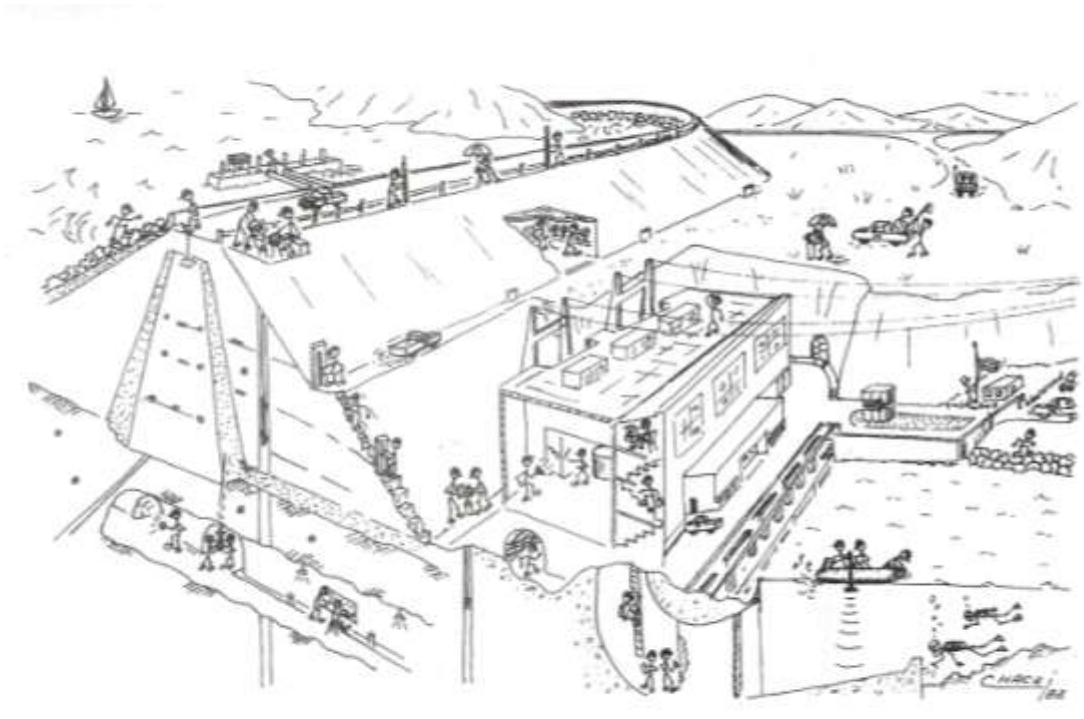
DAM SURVEILLANCE GUIDE

GUIDE DE LA SURVEILLANCE DES BARRAGES

Bulletin 158



International Commission on Large Dams - *Commission Internationale des Grands Barrages*

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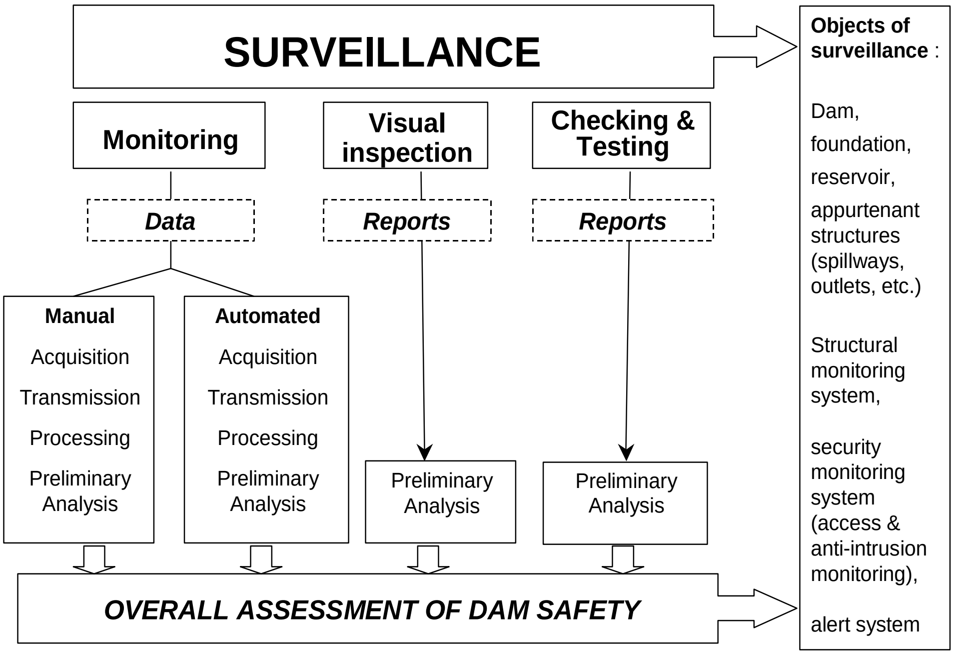
FOREWORD

The terms of reference for the present technical committee of ICOLD, on Dam Surveillance approved at ICOLD 2003 is to:

"Prepare guidelines for the optimal organisation of all components required for dam surveillance and monitoring (independently of the Automated Monitoring, already covered by Bulletin n° 118) with the purpose of dissemination in the fields of:

- *visual inspection methods and procedures for improving their efficiency;*
- *continued availability and maintenance of technical data (documentation management for storage of engineering data and all information needed for periodical appraisal of the dam condition and support of engineering judgement as well as knowledge transfer from one generation to the next);*
- *optimization of instrumentation and monitoring (depending on the dam type and condition) and upgrading of instrumentation (on old dams); and*
- *efficient management of monitoring data (acquisition, processing, conservation) and interpretation (of processed readings and observed data) to assess the present dam condition"*

The following figure (extracted from ICOLD Bulletin 118) explains the extent of the definition of the concept of "surveillance" to be used in this Bulletin.



Alejandro Pujol
Chairman of Surveillance Committee

1 Introduction

Dams are among the human achievements that while providing great benefits also create a potential risk to neighbouring populations, property, and the natural environment. Although the consequences of dam failure can be significant, in all but a few instances the probability of failure is very low.

The intrinsic risk of dam failure, consisting of consequences multiplied by the probability of occurrence of an event, is difficult to quantify accurately. Nevertheless, dam surveillance can help reduce the risk by the early detection of undesirable events. Any surveillance process should aim to reduce the probability of failure by:

- Documenting the behavior of the dam, its foundation and other components
- Utilising identified potential failure modes and the associated levels of risk
- Preparing and implementing Emergency Action Plans appropriate for the dam and its consequences of failure
- Implementing a program that can detect early the development of significant failure modes. A visual representation of the surveillance activities during the life of dams is presented in figure 1.1.

As a general rule, protection of persons and property is a social responsibility for government which must legislate, to enforce and control effective and efficient dam surveillance. A legal framework that clarifies the duties and responsibilities of the different parties responsible for the safe operation of a dam is necessary. However, the owner has the main responsibility for all aspects of dam safety including reducing the consequences of any dam failure. This Bulletin has been prepared for owners, managers, engineers and others responsible for the safe operation of dams.

The objective of dam surveillance is to make a timely and precise diagnosis of dam behavior that allows for the prevention of undesirable consequences. The monitoring system and surveillance programme have to be designed or redesigned considering potential failure modes associated with the higher levels of risk. They should be able to identify any abnormal behavior which could lead to potential reduction of safety.

It was decided to update Bulletins 60 and 68 of the "Committee on Monitoring". This update emphasises the following aspects:

- Routine visual inspection
- Special inspection (inaccessible areas)
- Checking and testing of Hydro-electromechanical equipment
- Monitoring parameters and devices
- Automation
- Maintenance of ageing monitoring systems
- Re-instrumentation of existing dams
- Recent developments
- Data management
- Dam documentation management
- Assessment of dam condition and behavior
- Assessment of routine dam safety monitoring programme

- Prioritization of maintenance, remedial and upgrading works.

According to Bulletin 138, analyses of dam performance should be reviewed using appropriate specialization to account for different points of view available from independent consultants.

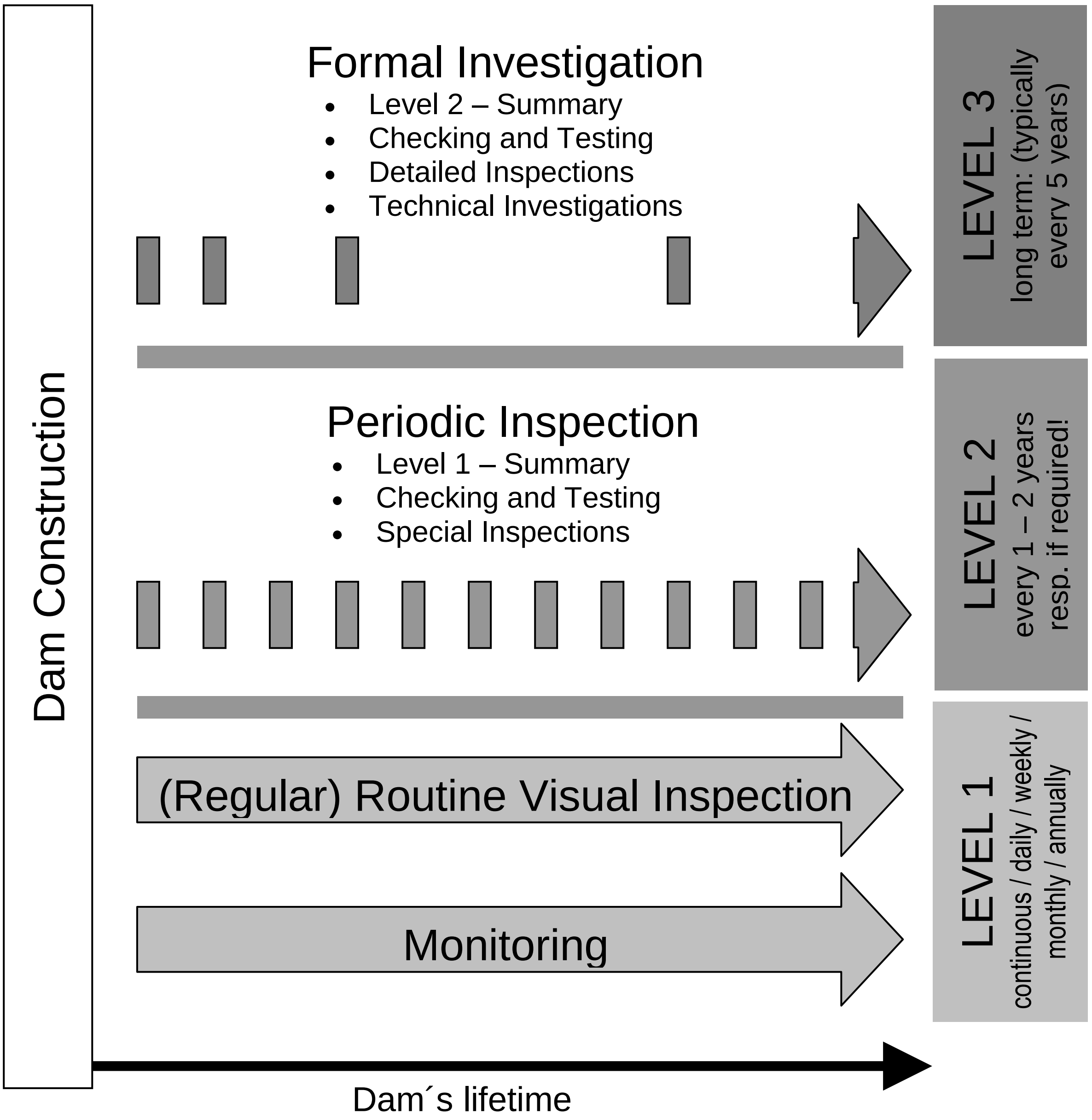


Figure 1.1 ***Visual representations of the surveillance activities during the life of dams.***

Monitoring equipment should also be useful for monitoring the effects of extraordinary situations including earthquakes and floods.

A great number of dams do not have state of the art instrumentation systems. Often existing instruments are obsolete or, for various other reasons, not reliable. Each dam that presents high risk should be carefully monitored and its monitoring systems should be improved according to the following flow diagram in figure 1.2.

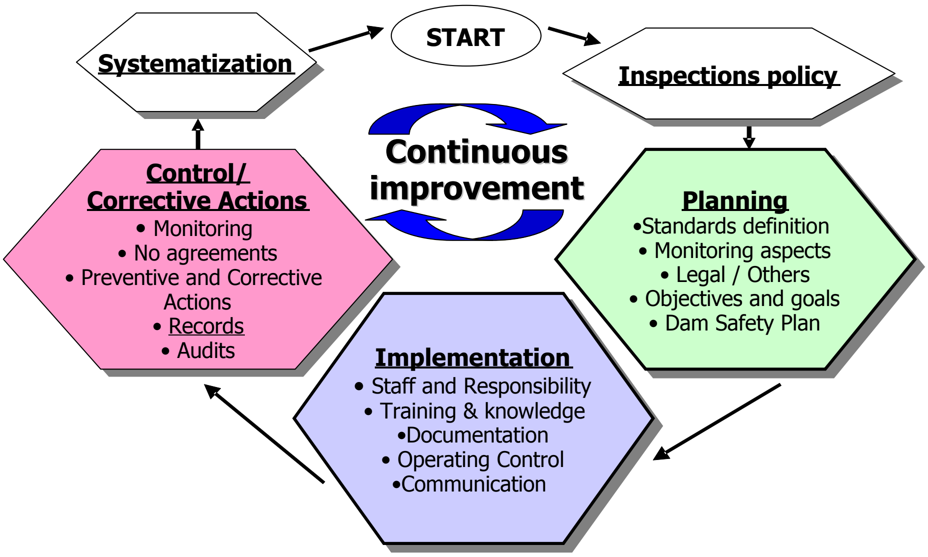


Figure 1.2 Flow diagram of the continuous improvement of the surveillance system

2 Visual Inspections and Special / Ad hoc Inspections

2.1 Definitions

´Visual inspection´ usually describes the regular routine inspection of the dam and its surroundings under normal operating conditions (Level 1, see Chapter 1, Figure 1.1). It has to be considered as an inspection by operational staff with a limited duration of some hours. Most of the following paragraphs (2.2 to 2.3) are related to this issue.

