determine precisely what that is, and if it will have any impacts on dam safety.

# 7 Conclusions and recommendations

The purpose of dam monitoring is to manage risks associated with the dam and to reduce the probability of dam failure through early detection of events that could lead to failure. Instrumentation has a key role in dam monitoring, but must always work together with other measures, such as visual inspections and testing of the facilities.

In this report, various matters concerning dam monitoring are presented. It is emphasised that a perfect monitoring system will not necessarily reduce the risk if the collected data is not evaluated regularly and correctly used to apply dam safety measures. It is therefore crucial to have an effective connection between data collection, evaluation, interpretation, and decision making. The goal is to convert raw data from the instruments to valuable information, which can be used to give the dam operator a better understanding of the dam's behaviour.

Many different components must be taken into account; especially measurement, communication and IT technologies, processes for data collection, evaluation, alerting, reporting, and decision making. Furthermore, neither the impact of human factors nor relevant regulations and guidelines should be underestimated.

In order to improve dam safety, it is necessary to improve these constituent parts and optimize their integration into the information workflow.

As a continuation of this study - and previous works by Energi Norge - the following keywords and comments are summarised:

- The study can be expanded with more analyses of typical fracture, and fracture progression mechanisms, relevant for Norwegian dams. This is especially relevant for different types of concrete dams.
- For embankment dams, turbidity measurements are mentioned as an area that can be improved in Norwegian practice. Examples from international dams should be studied.
- New technologies offer new opportunities, but also the potential for increased uncertainty. As an example, what does the emergence of 5G technology, that allows for better communication, but also potentially greater vulnerability to network failures, mean for dam safety?
- Costs for the installation, operation, and follow-up maintenance of instrumentation and monitoring systems are often overlooked. Cost estimates from suppliers and consultants who have experience with developing and implementing these systems on complicated projects should be included.

In conclusion, it is recommended that dam owners who are considering establishing large, integrated monitoring systems, gain experience and insight from those who have done similar works before. Industry representing bodies, such as Energi Norge, can play an important role here as a facilitator of knowledge sharing. The same applies to the respective national chapters of the Committee on Large Dams, which through their membership in ICOLD have developed a large network of contacts with the international community. Specialised consulting firms with experience working on international projects can also be an important partner.

# 8 References

[1] Energi Norge (2019), https://energifaktanorge.no/norsk-energiforsyning/kraftforsyningen/
[2] Hovden, J., Rausand, M., Sten, T. og Ulleberg, T (1989)," Storulykker i Norge. En utredning for NTNF". STF75 A89016 (ISBN 82-595-5411-9)
[3] Olje- og energidepartementet (2019), Forskrift om sikkerhet ved vassdragsanlegg (damsikkerhetsforskriften)
[4] EBL (2000), Håndbok for etterinstrumentering av dammer (Publ. 466-2000) (NVK Vandbygningskontoret / Ivar Torblaa)
[5] Sweco (2018), Damhistorikk og instrumentering, evaluering og dokumentering av eksisterende dammers sikkerhet
[6] BKK (2018), Bruk av damhistorikk med eksempler fra BKK. BKK Produksjon AS
[7] ICOLD (2000), Bulletin 118 Automated Dam Monitoring Systems
[8] ICOLD (2011), Bulletin 158 Dam Surveillance guide
[9] ICOLD (2000), Bulletin 118 Automated Dam Monitoring Systems
[10] ICOLD (2011), Bulletin 158 Dam Surveillance guide
[11] Defra (2011), Modes of dam failure and monitoring and measuring techniques
[12] USSD (2013), Routing Instrumented and Visual Monitoring of Dams Based on Potential Failure Modes Analysis
[13] USSD (2013), Instrumentation Data Collection, Management and Analysis
[14] ANCOLD (2003), Guidelines on Dam Safety Management
[15] ICOLD (2018), Bulletin 180: Dam Surveillance, lessons learnt from case histories - draft bulletin
[16] SPANCOLD (2000), Guías Técnicas de Seguridad de Presas – Auscultatión de las Presas y sus Cimientos
[17] NVE (2019), Veileder 3/2019 Overvåking av vassdragsanlegg
[18] RST Instrumentations (2018), Monitoring Instrumentation for Dams, Hydropower, Irrigation and Energy projects https://www.rstinstruments.com/applications/dams.
[19] ICOLD (2009), Bulletin 138: General approach to Dam Surveillance
[20] Wikipedia (2018), 2018 Laos dam collapse
[21] A.J. Schleiss, J.P. Tournier A.F. Chraibi (2019), Failure of Xe-Pian Saddle Dam D.