´Special inspections´ or ´Ad hoc–inspections´ are indispensable in case of unusual conditions and fall within the scope of periodic inspections (Level 2). Periodic inspections are conducted every 1 to 2 years as a comprehensive assessment of dam safety based on monitoring results (see chapter 1, Figure 1.1). The frequency of the periodic inspections should be established according to the particular phase of the dam's life e.g. ´during first impoundment´, ´some years after impoundment, ´dam becomes stable´, and ´long term operation´.

2.2 Visual Inspection

2.2.1 General

Visual inspections constitute a necessary component of dam surveillance. They allow for a comprehensive qualitative evaluation of the condition of the structure and its surroundings. Anomalies in the condition and behavior of the structure are most frequently identified by means of visual recognition of important changes.

Visual inspections should be performed at regular intervals by the operational staff, trained in and familiar with such procedures, and qualified for their level of responsibility. The personnel should be able to judge the significance of observed changes in respect of the safety of the structure and call for an inspection by a more experienced, qualified engineer.

Changes identified in the visual inspections have to be reported to the person in charge.

Specific inspection rules should be instituted for individual dams, considering their specific behavioral properties. The extent and frequency of visual inspections should be detailed and defined in the surveillance and monitoring procedures of each dam.

It is recommended to prepare a checklist, adapted to the conditions of the facility. The completed checklist and its entries can be used as a report of the visual inspection. The checklist should also describe the conditions of observation.

The results of the visual observations should be well documented and logged in the operational records. Important changes should be documented by means of photography. All relevant information, including photographs, should be recorded in a well structured database.

The use of fixed video cameras might be convenient in some cases (difficult access, special monitoring requirements), but by no means should replace the on site visual inspections.

2.2.2 Extent of visual inspections

The extent of visual inspections has to be defined considering the particular nature of and arrangements at the dam. In principle, visual inspections consist of checks on the structure to detect if any relevant changes have taken place. Besides detecting any visible anomalies, visual inspections should mainly focus on the identification of the following processes and their consequences:

- Seepage
- Displacements and deformations
- Cracking
- Signs of wear and weathering

The most important changes that might be observed at the different components of dams, appurtenant structures and dam surrounds are itemized in Tables 2.1 and 2.2.

Table 2.1: Extent of visual inspections of dams

Dam type	**Part of the dam**	**Changes**
Embankments (earth dams or rock-fill dams)	Downstream face	– Surfacing seepage water, turbidity – Soaked surfaces – Cracks, local settlements, local slides – Erosion (development of gulling) – Vegetation – Animal burrows
	Dam crest	– Cracks, local settlements – Erosion – Vegetation – Animal burrows – Condition of the road – Line of sight – check horizontal & vertical alignments
	Upstream face (accessible section)	– Vortex formation on the water surface – Cracks, local deformations, local slides – Bulging of surface sealing elements – Damages on the surface sealing element – Displacement of riprap – Vegetation – Animal burrows
	Inspection gallery	– Cracks – Leaking seepage water, turbidity – Sinter formations – Condition of concrete – Clogging of drainage system

	Contact between embankment and concrete structures or rock foundation	– Relative displacements – Local settlement – Leaking seepage water
Concrete dams	Downstream face (especially at poorly constructed points, contact with the rock foundation)	– Surface seepage water – Sinter formations – Ice formation – Cracks, or joint opening – Condition of concrete / masonry
	Dam crest	– Cracks – Joint movement – Condition of the road – Line of sight – check
	Upstream face (accessible section)	– Vortex formation on the water surface – Cracks, or joint opening – Condition of concrete / masonry
	Inspection gallery , shafts and adits	– Leaking seepage water, turbidity – Sinter formation – Clogging of drainage system – Cracks, joint movement – Condition of concrete / masonry – Line of sight – check

Table 2.2: Extent of the visual inspections – Appurtenant structures and dam surrounds

Structure	**Part of the structure**	**Changes**
Cutoff walls (if accessible)	Surface	– Cracks – Dislocations
Underground and abutments	Contact zones to the dam and dam surrounds	– Surfacing seepage water, boils, turbidity – Soaked surfaces – Cracks, local settlements, local landslides – Erosion – Vegetation
	Galleries (injection, drainage, inspection), shafts and adits	– Leaking seepage water, turbidity – Sinter formation – Condition (concrete, lining, rock) – Clogging of drainage system
Surrounds	Reservoir (surface)	– Floating debris – Pollution
	Reservoir (banks and slopes)	– Settlements and landslides – Cracks (as indication of slope instability) – Condition of infrastructure – Vegetation – Sink hole
	Downstream area	– Boils – Soaked surfaces – Vegetation
Hydraulic structures	Spillway	– Cracks – Erosion – Scour holes downstream – Displacements, or joint movement – Floating debris
	Intake	– Condition – Tightness – Leakages along conduits, turbidity – Displacements – Floating debris
	Bottom outlet	– Erosion, joint movement, cracks – Scour holes downstream
Electro-mechanical facilities	Power supply	– Availability at the point of use
	Gates and hoisting devices	– Damages – Oil leaks – Corrosion – Vandalism (Protection measures)

The visual inspection should also give indications of the changes of conditions for the inspection itself: changes in access, illumination, personal safety conditions, etc.

2.2.3 Seepage

Seepage monitoring systems should be considered as a basic and indispensable part of a dam monitoring system and as mandatory for dam safety. In addition to and independent from these measuring systems, visual inspections can be very effective to detect seepage either directly (e.g. surfacing seepage water) or indirectly (e.g. vortices nearby the upstream face or changes in vegetation).

In concrete dams seepage occurs in most cases through joints and cracks, at the contact with the rock and at poorly constructed joints. In embankment dams inspections should be made particularly to determine if seepage occurs on the downstream slope and at the contact with the rock mass (see tables 2.1 and 2.2).

In case of evidence of new seepage flows or significant increase in flows, the immediate notification to the person in charge is necessary. The quantity of the seepage flow should be estimated. At embankment dams a first check of the existence of material transport has to be done. Checking turbidity of the seepage water is recommended. In some cases and under particular circumstances, it may be useful to measure the temperature of seepage water.

For these preliminary checks within the scope of the visual inspection, tools such as measuring cylinders, stopwatches, measuring tapes, hoses, buckets and water temperature gauges can be helpful. Digital photographs and sketches should record over time the location and condition of changes that might be signs of seepage.

2.2.4 Displacements and deformations

Displacements and deformations of the dam body are critical indicators of dam stability. Early detection of such irregularities is necessary (see tables 2.1 and 2.2).

The geometry and location of any noticed sign of unusual displacements or deformations have to be inspected and recorded. If a significant change is being identified, the responsible engineer has to be informed immediately. Digital cameras, pocket rulers, measuring tapes, thickness gauges, hand levels, poles, plumb bobs and binoculars can be useful.

2.2.5 Cracking

In concrete dams cracking induces water leakage and weathering and disrupts the transmission of stress, having serious impact on the stability and impermeability of the dam. Crack widths vary according to the temperature distribution in the dam body. Special attention has to be given to construction joints between old and new concrete. Within the scope of the visual inspection, the occurrence of new cracks should be recognized. Typically, such a regular check is restricted to accessible or critical areas of the concrete structure. In case of a new or widening of existing cracks a detailed inspection should be undertaken.

Visible cracks in embankment dams indicate differential settlements of the dam body, which can cause serious seepage problems affecting the dam's safety. Cracks have to be recorded thoroughly. In case of evidence of new cracks, the responsible dam engineer has to be informed immediately.

2.2.6 Erosion, weathering and clogging

Erosion, once started, tends to progress rapidly in areas exposed to flowing water. Efforts should be made to discover early the existence and progress of erosion. In overflow sections, piers, aprons and sediment flushing sills, concrete is worn off by sand and gravel carried in the water or through cavitation. Special attention to wear should be given within the scope of visual inspections after the release of large quantities of water over a long period.

Weathering is driven by such actions as alternate freezing and thawing, wetting and drying and possibly also by sun radiation. The degree of weathering of concrete, asphalt concrete and all other materials, including the rock covering the surfaces of embankment dams, depends on the physical and mechanical characteristics of the material, construction control, maintenance, number of years in service and climate. Weathering can affect the impermeability and mechanical stability of the dam.

Drainage systems tend to clog with physical, chemical and biological materials, such as soil particles, salts and bacteria, which originate in seepage water.

Within the scope of visual inspection, visible signs of wear, weathering and chemical reactions degrading the concrete (e.g. loose material, cracks or color changes) and clogging of drainage pipes have to be recorded. As a result of critical observations, a detailed technical investigation of the structures should be undertaken. Typically, such an investigation will be done in the course of the next dam inspection. In some cases (e.g. increase of seepage rate, turbidity of seepage water, etc.) an immediate action is required.

2.3 Special Inspections / Ad hoc Inspections

Special inspections are indispensable in case of unusual conditions (e.g. significant increase of seepage flow, after earthquakes, after large flood events and storms), for dam safety purposes and within the scope of periodic inspections (Figure 1.1). Additionally special inspections are necessary, when an unusual condition is found at visual inspection or detected by a dam monitoring system.

Special inspections should be more comprehensive than the (regular) visual inspections and should be performed by qualified and experienced engineers. They are not part of the regular visual inspections.

Depending on the size of the reservoir, the importance of the stored water, the availability of deep outlets and other such matters, provisions for drawing down of the water level can be considered an adequate measure to get access to important structures of the dam on the upstream side.

Ad hoc inspections are performed to investigate the state of the dam, for example:

Underwater Inspections

- Remote observation vehicles (small submersibles with cameras)
- Diving
- Sonar sensing

Inspection of structures without direct access

- Camera remote control and fiber scope (e.g. inspection of drainage pipes)
- Abseiling (e.g. by using ropes from the crest)
- Digital imaging

2.4 Frequency

The frequency of visual inspections depends on the dam’s size, importance and potential consequences. A meaningful system of classification of dams according to these aspects should be used for the scheduling of inspections.

Visual inspections may be conducted daily, weekly or monthly for the different components of dams and appurtenant structures.

As a general principle, visual inspections should be performed at least on a weekly basis for large dams in densely populated areas.

Additional specific inspections are necessary on an area around some abnormality, when it is found at a regular inspection or detected by a dam monitoring system.

Special inspections which require daily or even more frequent controls might be necessary under flood events, earthquakes, storms and other extreme natural conditions or unexpected operating conditions

3 Checking and testing hydro-mechanical equipment

3.1 General

Outlet works such as bottom and intermediate outlets and spillways are essential facilities for safe dam operation. Functioning of these outlets and of gated spillways depend primarily (but not only) on the performance of their moving parts, which are classified as hydro-mechanical equipment.

It is vital for dam safety that these facilities can be operated – opened and closed – under all circumstances whenever needed. It is vital too that the gates remain as they are under all other circumstances.

Malfunctioning can lead to disastrous accidents as evident from literature. To ensure that the facilities will operate reliably and safely, an appropriate program for checking and testing them is indispensable, in fact over the whole period of dam operation and not just once after their installation.

The following sections give some general recommendations concerning the procedures for checking and testing of the hydro-mechanical equipment of these facilities, to minimise the risk of malfunctioning. The details, however, will always depend on the prevailing circumstances.

Points which are not addressed, but which are also of paramount importance are organisational aspects e.g. responsibilities, communication, training of the personnel, access to the site, etc.

3.2 Outlets

Usually, bottom outlets are equipped with stoplogs and trashracks at the intake structure and two gates. One gate for operation (service gate) and a second one upstream for maintenance. The maintenance gate should also perform the function of an emergency gate; this means, closing against flow should be possible. During normal operation of the reservoir, the service gate is closed and the emergency gate open – completely or at least a few centimetres.

Checking of the structural, mechanical and electrical parts of a bottom outlet can be classified as:

- inspection of those parts which are accessible during normal operation of the reservoir,
- inspection of the section which is usually under water and
- detailed inspection and maintenance of the mechanical and electrical equipment

Inspection of the accessible sections shall be carried out periodically by the dam attendant and at least once a year by the operator and the engineer responsible for dam safety. The annual inspection usually takes place in the course of testing the gates. It comprises inspection of the valve chamber, the equipment, service gate from downstream and outlet channel including the arrangement for energy dissipation and aeration.

Inspection of those parts which are under water during normal operation can be carried out either with divers and video inspection, when the stoplogs are installed or when emptying the reservoir e.g. in the course of flushing out sediments. The period of this inspection depends on the prevailing circumstances, 10 to 15 years seems to be appropriate for many cases. Points of specific interest are: sedimentation around the intake, trashrack, stoplog, intake channel, gates.

Detailed inspection and maintenance of the mechanical and electrical equipment requires disassembling them. The point of time for undertaking this depends on the results of inspection and performance during testing. At least about 40 years after installation, a closer inspection of the equipment seems advisable.

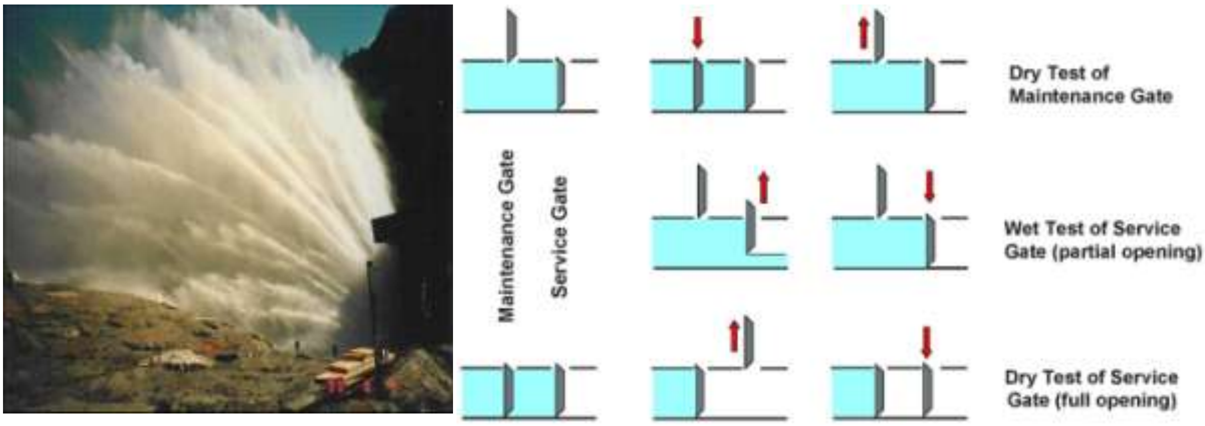


Figure 3.1 Typical procedures for the testing of outlets.

Testing of the hydro-mechanical equipment could follow a procedure as illustrated in Figure 3.1 with the following steps:

- "dry" test (without water discharge) of both gates over the whole lift of the gates,
- "wet" test (with water discharge) of the service gate,
- restore to the initial condition.

The normal power supply as well as the emergency power system should be utilized for gate operation and, if foreseen, also manual operation should be employed. The tests should be carried out at a reservoir water level as high as possible.

Tests once a year seem to be appropriate for many cases. Most of the wet tests can be limited to a small amount of water discharge. Full opening of the bottom outlet is, however, desirable at least once every five to ten years, provided no flooding is provoked at the downstream river bed. If the downstream river bed is dumped with snow and ice during the winter period, at least once a test under such unfavourable conditions should be carried out. A check of the downstream riverbed with regard to people in endangered zones is mandatory before each wet test.

For bottom outlets which can be operated from remote control centres, the tests should include checks of communication between control centre and site. Weak points could be identified by analysing the system and testing it as close to reality as possible.

At least the following items from a test should be recorded:

- date, time and reservoir water level
- test procedure
- required oil pressure or consumption of electricity for starting opening and during opening and for closing the gates
- time needed for gate operation
- amount of water discharge, or percentage open
- particular observations e.g. color of water, vibrations, noises, aeration.

It is advisable to create check-lists for the inspections and tests. In general, the inspections and tests should be carried out by the personnel familiar with the facilities and their whole history. In addition, it is wise to have outside experts inspections from time to time – about every five years.

3.3 Gated spillways

Gated spillways are inherently less reliable than free flowing spillways. On the other hand, they provide some flexibility in the handling of floods. Besides proper design and construction, regular inspection, testing and maintenance of the gates and their equipment is mandatory for dam safety. To be able to maintain the gates under dry conditions, gated spillways should always have facilities to install stoplogs upstream of them.

The strategy for checking and testing the facilities depend, of course, on the type of gates and other circumstances such as power supply, operating programs, etc. Many points mentioned above for checking and testing of bottom outlets also apply to spillway gates. In the following, only those points that are specific to spillway gates are mentioned.

In the case of floods, gate operation has to follow specific procedures, which have to be developed in advance and the persons involved must be aware of them. These procedures depend on real-time input data, the most important one is the reservoir water level. Therefore reliable data acquisition and processing is important. The possible sources for incorrect data should be analysed and appropriate tests should be conducted. Indicators for gate position are also key elements, especially for the case of operation from remote control centres.

Sometimes gate operation is automated. In these cases, not only the input data but the whole process of gate operation has to be analysed and tested. Very critical are black-box solutions for gate operation without a simple backup system.

A further point to be looked at is the danger of clogging of spillway sections by debris and the performance of the gates when loaded by debris. Formation of ice is also a matter which has to be taken into account.

Regular inspection carried out by the dam attendant should focus on floating debris accumulated near the gates, accumulation of materials in gate grooves or chain links, the state of the mechanical and structural elements, and of pipes and sealing parts. Frequency should be about once a week.

Inspection after a flood event should pay special attention to damages to structural and mechanical elements, deterioration to chutes and stilling basins, state of rockfill protection, deposited materials and floating debris.

Periodic tests and inspection by operators shall be carried out at least once a year. The tests should comprise operation of the gates, testing of the automatic monitoring system including triggering of alarms, as well as testing of the emergency power supply units. The inspections should cover all the mechanical and electrical parts of the gates themselves and the sealing parts, the bearing elements and the mechanical and electrical components for operation.

3.4 Power supply and telecommunication

Reliable power supply is crucial to the safety of most dams. Power supply is necessary for the operation of gates and valves, the automatic monitoring system, telecommunications, lighting, transportation facilities, etc.

In general, dams are equipped with a primary system and an independent emergency system for power supply. The emergency system may consist of an independent line of electricity supply, a stand-by unit at site or installations for manual operation.

Important points to be checked are:

- Capacity of systems (primary and stand-by) in comparison with required power for example operation of hydro-mechanical equipment. How many gates or valves can be operated at the same time?
- In the case of two lines of electricity supply: How independent are these two lines? Where are the weak points?
- In the case of a stand-by unit: Where is the unit? How many persons are necessary to operate?
- For manual operation: Installation for manual operation, required time and persons for operation, access to the site, emergency lighting.

Stand by units should be tested and maintained regularly – testing for example four times a year. Gate operation with the emergency system should also be tested – for example once a year in the course of the general annual tests.

Telecommunication from the dam site to for example the control centre is necessary for:

- Transmission of data – measuring values and messages – from the automatic monitoring system
- Messages from the protection system against vandalism and terrorists and also for lone workers
- Transmission of pictures from video cameras
- Remote operation of gates and valves
- Communication between persons.

The communication line between site and control centre should be redundant, at least for significant sites. The availability of the public handy network is already very high in many regions, but it might be insufficient, especially in the case of extraordinary events. Therefore, tests on a quiet and sunny day are not representative for emergency situations and this has to be kept in mind when assessing the communication system.

Communication between persons requires not only reliable communication lines but also updated telephone numbers available where they are needed. Safe communication also needs persons who are familiar with the situation and who know exactly what to do. This can only be expected, if people are trained and not overloaded.

If remote operation of gates and valves is possible; tests should cover remote as well as on-site operation.

In general, testing and checking of the communication system depends strongly on the individual situation. It should cover not only the reliability and availability of the installations, but also the human component.

4 Monitoring parameters and devices

4.1 Basic concepts

4.1.1 Monitoring phases

The dam monitoring system is a measurement system, which if well conceived, allows the effective monitoring of the behavior of a dam and its foundation subjected to the applied loading conditions. Checks are necessary first during the construction phase of the dam, the first filling and finally during ongoing operation in order to detect any signs of abnormality and take action promptly.

The analysis of the obtained data gives an appreciation of the dam’s short and long term behavior. This analysis is absolutely necessary to complete and improve the understanding of the engineer.

Moreover, the collection of data related to the surroundings of the dam such as the weather conditions, hydrology, stability of the terrain, the risk of avalanches and falling ice, is also part of the monitoring of water retaining structures.

4.1.2 Layout of monitoring devices

There is no rule establishing the number of monitoring devices that are to be installed. This number varies according to the type of dam and its dimensions, the mode of construction, the age as well as the conditions specific to the site, in particular those related to the foundation. The experience acquired in the domain of water retaining structure behavior analysis must also be taken into consideration.

The monitoring systems need to be designed in such a way that it is possible to measure loads such as the hydrostatic pressure and the temperature which act on the structure (causes) as well as the different parameters (magnitudes) that characterize the behavior of a dam (consequences). The direct loads and external conditions will create not only deformations and temperature variations, especially in the dam body, but also hydrostatic pressures (uplift, pore pressures) and seepage (water infiltration).

4.1.3 Parameters measured by monitoring devices

The main parameters that are usually monitored for embankment and concrete dams, including their foundations, can be found in table 4.1.

Table 4.1: Significant parameters for the monitoring of the behavior of the dam and its foundations

Concrete Dam	**Embankment Dam**	**Foundations**
Structural deformations	Deformations of the dam body	Deformations Abutment movements
Special movements (cracks, joints)	Special displacements (links with a concrete structure)	Special displacements (cracks, diaclases)
Dam body temperature	Dam body temperature to detect seepage (possible)	Dam body temperature to detect seepage (possible)
Uplift pressures (Contact concrete-foundation and in the rock)	Pore pressures in embankment dam body and piezometric level	Pore pressures Deep body uplift pressure Piezometric level Phreatic line level
Seepage and drainage rates	Seepage and drainage rates	Seepage and drainage rates and resurgences (sources)
Chemical analysis of seepage water Turbidity (possible)	Chemical analysis of seepage water Turbidity	Chemical analysis of seepage water Turbidity

The monitoring system must be adapted to the particularities and the importance of the dam. Its design must take into account the fact that the structure and its foundations form a whole. Nevertheless, the system must clearly allow the behavior of one or the other to be distinguished. The monitoring system is not inflexible and it is necessary to check it regularly to make sure that it is still suitable. If not it will be supplemented, adapted or even modernised.

The monitoring system should be extensive enough so that in case of abnormal behavior, useful data could be recorded in order to find the causes of the problem. The installation of supplementary instrumentation may prove necessary.

4.1.4 Instrumentation characteristics

It is essential to choose the measuring instruments very carefully taking into account the different parameters to monitor, the construction technique and the technical installation possibilities. The monitoring equipment is chosen according to the needed measuring range. It should be remembered that some measurement instruments can obtain more precise readings than what is actually needed. It is important to make sure the instruments are installed correctly in order to ensure a high reliability of the readings which is a condition for adequate interpretation of the results.

Priority must be given to instruments that are:

- simple in their concept and use,
- robust,

- not sensitive to outside conditions (temperature, humidity, current overloading),
- long-lasting (longevity is essential especially for instruments that are integrated in the dam body during construction),
- precise,
- reliable, and
- easy to read.

If the instruments are not integrated in the dam body, they must be of easy access and replaceable. When replacing an instrument, it is essential to ensure continuity in the measurements. Also to prevent a breakdown or malfunction, it is advised that the system, as far as possible, is sufficiently redundant. It is also useful to cross check data using two different methods of measurement (for example, pendulum – polygonal, settlement gauges – leveling).

4.2 Measuring External Load parameters

External loads (especially hydrostatic pressure) directly affect the dam. The outside conditions affecting the dam are mostly atmospheric conditions on site (ambient temperature for example).

Hydrostatic pressure being an important load, the changes in the reservoir water level must be read and recorded even if the reservoir stays empty most of the time as it is in the case of detention ponds. The measuring range must extend beyond the dam crest in order to follow extreme values of the water levels in case of floods. Moreover, water temperature is also a parameter to record.

In case of important sedimentation (changes in the loads, marked decrease of useful volume, risk of blocking outlet works), it is necessary to check their level regularly. Bathymetric readings could be performed in this case, as often as necessary according to the amount of sediments accumulating.

The atmospheric conditions (temperature and air humidity, rainfall, snow) are equally important data. The ambient temperature has an important effect on the deformations of a concrete dam. The variations of temperature in the body of the dam can be monitored by temperature sensors placed directly in the dam body during the concreting. They are installed at several elevations and distributed across the thickness of the concrete section. The thermometers situated close to the surface are extremely influenced by the local external conditions (air and water).

It is recommended to record if precipitations fall as rain or snow. Finally, it is necessary to note that precipitations and the melting of snow sometimes have a direct influence on the infiltrations within the foundation, as well as on uplift pressures.

In some cases, seismic monitoring at a dam site is recorded.

4.3 Measuring Response parameters

The objective is to know the horizontal and vertical displacements at a given point. According to the dam configuration (with or without galleries and/or shafts), measurement points are located at different elevations and inside the dam or fixed on the downstream face following horizontal and vertical lines. If possible, the measurement axes are extended into the rock to also ascertain the foundation deformations. The devised network thus allows horizontal and vertical deformations of the structure to be obtained. For small dams, it is at least necessary to foresee the measurement of crest deformations.

Horizontal deformations (radial and tangential deformations) can be determined along vertical lines by direct and/or inverted pendulum measurements. In the case of a new inverted pendulum, the drilling techniques currently in use allow the verticality to be guaranteed. The possibility of sliding an auto-centring guide wire along the length of a slotted tube also exists, which allows measurement points to be established at different elevations. This solution has been successfully applied as a complementary monitoring device by installing an inverted pendulum in the foundation and in a dam which has no control galleries and shafts. Angular and distance measurements (vector measurements) taken on external targets, just as alignment sightings, are simple geodesic methods used to measure deformations on small structures. Horizontal deformations can also be determined by wire alignment which can be installed in a straight horizontal gallery or along a parapet which is equally straight.

Leveling allows vertical movements to be ascertained (settlement or heaving) of the structure. Local deformations, for example those of the upper part of the dam, can be determined by the installation of extensometers. Measurements taken by inclinometers (with possibility for automation) allow the actual deformation to be calculated or compared with the pendulum measurement.

Concrete dams are not exempt from cracking and even though visual inspection of cracks and logging on paper may be sufficient, it is suggested to monitor the opening of certain cracks using for example micrometers, joint meters or deformation meters. At the very least, it is possible to place telltales (with cement mortar) across the crack; however, this solution is not optimal. Besides, pins are also placed to measure the joints of the structure.

4.3.1 Monitoring of embankment dam deformations

For embankment dams, the objective is firstly to know the evolution of vertical deformations (settlements) and horizontal deformations at the crest, but then also if possible, settlements at various elevations, and in particular settlements in the foundation. Inclinometers with settlement plates are mainly used for this purpose to obtain three dimensional deformations relative to the crest or the foundation. In general, horizontal displacements of points are determined by geodesic measurements such as angular and distance readings (vector measurements), alignment sightings and polygonal surveys. Concerning vertical displacements (settlements or heaving), leveling as well as settlement meters or hydraulic settlement gauges are used.

4.3.2 Monitoring of foundation deformations

Extensometers allow rock foundation measurements to be carried out according to the different directions. The choice and orientation of the instruments will depend on the geology and on the direction of the forces notably transmitted in the case of arch dams. To better ascertain foundation deformations, it is recommended to place extensometers in at least 2 directions or to create a tripod. An extensometer can contain up to 6 bars of different lengths in the same drill-hole. In particular cases, bore-hole deformation instruments can be used to measure deformations in three dimensions, typically at one meter intervals.

Precise horizontal measurements in two directions (for example upstream - downstream, left bank – right bank), can be carried out using an inverted pendulum (perhaps equipped with an auto-centring guide-wire that allows measurements at different elevations) or an inclinometer.

Leveling, settlement gauges and hydraulic settlement cells are among the available techniques that can be used to measure settlements in soft ground.

Abutment movements can be monitored by means of geodetic surveying.

4.3.3 Geodetic deformation measurements

Inherently only relative deformations can be obtained and they must be completed by using a local reference space (geodetic network) to which it is connected. Thanks to the geodetic network, it is possible to measure the displacement of benchmarks with respect to a network consisting of (assumed) fixed stations or reference points. This method presents the advantage of determining the “absolute” displacements.

An extended network can be coupled to the local geodetic network whereby points could be measured by means of GPS (Global Positioning System). The GPS offers an appropriate method that can be integrated to the control network consisting of points which are geologically stable and situated outside of the influence zone of the reservoir basin. The incorporation to existing geodetic networks can be realised with the conventional terrestrial method or the GPS. The combination of the GPS with terrestrial geodetic measurements constitutes a hybrid network.

With respect to the survey network triangulation and/or trilateration), the installation of fixed points outside the zone of the dam requires collaboration between the surveyor, engineer and engineering geologist. Network points shall be installed both upstream and downstream of the structure.

Control or measurement points could be installed on the crest, in galleries and/or on the downstream face of the dam, as well as on the terrain. It is sometimes useful to incorporate pendulums and the heads of extensometers in the geodetic survey network. When pendulums are incorporated in the survey network the accuracy of the measurements increase but the redundancy (independent checking of the results of the two systems) may be lost.

Deformations can be obtained by distance and angular measurements (vector measurements) and by alignment. The polygon gives information relative to the planar displacements.

Leveling allows vertical displacements to be determined. We distinguish precision leveling (direct measurement of the difference in elevation between 2 points) and the topographical leveling (angular measurement between 2 known points). It is recommended to extend the development of the leveling scheme as far as possible downstream of the dam as well as along the upstream banks. The equipment consists initially of a theodolite, levels, distance meters and then accessories such as targets, reflectors, optical plumbs, backsights, invar wires etc.

4.3.4 Seepage rates and drainage

The hydrostatic load provokes seepage infiltrations across the water retaining structure and the foundation.

In the case of concrete dams, seepage rates remain in general concentrated along zones where the concrete is less watertight. Water can in particular find preferential seepage paths for example across vertical joints and horizontal construction joints as well as at the contact between concrete and rock. Seepage within the foundation creates uplift pressures the evolution of which must be followed attentively since the influence on the stability is not negligible.

For embankment dams, seepage similar to that in ground develops because the materials of construction used are more or less permeable. Seepage through and under an embankment dam are at the origin of interstitial pressures which take on a primordial importance for the stability of the structure. Water infiltrations must therefore be closely monitored since each deviation from the normal state represents an evolution of interstitial pressures that could place into question the safety of the water retaining structure.

The seepage rate varies according to the reservoir elevation and it can also be influenced by atmospheric conditions and the melting of snow. The total water discharge rate gives an indication of the global behavior of the infiltrations. The layout of measurement stations is delineated such as to measure partial discharges for predefined zones. This procedure allows, in the case of anomalies, to localise the critical zone and to investigate the causes.

For concrete dams, water infiltrations are directed to gallery channels and then towards discharge measurement stations. Seepage water from embankment dams can be collected in drains situated downstream of the core or at the interface of an impermeable membrane and from the body of the dam and directed to a discharge measurement station.

The discharge rate of seepage and drainage at the outlet can be measured by volume (with a bucket and stopwatch), by a calibrated weir, a venturi or by variation of water head in a tube. A reduction of discharge can indicate a clogging of drainages.

Paying attention to temperature distribution readings along a fiber optic cable also allows leakages within the interior of the embankment dam or behind a membrane to be detected. Seepage flow rates can in some cases be estimated by thermal analyses of measured temperatures.

For embankment dams consisting of materials that are erodible or that are based on such materials, it is also desirable to proceed with regular checks of the turbidity and periodic chemical analyses of seepage water. Turbidity measurements allow an estimation of the content of fine particles; as for the chemical analysis, this gives information relative to dissolved materials (for example, those coming from the grout curtain).

The discharge of water within the foundation of the structure as well as water originating from drainage drill-holes or drainage galleries, are equally measured. These readings, jointly with those of uplift pressures, give information relative to the state of the grout curtain and the efficiency of the drains. A reduction of the discharge can indicate a clogging from the reservoir or also the drainage system.

Resurgence discharge readings downstream must also be carried out since a variation of discharges can indicate an anomaly in the underground water circulation network. Volumetric discharge measurement can be made perhaps using a calibrated weir.

Finally, the reading of the fluctuation in the level of the phreatic surface is sometimes suggested (for example downstream of the embankment dam). Level readings can be carried out using a calibrated probe which is lowered into an open drill-hole or by the use of a pressure sensor with recording device.

4.3.5 Pore pressures and piezometric level

In an embankment dam, it is important to check the evolution of pore pressures (in particular in the core and the foundation). The pore pressures must not exceed the values allowed in the design. Measurement can be achieved by placing and monitoring pneumatic, hydraulic or electrical pressure cells. The monitoring will be improved with the increasing number of measurement profiles as well as the number of cells per profile. This provides a certain level of redundancy which is justified because of the high level of failure of cells.

We can simply control the evolution of infiltrations, such as the equipotentials, at given points. Hence, we use a tube in which we read the height of the piezometric head. When these tubes are installed in permeable soil, the measurements are reliable and durable. If on the other hand, these tubes are found in impermeable terrain, a time delay which is relatively long is necessary before noting a change in the piezometric level; this is due to the displacement time of the volume of water in question. In such a case, closed piezometric cells are more appropriate.

Pore pressure changes in clays or rock imply very small water volume changes and diaphragm piezometers such as vibrating wire piezometers are much better suited for this objective as they respond to extremely small water volume changes, in the range of less than 0.001 cm^3 for the full measurement range of the transducer.

4.3.5 Uplift pressures

The construction of a grout curtain and sometimes drainage drill-holes allow these uplift pressures to be limited in the design and this is why the efficiency of these measurements must be checked. Uplift pressure, of which the values usually vary as a function of the reservoir water level, are measured at the concrete-rock interface and in certain cases, at different depths within the foundation. Uplift pressures vary from upstream to downstream and it is desirable to distribute several measurement points along the base of the concrete structure and if possible at the intersection of several sections.

The measurement of uplift pressures at the concrete-rock interface can be made using a tube equipped with a manometer or pore pressure gauges. As the rate of water infiltration is slow, despite the important pressure slopes in question, the effective pressure will only sometimes be reached after a long period (days or months). To avoid erroneous measurements, the tube-manometer system must be continually maintained under pressure and air relief device.

4.3.6 Other measurements close to the reservoir

A flood event can lead to scouring at the dam toe which could compromise its stability. Topographical or bathymetric readings carried out periodically (every 3 to 5 years) or following an exceptional flood event allow the shape and the depth of the scouring to be determined.

In certain cases, it is imperative to monitor the development of unstable zones that could, during a slide, create a wave in the reservoir and consequently the possibility of overtopping of the crest. The significance of potential slides determines the level of monitoring and type of instrumentation. Several options are available and these devices are still being refined (see chapter 8).

Furthermore, important ice falls that could reach the reservoir can equally constitute a risk of overtopping. The monitoring of glaciers can be carried out using photogrammetry or direct deformation measurements according to the specific techniques.

4.4 Measuring Structural Integrity

Geophysical methods have found a use in the geotechnical investigation of water retaining structures (both embankment and concrete dams). Several of the methods are mentioned in the Annexure.

For in situ stress measurements the over-coring method is widely accepted. Depths of cracks are typically estimated by means of ultrasonic methods. Approximate values of concrete strength and elasticity parameters can be determined with the Schmidt hammer.

Cores drilled for test purposes may be valuable at a later stage (i.e. for long-term monitoring). These cores should therefore preferably be stored inside the dam under similar conditions so the in-situ concrete/RCC is readily available for tests.

4.5 Available Instruments

Tables that summarize the various types of devices available to measure the different measuring parameters are included as an Annexure.

5 Automation

5.1 General

Automated monitoring systems provide the engineer with a powerful tool that, when used properly, can contribute immensely to the construction and operation of safe dams of all kinds. Dam monitoring includes the successive phases of acquisition, transmission, treatment and analysis of data. Automation can be applied to the first three phases, while the analysis requires the judgement of engineers and technicians specialized in dams.

The dam owner who decides to automate the dam monitoring process must both define very precisely the objectives and assume the need of a more specialized technical service for the system maintenance and behavior evaluation. Experience shows that to make good use of the advantages and capabilities of an automatic system, three circumstances must coincide:

- A good automation project that clearly defines the aims.
- A preventive and corrective maintenance service with short response times.
- A technical service, headed by an engineer expert in dam safety, for continuous analysis and interpretation of the information generated by the system.

The operation of an automatic monitoring system can cover the following periods:

- Construction.
- First impoundment of the reservoir or first operation.
- Normal operation of the reservoir.
- Extraordinary event.

The project for an automated monitoring system involves the participation of a multidisciplinary team (civil engineers, geologists, electronic and IT specialists, etc) with expert knowledge and wide experience in design and operation of similar systems for the acquisition, transmission and treatment of electric signals.

ICOLD Bulletin Nº 118 (“Automated dam monitoring systems, guidelines and case histories”) deals with the subject in a very detailed way including information about the technological development and experiences obtained from case histories and is addressed to those who carry out an automatic data monitoring project.

5.2. Objectives

The main purpose of dam surveillance is to detect anomalies, by attracting the attention of the responsible persons as soon as possible, in order to take preventive measures to preserve lives and property. In this context, automated systems can contribute to a faster and more efficient response to the evaluation of dam safety.

It is essential for the owner to define the reasons for which he wishes to automate monitoring procedures. Automation is not adequate in itself, because the only objective reason for installing an automatic and remote monitoring system is to improve the quality and reliability of a classic monitoring system.

The main reasons for automated dam monitoring systems, their advantages but also limitations to be taken into account, are shown in Table 5.1.

Table 5.1 Objectives, advantages and limitations of automated monitoring systems

Objectives	Advantages	Limitations
– Dam access difficulty. – High risk dams. – Integration of monitoring data into existing communication networks. – Implementation of emergency action plans. – Reduction of manpower for data reading.	– Avoids access limitations linked to the weather conditions. – Provides specific monitoring with a large number of measurements and a high reading frequency in case of anomalous behavior of the dam. – Reduces operation problems of the crew during unforeseen incidents. – Increases flexibility in selecting the required data, ease in varying the reading period and data recording. – In very large dams there is an important reduction of measuring time and faulty readings due to human error. – Improvement of the accuracy and quality of data due to a higher frequency of readings. In addition the recording and reading errors will be fewer and more easily detectable. – Quick conversion and adjustment of measurements in technical representative values. – The system could be used to trigger alarms or initiate a remote warning message if values are out of the	– The qualified dam personnel spend less time at the dam with the consequence that regular visual observations will not be performed. – The obsolescence of the electronic equipment due to rapid technological progress requires a continuous update of the electronic devices for communication as well as of the hardware and software products. – The possibility of generating excess data, encouraging a “file and forget” attitude and therefore failing the early detection of anomalies or blindly accepting the validity of data. – The high initial implementation cost and standing costs for maintenance carried out by specialized staff. – The need of regular field checks and maintenance

	permissible range. – Easy visualization and presentation of obtained data either by an operator or automatically and previously programmed. – Allows a quick incorporation of new processing methods of the existing information. – Instantaneous data transmission of the processed information to the control centre. – Local memory availability to store a large amount of information in case of seismic activity. – Remote real time access to all the information, allowing a faster and more specialized analysis about the safety of the dam. – There are control parameters that might be checked exclusively by means of automatic systems, for example the dynamic behavior of structures which are located in seismic zones.	by specialized staff in the fields of computer, electronic and communication technologies. – The need for a reliable and continuous source of power. – A higher vulnerability of electronic and communication equipment during adverse weather conditions.

5.3 Architecture of Automatic Monitoring Systems

Usually solutions for automated dam monitoring systems are based on distributed control architecture.

In general, these systems consist of:

- A sensor network. Its function is to support the automation system with all data recorded by the sensors and instrumentation.
- The distributed peripheral equipment. These are control elements located close to the sensors that, with higher or lower degree of intelligence, centralize, digitalize and transmit the information from the field instruments to the control station.
- The Field Bus. Term used for designating all elements that participate in the transmission of information between the distributed periphery and the control station. Among them, transmission media (fiber optic and metal cable, radio), communication protocols and media adapters can be pointed out.
- The Central Control Station. Its functions depend basically on the intelligence level of the distributed peripheral equipment, but in general it acts like a “master” of the existing Field Bus through which it receives the data from the

sensors. In addition, usually the Central Control Station provides all functions for the supervision, control and acquisition of the data (SCADA) that is necessary for real-time management of the monitoring system.
- The Data Processing Center (DPC). Connected to the Central Control Station in a local or remote way, forms a client/server architecture that permits access of multiple work places and provides the services of recording, management, processing, visualization and analysis of the monitoring data required by the engineer.

5.4 Number and types of instruments to be automated

The complete automation of a dam monitoring system may involve a significant cost. For that reason it is recommended to classify groups of instruments with different priority on the importance of anomalies to be detected.

- Detector instruments: To define with a potential failure mode analysis such as internal erosion, instability caused by uplift pressures, etc. In case one of these instruments initiates an alarm, selected sensors can be activated automatically by the system to perform frequent readings in order to confirm and follow the evolution.
- Support instruments: Dedicated to carry out measurements that are less relevant for a quick overall safety assessment. Their readings are not used to generate real time alarm signals. In this group are the ones installed to verify design assumptions, to monitor ageing processes or to follow the first impoundment. The results of the readings have to be analyzed periodically.

The design of a monitoring system should contemplate the redundancy of the most important sensors and control devices. This applies specially to the key points (detector instruments), in order to guarantee the data acquisition and the viability of data processing and analysis.

5.5 Limits for alert and alarm values

Automated systems allow changing the data acquisition frequency, the error detection and mainly the threshold definition for different control variables used for sending out alert and alarm warnings. Thresholds must be established as a consequence of previous detailed studies supported by deterministic or statistical behavior models. Validation and evaluation of possible alert or alarm messages must be performed by an expert.

Another fact to be considered is that the behavior of structures, including dams, is not constant with time, so frequently irreversible effects are reflected in derivations of the temporal trend of control variables. Due to this fact the threshold values must be revised periodically.

Alerts must be considered as early warnings that are sent out by the system when a change from the usual behavior is detected and must be interpreted by the responsible dam safety team.

For example, in every structure there may be different warning levels which will allow alerting the responsible team about any deviation from the normal functioning or the one expected due to previous safety investigations, such as:

- **Alert**
  The measured data is out of the expected range, taking into account the common changes due to cyclic or stationary loads.
- **Alarm**
  The maximum level forecasted by the engineering board whereby the safety coefficients for the structure are surpassed.

In any case it is necessary to establish procedures to check and validate the data before alarms are generated. The control parameters and measurement instruments that could be involved in the alarm system are, for example: pore pressures (piezometers), seepage (flowmeters), global deformations (pendulums) and local deformations (extensometers), etc.

6 Maintenance and ageing of monitoring systems

6.1 General

Every part of monitoring equipment has limited operating life or limited time of measuring reliability. Proper design, good installation, regular checking, testing and maintenance can prolong working life of each device.

6.2 Instrument consistency and data validity

Monitoring devices and visual inspection are sources of basic data for dam safety evaluation and dam performance monitoring. The amount of measured data or its quality can impact data evaluation accuracy, conclusions and decisions about dam safety. This should be taken into account during the design, construction and operation of any water retaining structure.

6.3 Maintenance, checking and testing of the monitoring system

The tasks of maintenance, checking and testing should be well defined for every system component. A detailed description of the series of activities to be carried out should be given in a specific operation and maintenance manual (O&M) including information on the following topics:

- Frequency of inspection.
- Maintenance and service tasks (cleaning, lubricating, disassembly, checking of energy supply, etc.).
- Performance test procedures.
- Calibration instructions.
- Trouble-shooting.
- Assessment of the operational readiness.
- Repair and replacement instructions.

Monitoring systems may be very complex, especially in case of automated data acquisition. The O&M Manual should cover all aspects related to each element. In general the following elements should be considered:

- The instruments for quantitative measurement of the control variables to monitor behavior of the dam and its foundation and to perform geotechnical and structural analysis. Every instrument must have a specific and well defined purpose. The majority of the instruments can be classified into optical, mechanical, hydraulic, pneumatic and electric devices.
- Reading units. Automated data acquisition systems may require additional sensors to convert the instrument measurement into an electrical signal.
- Data acquisition systems.
- Cabling and communication links.
- Data transmission and remote control systems.
- Data management systems.
- Power supply systems.
- Protection systems against high voltage induction and lightning.

The system elements can be classified into three groups: portable readout units, retrievable components and elements embedded in the dam body or the foundation. The latter ones are usually inaccessible and maintenance tasks cannot be carried out.

The frequency of the maintenance tasks depends on the complexity of the system and its components. It is important to establish a regular frequency. As a general rule manual systems should be checked at least once a year and automated systems at least every six months.

Maintenance tasks must be carried out by experienced personnel to ensure a reliable system operation and to avoid damaging or destroying the instruments. Special attention must be given to maintenance of hydraulic circuits and to electronic devices. The intervention of specialists may be required for different systems (electrical, electronic, pneumatic, hydraulic, mechanical, optical, etc.). The quality of maintenance works depends strongly on the professionalism, training, vocation and motivation of the personnel involved as well as on paying attention to details. The technicians in charge of data management and analysis should supervise and check the maintenance tasks and if necessary notify operation problems, deterioration or damage. All the maintenance tasks must be carefully documented.

Automatic monitoring systems require specific testing procedures. First of all it has to be ensured that the digital value in the final data base corresponds to that at site. In addition, automatic measurements must be validated with manual readings at regular intervals wherever this is possible – and it is achievable for many types of instruments as for pendulums, extensometers, piezometers, seepage measuring weirs, water level transducer, etc.

An interruption in the automatic monitoring system – e.g. failure in an electronic unit, breakdown of energy supply, failure in data transmission, etc. – should always lead to alert message in the control centre.

An independent source of electricity should always be available. Within a specified time it should automatically provide reliable electric power to critical devices.

Threshold values which result in an alarm when exceeded should also be tested regularly. These tests should be carried out as realistically as possible – e.g. by impounding a seepage measuring weir to that height which corresponds to the threshold value. These tests should not only cover the installation at site but also the procedure which has to follow such an occurrence. That means, it should also be checked that:

- Signal is transmitted to the right place, e.g. the control centre.
- Person in the control centre gets aware of threshold alarm.
- Correct actions are carried out, e.g. information to dam safety engineer.

It is strongly recommended to create a technical file to register any relevant information relating to the monitoring system, such as the installation process, commissioning, maintenance, checking and testing, faults, repair and re-instrumentation works. A complete file about the history of the monitoring system and maintenance tasks facilitates the knowledge transfer in case of change of personnel.

Figure 6.1 shows the main aspects of a maintenance cycle of dam monitoring devices.

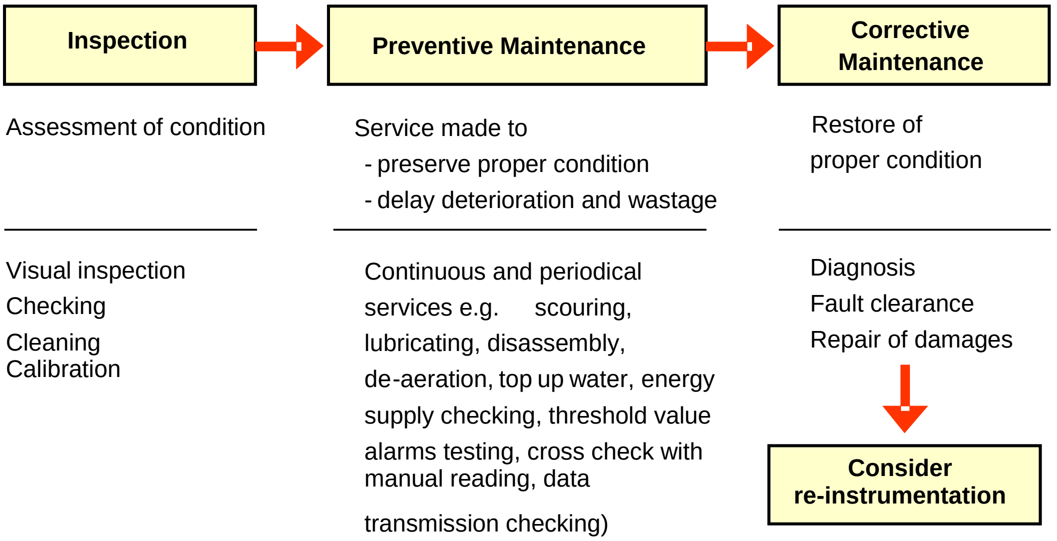


Figure 6.1: Maintenance cycle of dam monitoring devices

6.4 Calibration

Calibration of all measurement devices (including survey equipment) must comply with manufacturer recommendations and existing international standards for quality control and regulations such as ISO and others relating to metrology.

The devices must be regularly calibrated according to manufacturer's instruction manuals. Some devices may be calibrated in-situ; others require to be sent to the manufacturer for factory calibration, e.g. portable readout units. Components embedded in the dam body or the foundation usually cannot be recalibrated due to inaccessibility.

The manufacturers normally provide calibration devices or data quality control techniques for most of the monitoring instruments like invar gauges to check extensometers or manometric balances for manometer calibration, mercury barometers for contrasting electronic barometers used in micro geodesic distance measurements, etc. Some suggestions for suitable intervals are set out in Table 6.1.

Table 6.1: Suggested intervals for calibration of monitoring devices

Measurement instruments calibration	**Suggested intervals**
Calibration of coordiscope and dial gauges	every measurement tour
Cross checks of automatic and manual readings	four times a year
Calibration of pressure gauges	every two years
Comparison measurements of topographic instruments for micro geodesic survey	before and after each measurement
Check up in a polygon with fixed monuments	every 6 months
High precision total stations (calibration in factory - proper operation, data quality and stability)	every three years

6.5 Ageing and obsolescence

Ageing in general is a continuous process. Ageing of dam monitoring devices can lead to lower accuracy of measured data or even missing measured data (in case of failure of measuring device). Insufficient amount or lower accuracy of measured data for dam evaluation may cause inaccurate conclusions of dam safety assessment and lead to wrong decisions about remedial measures. In extreme cases it misses detection of a serious deterioration process that could cause dam failure.

Ageing (or malfunction) of dam monitoring devices depends especially on:

- Type of sensor (monitoring device) and principle of function (mechanical, optical, vibrating wire, ultrasonic, electrical, etc.).
- Quality of monitoring device (used materials, manufacturing procedures, sufficient range of measured loads, expected operating life and guaranteed precision in connection with design operating condition - sensors that incorporate internal electrical / electronic components and/ or delicate mechanical components are more liable to alter their features with time).
- Connection between sensor and reading point.
- Site conditions or stability of environment (ongoing construction works, unexpected displacements or pressures, aggressive water, extreme temperatures, stray electrical currents, biological impacts, vandalism).
- Process of placement of instruments into constructions (quality of instrumentation works, difficulty of instrumentation works, right position in construction).
- Regular maintenance, checking and testing of monitoring device.
- Extraordinary events (flooding, lightning strikes, military action, damages caused by operating staff or dam reconstruction works, etc.).

There is very little information about the importance of the ageing of instruments in the quality of data. The manufacturer's technical specifications indicate laboratory features and accuracies. The real operating conditions of the instruments tend to be very different and diverse, since they are subjected permanently to mechanical and hydraulic forces, temperature changes, exposure to water, etc.

The service life of dams usually exceeds several decades or even centuries. Therefore monitoring systems should be designed for long-term operation. The regular operations of maintenance and calibration of equipment along with the analysis of plausibility of the supplied data, allow the detection of abnormalities related to the instruments and sensors. For the components permanently accessible, as the portable readout units and retrievable components, repair or replacement allows re-establishing the proper operation. In case of embedded components installed inside the dam body or the foundations and therefore inaccessible, malfunctioning cannot always be remedied.

Ageing of dam monitoring devices is usually quicker than ageing of the monitored dam. At the end of operating life or in case of failure of monitoring devices there is a necessity of replacement. Change from old to new monitoring equipment may produce an inconsistency in the procurement of measurement data. Data obtained with the old and new equipment very often belong to two different basic entities even if measured simultaneously.

Proper selection of the monitoring devices is of particular importance and the following main principles should be considered:

- Monitoring sensors and cables must be of reliable quality (maximum longevity, guaranteed accuracy, etc.).
- Monitoring instruments are designed and placed in adequate numbers; a certain failure rate has to be taken into account (if there is no possibility to change the device, there should be redundancy).
- Location of instruments (and the cable routing) must be carefully selected, (i.e. cables should not pass through zones where shearing or excessive plastic deformations are expected).
- Placement of measuring instruments and their protection during the construction works have to be done with utmost care (checking and testing of installed devices before continuing construction works).
- Protection of measuring devices during dam operation – final placement with respect to future purposes (traffic, manipulation and operation staff corridors, etc.), site and environmental conditions.

In existing dams with monitoring systems in operation for many years, the likelihood of alteration of the data by the effects of ageing is greater, not only due to the time since its installation and commissioning, but also due to the lower quality of the instruments manufactured a long time ago. If the ageing process does not cause a total instrument failure but provides erroneous data, it can be detected applying techniques of analysis of plausibility.

When the results of the response of electric instruments, such as vibrating wire sensors and other types, are beginning to indicate slight changes and sustained in time, the possibility of having a problem of ageing which produces the relaxation of the sensor system should be investigated. In such cases and depending on the relative importance of the control variable it is essential to check by installing a new instrument in order to validate or rectify the measurements obtained.

Obsolescence mainly affects the automatic systems composed of electronic elements, communications systems and computer systems for the acquisition and management of the data. The constant technological innovation in this field obliges the renewal of hardware devices and software, usually because of lack of spare parts or because additional performance features are required (transmission and remote control, integration into other data management systems, etc.).

7 Re-instrumentation of existing dams

7.1 Existing versus new dam instrumentation

The monitoring demand at existing dams is similar to new dams. The monitoring parameters (loads, response and structural integrity etc) as well as the available instruments remain the same for both new and existing dams. The monitoring phases are however narrowed to the operation and for back analysis. The two main drivers for re-instrumentation are to restore the monitoring level at the dam or to obtain additional information. The re-instrumentation can be classified into two categories:

- Firstly, the replacement, refurbishment and/or upgrading of the existing conventional instrumentation. For example, the replacement of non-functional, damaged or technologically obsolete instruments (outdated instruments that cannot be maintained and/or automated). Only instruments serving a useful purpose will be replaced.
- Secondly, complementary instrumentation to provide additional information. For example, existing measurements of leakage/seepage will be complemented with instrumentation to determine their pore pressure distributions, rate of seepage and seepage paths. New instruments may also be added to monitor new situations or parameters that were not considered when the initial monitoring program was implemented during the construction of the dam.

The major drawback with re-instrumentation is that instruments cannot be installed inside the dam body during the construction, they have to be retrofitted. However, re-instrumentation of existing dams can sometimes be more cost-effective as it is not dictated by construction activities. Uncertainties and problems encountered during construction have been removed from the list of instrumentation risks.

With the re-instrumentation the focus is as a rule narrowed down to dam safety issues that are important for the monitoring of the dam during operation and ageing. The observed behavior of the existing dam also helps with the choice of additional instrumentation for the verification and refinement of the behavior models. In practice, the re-instrumentation of existing dams contains therefore elements of both the above-mentioned categories, viz, upgrading and additional information.

Extensive new developments in dam instrumentation have emerged on the dam monitoring market during the past decade or two. Many of these developments are spin-offs of developments in other commercially viable fields of technology. The main advantage of some of these instrumentation methods are that they can be installed in existing dams with relatively limited installation work. Promising complementary instrumentation alternatives are described in Section 4 and 8.

The main advantage of re-instrumentation is that it can be done as the “main contract and not as a subcontract under the main dam construction contract. Instrumentation is more often than not the Cinderella of construction activities and installations have to be performed under difficult conditions, which seldom results in good records of accomplishment.

During construction, contractors tend to delay orders for instrumentation creating their own construction programming crisis. Few dam instruments (sensors) are shelf items and the majority of dam instruments are being manufactured on order. Dam instrumentation therefore earned a dubious reputation amongst some decision-makers in the dam engineering fraternity in some parts of the world.

These negative perceptions often precipitate into reluctance for the support of anything more than the bare minimum as far as instrumentation is concerned. As a rule these systems are not performing satisfactorily, and have to be re-instrumented to get the system to function as originally intended. Under these circumstances a request for re-instrumentation can be both an embarrassing and a challenging task.

7.2 Purpose-driven investigations/instrumentation

The only means to regain credibility and to counteract deep-rooted negative attitudes towards instrumentation is to present the facts unbiased (and not to lose ground by throwing mud). Motivation for the re-instrumentation of existing dams therefore provides the ideal opportunity to set all records straight by giving a critical review of the original monitoring system.

The review of the existing instrumentation and motivation for the additional instrumentation must be credible, factual, honest and well balanced. For the informed engineer and more so for the dam safety team, dam instrumentation is vital for the execution of their task and for their own personal development (i.e. including instrumentation objectives to gain insight into problems stretching wider than just the specific dam).

The choice of instruments should be purpose-driven and not be a case of instrumentation for the sake of instrumentation. Instrumentation is not a means in itself; every instrument should have a specific purpose in so far as providing answers for specific dam safety related questions. For example, piezometers are installed in embankment dams constructed with relatively low permeability fill material to monitor pore pressure development during construction.

These instruments are essential in order to prevent the development of hydraulic fracturing due to excessive pore pressure development in the fill material or foundation when the construction rate is faster than the rate of dissipation of pore pressures. These piezometers are strictly speaking only required in a few representative locations in the embankment in order to determine the safe rate of construction. After the end of construction, these instruments have served their purpose and become obsolete or of secondary importance. They can still provide useful information with regards to the development of the phreatic line at these particular locations.

Replacement of these piezometers that have served their purpose should therefore only be undertaken when the secondary information is of prime importance. Special precautions will have to be taken in these instances as discussed in section 7.3.

Another major issue is the timing of re-instrumentation of existing dams, i.e. when should it be considered and in the case of an owner with more than one dam, how the re-instrumentation of these dams should be prioritised. The one extreme is to keep all instrumentation at the state of the art, whilst the other extreme is just to allow it to degrade until it is obsolete.

These extremes are neither practical nor justifiable. In order to comply with the principle of due diligence, two types of decision-making methodologies are being used to assist with the prioritisation of re-instrumentation, vis-à-vis, the deterministic ranking methodologies and probabilistic decision making models.

Various ranking methodologies are being used. In principle, numbers are assigned to the relevant aspects of instrumentation in order to come up with a final number. A portfolio of dams can then be ranked according to these values to determine their order for refurbishment. Alternatively, a cut-off value can be assigned and the instrumentation of all dams below that number is then up for refurbishment.

The major advantage of these methodologies is that decisions are taken on the same basis and in a structured manner. These methods do not necessarily guarantee good decision making. The major disadvantages are that they are strictly speaking “black-box” decision-making tools that could be biased by the subjectiveness of the analyst.

7.3 Precautions

Instruments installed in the body of a dam may cause potential weak or failure zones and must be properly designed and installed. Any intrusion in the dam body carries with it the risk of developing, over the long-term, seepage paths along the tubing or cable that may lead to erosion (and finally the possibility of piping in earth fill dams). Non-destructive techniques should as far as possible be considered instead of instruments requiring drilling.

Re-instrumentation therefore has to be planned and executed with care and due diligence, especially in embankment dams and more particularly in clay cores and foundations. Drilling with water or air must be avoided as far as possible. If there is no other way out it must be done with utmost care and supervision to reduce the risk of hydro- or pneumatic- fracturing by limiting the air and water pressures. These values depend on density of the material, pore pressures and depth of the hole.

In only a few isolated situations would it be necessary to re-install standpipe piezometers (for example for the extraction of water samples). If these piezometers really need to be replaced it is recommended to use only low risk techniques, such as augering, shelbying or sonic drilling of the holes. The first two drilling methods are cumbersome, the latter relatively fast and safe and preferred. Retrofitting pore pressure gauges/piezometers is seldom warranted on a cost-effectiveness basis.

Re-instrumentation therefore mainly consists of additional instruments in newly drilled holes. The very same principles as discussed above for earthfill dams do apply for concrete dams and their foundations.

8 Recent instrumentation developments and applications

8.1 General

A number of instrumentation and monitoring techniques have found new applications in the surveillance of dams during recent years. Extensive research has been performed in several countries in order to improve, verify and evaluate “new” parameters, new monitoring equipment and their applications in order to find complementary ways to retrieve information about the performance of dams.

Recent developments in instrumentation technology have improved our ability to monitor dams in several ways:

- Improved monitoring accuracy provides better data evaluation (e.g. for resistivity and Self Potential measurements)
- New technology with improved monitoring frequency and spatial resolution results in new applications (e.g. laser scanning and fiber optic measurements of temperature and strain)
- New methods (e.g. Global Navigation Satellite Systems)
- Improvements in data evaluation have provided better understanding of the physics of the data measured.

The list of methods presented below is not complete, but contains methods that recently have shown significant progress and have been documented to be successful both in research projects and for practical use. Commercial methods, mainly developed by one company using protected technology have not been included below. Methods only applicable for site investigations are also excluded.

Some key aspects of the selected methods included in this bulletin are presented in Table 8.1, and further discussed in the following sections.

Table 8.1: General comments on the application of some methods for dam monitoring and investigations

Equipment Measuring device Measurement methods	**Fundamental parameter Measured**	**Application**	**Research / Experience**
Bi-Triaxial joint and/or crack Gauges	Deformations and rotations with high accuracy.	Devices are placed where there are deformations or rotations to detect movements in specific joints/cracks	Monitoring devices were developed and tested in South Africa. Successful installation and use for 15 years.

Equipment Measuring device Measurement methods	**Fundamental parameter Measured**	**Application**	**Research / Experience**
Vibration Measurements	Dynamic reponse (modes and frequencies)	Long term monitoring of the integrity of concrete structures	Either forced or natural ambient loads are used for excitation. Change in dynamic response under the same loading conditions indicate changes in the integrity of the structure
Distributed Fibre Optic sensing	Temperature and strain are measured in optical fibres using laser light.	Cables are installed in new or old dams for seepage evaluation using temperature and strain analyses for movement detection	Basic research since 1996 in Germany and Sweden. Further research especially in France, Austria, the Netherlands and US. Over 100 installations for temperature measurements worldwide and about 25 installations for strain in Sweden, Germany and Brasil.
Global Navigation Satellite System (GNSS)	Accurate distance measurements between orbits and sensor.	Local monitoring of movements.	Extensive research with improved accuracy for different applications. Applied for dams in several countries such as Portugal, US, Japan.
Laser scanning and digital imagery	Accurate distance measurements using laser with high spatial resolution over surfaces	Provide a three dimensional geometric model of dam. Deformations can be detected by regular measurements	Technolgy continuously improving by lasers, sensors and digital image processing. Method is used in several countries as a normal procedure.
Multi-beam bathymetry	Echo-sounding	Bathymetric surveys	High resolution underwater surveying producing a digital three dimensional representation of the surfaces
Resistivity	Active electrical method that can detect changed material properites	Electrodes are placed on the crest or at the dam toe.	Research and long term field measurements have been performed especially in US, Canada, France and Sweden.
Satellite Synthetic Aperture Radar (Satellite SAR)	Photogrammetry method using Satellite images	Surveying of dams and their surrounds as well as monitoring of movements at 35 day intervals	High resolution surface surveying method producing a digital three dimensional representation of the surfaces

Equipment Measuring device Measurement methods	Fundamental parameter Measured	Application	Research / Experience
Ground survey Aperture Radar (GBInSAR)	Photogrammetry method using ground station images	Surveying of dams and their surrounds as well as monitoring of short term movements	High resolution surface surveying method producing a digital three dimensional representation of the surfaces
Ground Penetrating Radar (GPR)	Detect changes in properties of near surface soil layers, localization of defects or voids in concrete structures	Nondestructive and rapid method based on measuring transmission time for radar signals reflected from or transmitted through a media	Localization of seepage zones, sinkholes and deterioration of cores in embankment dams. Monitor remedial grouting of dams. Limited survey depth
Self Potential	Passive electrical method which is sensitive to the flow of seepage water	Electrodes are placed on the dam surface both for investigation and monitoring	Research and long term field measurrements have been performed especially in US, Canada, France and Sweden.
Borehole Instruments	Electro-Mechanical devices used to measure deformation	Devices are placed where movements/tilts occur and can be observed	Recent developments allow continuous monitoring.

8.2 Bi-triaxial Crack Gauges/Joint meters

Triaxial crack gauges are quite common and several versions are in use, but only a few are available commercially. These devices are ideal for both long-term behavior of concrete structures as well as early recognition of unexpected behavior. In concrete dams, they are installed across joints and active cracks. Movements across these joints are usually not only pure translations, but a combination of translations and rotations. The advantages of these gauges are:

- Relatively inexpensive, simple to manufacture, easy to install and to read
- Durable, rugged, reliable, no or low maintenance requirements
- High precision results are possible; suitable for “forensic engineering applications” with regard to the study of joint and crack movements.

The major disadvantage is that the results are dependent on the diligence of the operator taking the readings with a digital dial gauge.

During the 1990’s engineers and technicians of the Department of Water Affairs (DWA) of South Africa developed several types of 3-D crack gauges. These gauges are not patented. The most widely known and used version is the Bi-triaxial version, which was specifically developed to enable the measurement of deformations and relative rotations in all three dimensions. Regular and systematic measuring of these translations provided valuable information (with regards to relative translations and rotations).

The DWAF2001 Bi-triaxial crack gauge (Figure 8.2.1) is an all-stainless steel unit consisting of two identical halves. Readings are taken with a digital micrometer at the two sides of the gauge (tilt measurements with a hand held tilt meter is only used when studying horizontal cracks/joints). Readings are taken manually and the quality and consistency depends mainly on the operator. These readings can be improved when a PDA/barcode reader is used to record the readings directly from the digital dial gauge.

For more than 15 years these crack-tilt gauges have been successfully used to measure deformation and rotations in concrete structural elements. Recently, a more compact Bi-Triaxial version was developed with permanent digital sensors. These gauges can be wired directly to automatic data acquisition systems.

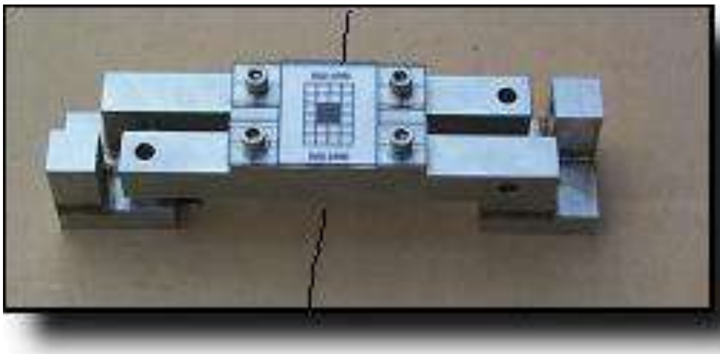


Figure 8.2.1: Photograph of the DWAF2001 Bi-triaxial crack gauge with assembly unit and tell-tale face.

The accuracy obtained with the DWAF 2001 is high and typically varies between +/- 0.001 and 0.01mm for translations (depending on the particular digital readout unit and the diligence of the operator. When there are rotations across a joint or crack as shown in Figure 8.2.1, it is easy to visualize that the readings taken through the two visible measuring positions would change in opposite directions. This phenomenon is used to calculate the rotations across joints. It is therefore helpful to display the differences between the readings for evaluation purposes as shown in Figure 8.2.2.

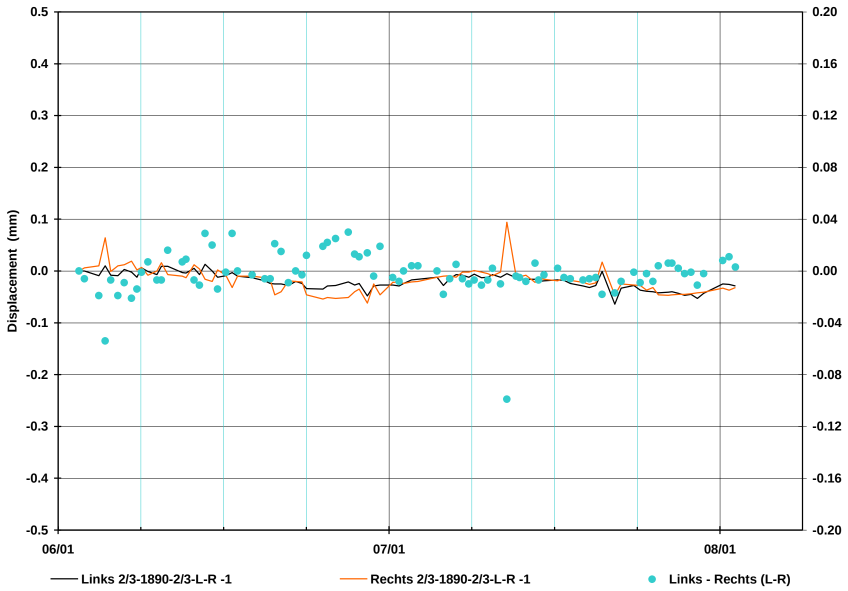


Figure 8.2.2: Typical display of the results of one of the readings of a DWAF2001 3-D Bi-Triaxial gauge installed across a vertical joint (the blue dots are the difference in readings between the two arms of the gauge).

Reference:

Oosthuizen, C, Naude, PA, Dorfling CJ. (2003). A simple 3-Dimentional crack-width-tilt gauge out of Africa. Proceed. 6th Int. Conf. on Field Measurements in Geomechanics. Oslo, Norway.

8.3 Dynamic vibration measurements of natural ambient excitation

An important parameter to measure is the “integrity” of all types of concrete dams during their whole life and means to detect early signs of deterioration (e.g. cracking and/or swelling action due to chemical reactions in concrete). Changes in the dynamic behaviour of concrete dams under similar loading conditions are indicative of changes in integrity. These measurements may either use forced or natural ambient forces (wind, spilling water etc) to excite the dam wall. These analyses are useful for the calibration of Finite Element models for these dams.

8.4 Fibre Optic Sensors

8.4.1 General

Temperature measurements can be used as an indirect means to determine the presence, location and quantity of seepage flows through embankment dams or in the foundation. An intact part of the dam with low seepage flow will then generally have a different temperature distribution than in a part with a zone of higher seepage.

Leakage detection by means of temperature measurements have been typically implemented through two major approaches. Firstly the passive method, which employs natural temperature variations as a tracer to detect and quantify anomalies in the flow field and secondly the active method, which allows detecting the presence and movement of water by evaluating the thermal response after external heat is induced.

8.4.2 Distributed fibre optic temperature sensing

Distributed fibre optic temperature sensing (DTS) in concrete dams is useful if a large number of measuring points or an accurate representation of the temperature gradients is required. In embankment dams and dikes, the internal temperature field is a function of the flow field. External temperature variations propagate within the dam body by means of conductive and convective heat transport processes, influencing the internal temperature distribution. This close interaction between the flow field and the temperature field allows using temperature as an easily measurable parameter to detect leakage or variations in the seepage pattern.

For distributed fibre optic temperature measurements a fibre optic cable is installed in a structure along a predefined monitoring section. The resulting measured temperature values have accuracy better than ± 0.1°C and a spatial resolution of around 1.0 m. The measurement length of standard devices is up to 10 km.

Since the measurement is carried out along a single cable the installation is easier to evaluate compared to an installation of many individual temperature probes. Due to the use of optical fibres the measuring system is insensitive to electromagnetic interference (lightning, creeping current, etc.) as well as to erosion. The measuring system requires generally external calibration of the temperature after the installation of the cable.

The impulse transmitter/receiver can be easily replaced in case of damage or failure. The cable which is used as a sensor is integrated in the structure when installed and therefore well protected. It is not expected to fail under normal operating conditions.

8.4.3 Seepage measurement using passive fibre optic methods

The natural seasonal temperature variations in the reservoir water and the ambient air are the fundamental factors for the temperature distribution in an embankment dam. The pattern of these variations depends on the local climate, and the character of the river/reservoir. In the tempered climate zone the seepage water enters into the dam as cold water during winter and warm water during summer. Seasonal water level variations in the reservoir will change the seepage flow and the inflow water temperature if horizontal temperature stratification in the reservoir occurs.

The temperature field inside the dam will thus be a result of the seasonal temperature variations on the surface of the dam and on the seepage flow rates passing through the dam (Figure 8.4.1).

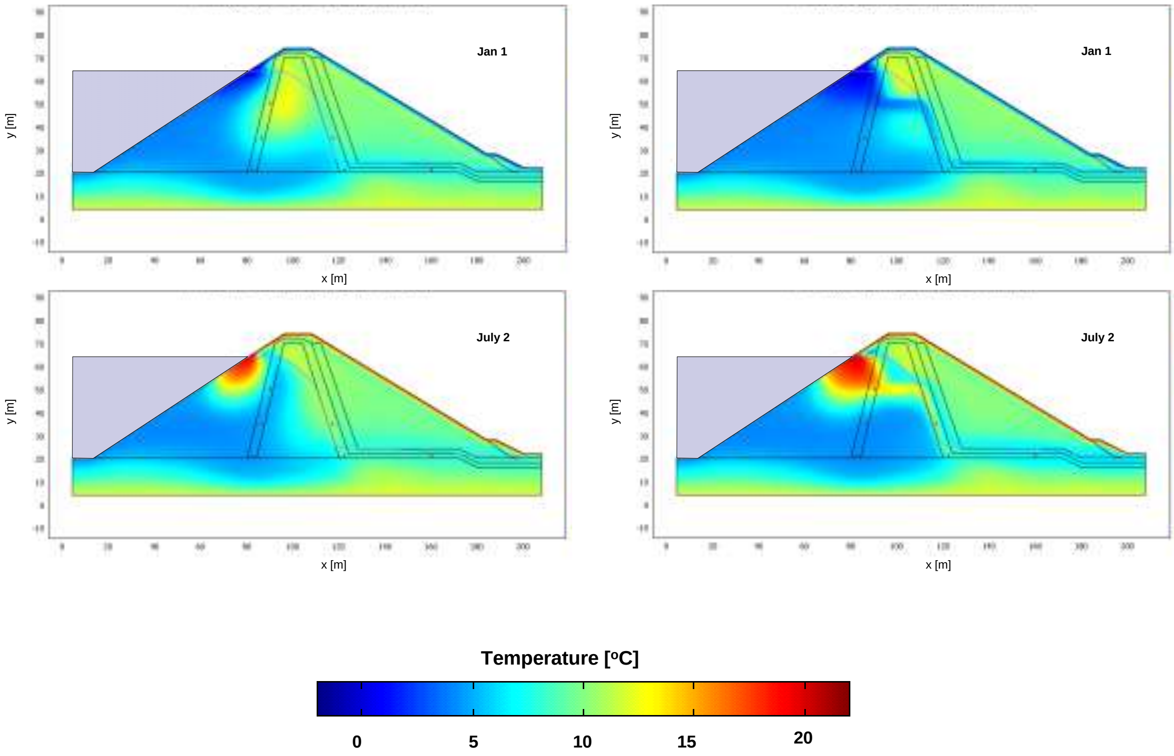


*Figure 8.4.1: **Calculated temperatures on January 1 and July 2 for a 60 m high (intact dam (left) and a dam with a leakage zone with 2 m height and 50 times higher hydraulic conductivity (right). As boundary conditions a sinusoidal water and air temperature variation were assumed (water - mean temperature of 10°C and an amplitude of 9°C, and air - mean temperature of 10°C and an amplitude of 9°C).***

8.4.4 Seepage measurement using active fibre optic methods

Active methods were developed to provide a controlled method for seepage/leakage monitoring. The most common method is the heat-up method developed upon distributed fibre optic temperature measurements which uses a distributed heat input along the fibre optic cable for a certain time interval. Electric current produces the linear heat input, if applied on the copper wires integrated in the cable.

The method is based on the thermal response of the cables surroundings to the additional heat and can indicate whether the cable is within a moist, a partially saturated or fully saturated medium, and whether seepage flow is present or not.

Installations using active methods only provide information on the direct surrounding of the cable. The method can be used to detect leakage through thin sealing elements such as geomembranes, asphaltic linings or concrete slabs by placing the cable directly underneath them.

8.4.5 Distributed fibre optic strain sensing

Similar technology, as described above for temperature measurements, can be used to measure the strain in an optical fibre by using **d**istributed fibre optic **t**emperature and **s**train **s**ensing (**DTSS**). The unit is capable of measuring both strain and temperature at 1 m intervals over long distances in optical fibres.

This strain sensing technology allows a full coverage of an entire dam. By repeated measurements strain changes along each meter can be detected. Local movements could be detected at an early stage, if the movements of the dam could effectively be transferred into the cable. This would provide useful and additional information to the local surveying points which normally are used in order to detect movements.

The location as well as the strain in the fibre will be detected. However, the absolute value of the movement is difficult to estimate. The system can detect strain changes (movement changes) in the dam and can therefore be used either as Early-Warning-System with continuous monitoring, or as an investigation tool to measure movements regularly.

References:

Johansson, S. and Sjödahl, P. (2009): A Guide for Seepage Monitoring of Embankment Dams using Temperature Measurements, CEATI Report No T062700-0214, CEATI International Inc., Montreal, Quebec, Canada, www.ceati.com.

Perzlmaier, S.; Straßer K.-H.; Strobl, Th.; Aufleger, M. (2006b): Integral Seepage Monitoring on Open Channel Embankment Dams by the DFOT Heat Pulse Method. In: Proceedings of the 22nd Congress of the International Commission on Large Dams (ICOLD), June 06, Barcelona, Spain, Q. 86 – R12, S. 145 – 164.

Perzlmaier, S.; Aufleger, M.; Conrad, M. (2004): Distributed Fiber Optic Temperature Measurements in Hydraulic Engineering – Prospects of the Heat-up Method. Proceedings of the 72nd Annual Meeting of the International Commission on Large Dams (ICOLD), Seoul, Korea, 16.-22. Mai 04.

8.5 The Global Navigation Satellite System (GNSS)

The Global Navigation Satellite System (GNSS) is the current designation of an ensemble of satellite based positioning systems, such as the GPS-NAVSTAR of the U.S.A., the GLONASS of Russia, the GALILEO from the European Union and the Beidu-Compass from the People's Republic of China, that may be used to acquire absolute or relative positions (3D Cartesian co-ordinates).

The GNSS positioning is based on the measurement of the distances between a receiver's antenna and, at least, four orbiting satellites. The receivers are usually equipped with less precise quartz clocks and a replica of the codes. The time interval between the emission and the reception of the coded navigation message is measured in the receiver. Due to the error of the receiver's clock, the distance derived from the time interval is a pseudo-distance. Four pseudo-distances and the known positions of the four satellites allow the determination of the receiver's position as well as the receiver's clock error.

A recent development which appears promising for GNSS monitoring of dams is the implementation of continuously operated reference stations (CORS) in certain countries, and the prospect that similar networks of reference stations will gradually be implemented on a larger scale and in more countries. CORS networks enable much improved horizontal and vertical positioning accuracies at relatively small cost for users. Depending on the spacing between the stations, accuracy can be improved. Typical accuracy for displacement monitoring at the crest of dams is in the range of 3 mm relative to the nearby CORS stations.

The relative method with the carrier phase is best suited to monitoring displacements in large dams. The most important constraint of the space positioning methods is the necessity of the stations to have a clear horizon, in order to receive the satellite signals under good conditions. On the other hand, two important advantages over conventional survey methods are:

- the possibility of measuring baselines between non inter-visible stations; and
- within reasonable limits operable under unfavorable weather conditions (wind, fog, rain, etc.).

Several discrete measurements, carried out simultaneously with the GNSS and geodetic surveying methods in dams produced displacements within the millimeter range (Fig. 8.5.1). Remarkable was the agreement between vertical displacements measured with the GNSS and the geometric leveling. Provided clear sky conditions exist, GNSS appears to be competitive with ordinary surveying methods with respect to precision, robustness and cost.

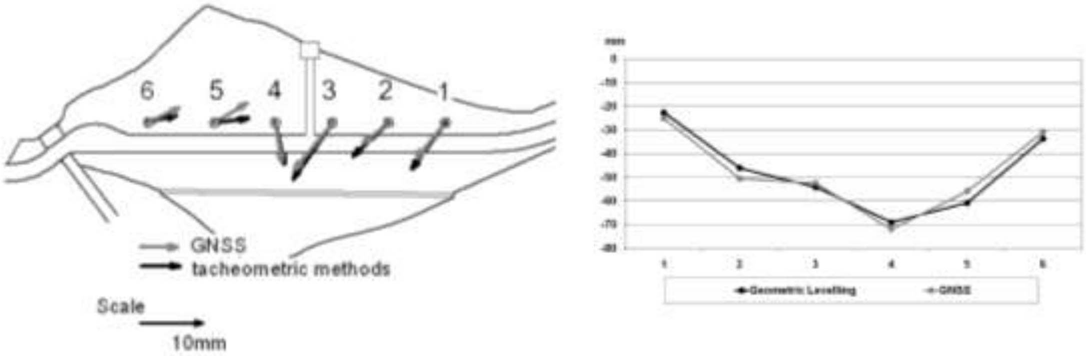


Figure 8.5.1: Comparison of horizontal and vertical displacements obtained by GNSS and classical geodetic methods. Loureiro earthfil dam (Portugal).

In concrete dams, permanent GNSS stations, may be advantageously integrated with plumb wires to provide absolute displacements with adjustable measurement frequency (down from 50Hz). Such an integrated displacement monitoring system has redundancy and precision enough to qualify it to be a primary component of any early warning system.

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Behr, J., Hudnut, K. and King, N. (1998). *Monitoring Structural Deformation at Pacoima Dam, California Using Continuous GPS*. Proceedings of IONGPS98, Nashville TN, USA.

Rutledge, D. R.; Mayerholtz, S. Z.; Brown, N. E. and Baldwin, C. S. (2006). *Dam Stability: Assessing the Performance of a GPS Monitoring System*, GPS World, Vol. 17, nº 10, October 2006.

Yamaguchi, Y.; Sakamoto, T.; Kobori, T. Ikezawa, I.; Itaya, H. and Iwasaki, T. (2008). *Utilization of GPS for Exterior Deformation Measurement of Embankment Dams*. Proc. of the Symp. "Operation, Rehabilitation and Up-grading of Dams", ICOLD, 76th Annual Meeting, Sofia, Bulgaria, 2-6 June 2008.

8.6 Laser scanning and digital imagery

Laser scanning is a well proven and reliable technology that produces information with adequate quality. It can provide a three dimensional (3D) geometric model of dam site with metric quality (Fig. 8.6.1). However, as a new technology, developments are still occurring regarding hardware and software as well as methodologies and operational procedures.

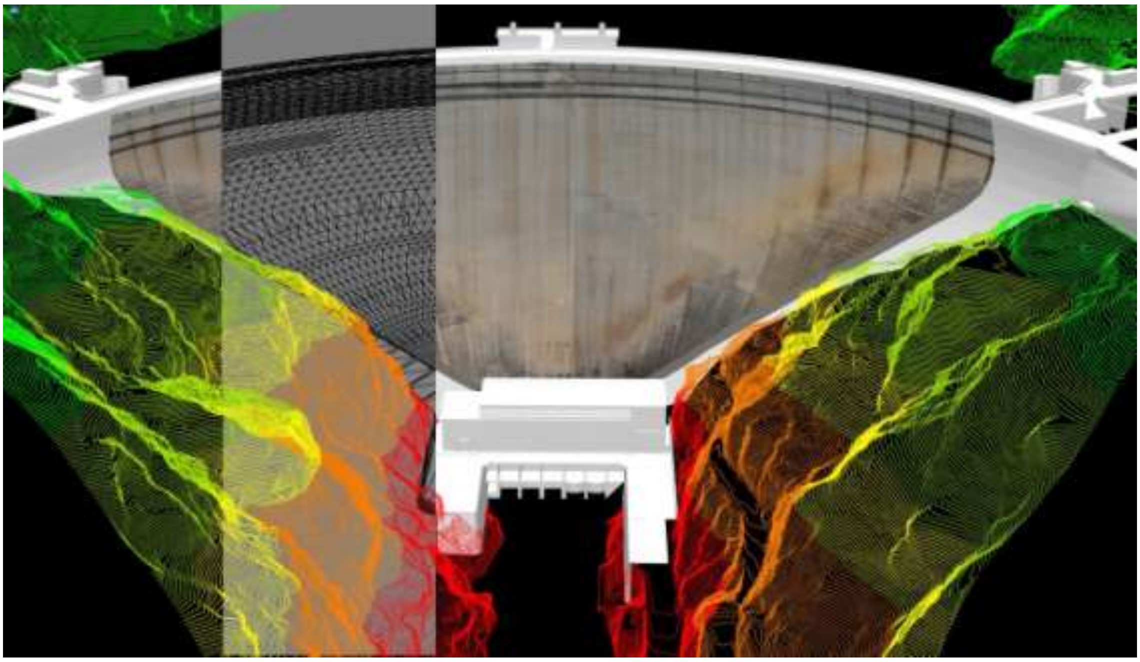


Figure 8.6.1: Example of application of laser scanning. Cabril arch dam (Portugal).

This data can provide information about:

- the geologic conditions of the foundations;
- downstream steep or unstable banks as well as existing retaining works;
- the entire dam, its abutments and appurtenant structures in an early stage of its service life;
- the visible part of the dam, its abutments and appurtenant structures, the visible part of unstable banks of the reservoir, downstream unstable banks and their retaining works, during the service life of the project.

By regular measurements valuable information concerning surveillance program can be achieved:

- deformation monitoring of whatever surface (dam wall, banks, etc.) has been recorded previously and is recorded periodically or whenever judged convenient;
- determination of the three dimensional displacement vectors of representative surface marks (should these still be needed);
- on line, structured codification into an electronic database of the information collected during traditional visual inspections.

The scope of the first two activities is well defined. The deliverables of the first one (isolines, volumes, cross-sections of deformation) are now accessible and affordable given the speed of the data acquisition and data processing. The deliverables provided by the second activity are comparable to the well established geodetic monitoring method. The deliverables and procedures related to the third activity, given the huge amount of collected data and the novelty of the technology deserves supplementary explanation that can be achieved in the references below.

References:

Lerma G., J.L., Van Genechten, B., Heine, E. and Santana Q. (2008). *M.3D RiskMapping. Theory and Practice on Terrestrial Laser Scanning. Training Material Based on Practical Applications*, Universidad Politécnica de Valencia, Spain 261 pp.
Berberan, A., Portela, E.A., Boavida, J. (2007). *Assisted visual inspection of dams for structural safety control*, The International Journal on Hydropower and Dams, Volume 14, issue 2.

Boavida, J., Oliveira, A., Berberan, A. (2008). *Dam monitoring using combined terrestrial imaging systems*, 13th FIG Symposium on Deformation Measurement and Analysis, LNEC, Lisboa,

8.7 Multi-beam bathymetry

Ship born multi-beam bathymetry, Figure 8.7.1 uses a high resolution echo-sounder permitting the investigation of a surface defined by a cone with 120° aperture. This is equivalent to a strip 3.4 times the depth of water (max 60 m from a ship), with a density of more than 50 points/m^2 at the depth of 10 m below water level, the sensitivity decreasing with depth. The use of a Remote Operated Vehicle (ROV) eliminates the depth restriction and makes it possible to get closer to deep targets.

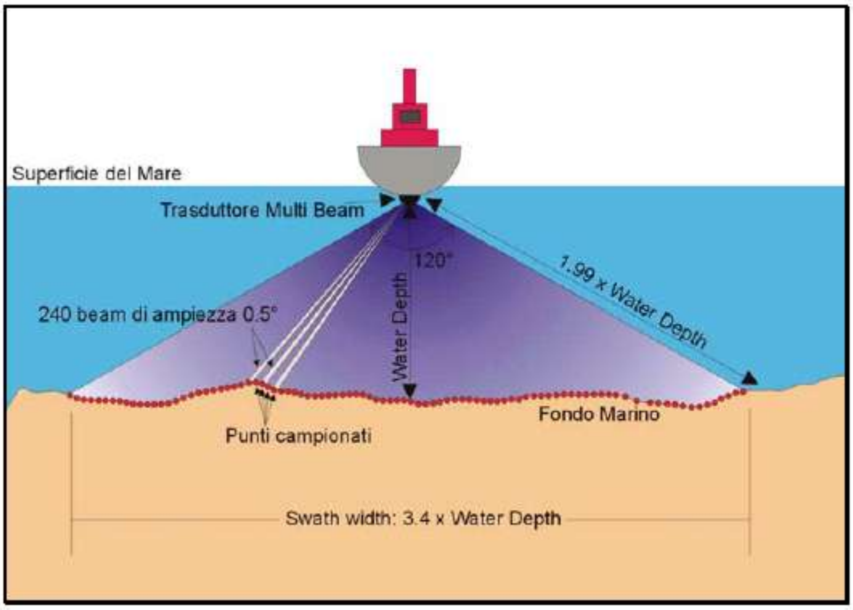


Figure 8.7.1: Multi-beam bathymetry technique

Both the boat and the ROV are generally connected by a UHF system to a GPS point on shore. All the information is then processed with speciality software resulting in a three-dimensional image and/or a plan and sections in dxf/dwg format for immediate engineering use.

Advantages:

- High resolution restitution, to 0.20 m or more in depth
- Possibility to measure cavities in dykes
- Three-dimensional vision

Limitations:

- Higher cost than traditional methods, while a wide spread use of this technology could result in a reduction in costs.
- Sensitivity to water turbulence, due to bubble-air or waves, causes loss of resolution.

Figure.8.7.2 is a typical example of a three-dimensional image of a bottom outlet of a dam with surrounding sediments.

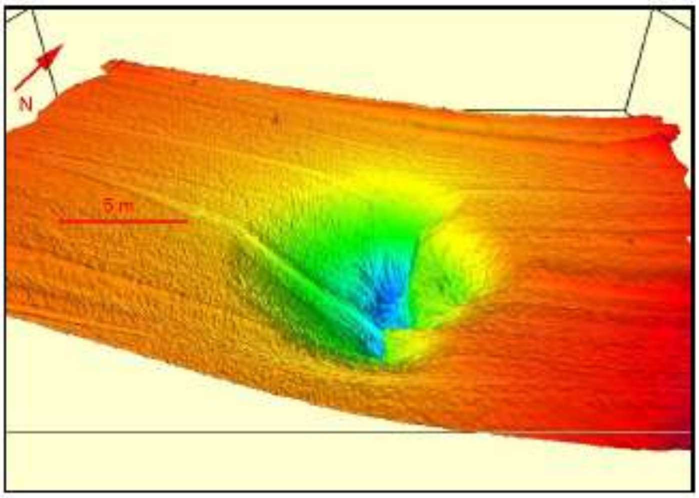


Figure 8.7.2: Three-dimensional vision of a bottom outlet with surrounding sediments

8.8 Borehole instruments to measure three dimensional deformations

In the 1970's the Federal Institute of Technology in Zurich Switzerland developed measuring systems to enable measurement of strain profiles in soil, rock and also in concrete structural elements. For more than 25 years these borehole instruments have been successfully used to measure profiles of deformation and displacement in soil, rock and in concrete structural elements for different applications in geotechnical engineering projects. Recently, these measuring systems were redeveloped with new characteristics including digital sensors, new data acquisition system and new hardware.

With these instruments the quantitative distribution of deformation along a line is detected by measuring profiles of strain and lateral displacements. Measuring casings are installed in a borehole and the space between the borehole wall and the casing is filled with a suitable grout. The measuring casing consists of a series of reference points, each spaced at a distance of 1m within the casing. An instrumented probe is used to measure relative displacements of adjacent reference points at the constant distance to each other as schematically shown in figure 8.8.1.

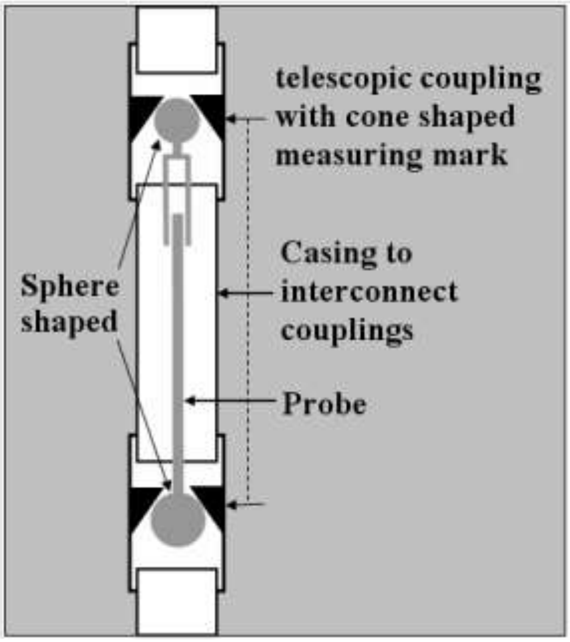


Figure 8.8.1: Schematic layout, of the measuring casing with the probe

The reference points with the cone-shaped measuring mark are constructed as telescopic couplings to enable axial movements along the measuring casing. To obtain high precision readings, the two sphere-shaped measuring heads of the probe are in contact with the two adjacent cone-shaped reference points. When the sphere is in contact with a cone-shaped surface, the centre of the sphere is uniquely defined. To be able to move the probe along the borehole from one position to the next, the spherical heads of the probe and the cone of the measuring mark are specially designed. In the sliding position the probe is moved along the borehole until it is located at the reference points. Then, the probe is rotated by 45°and brought into measuring position.

In the probe, elongation is measured by means of a linear variable differential transformer (LVDT). Horizontal displacements are calculated from the inclination of the probe which is measured by means of an internal biaxial accelerometer that measures the angle of the probe axis relative to the direction of gravity.

The accuracy obtained with the instrument is remarkably high. The relative displacement between two adjacent measuring marks can be measured axially to the measuring casing to between +/-0.002 to 0.003mm/m and laterally to the measuring casing to +/-0.05mm/m. Figure 8.8.2 shows the u, v and z components of displacement measured with the instrument at a dam over a 11 year period of time.

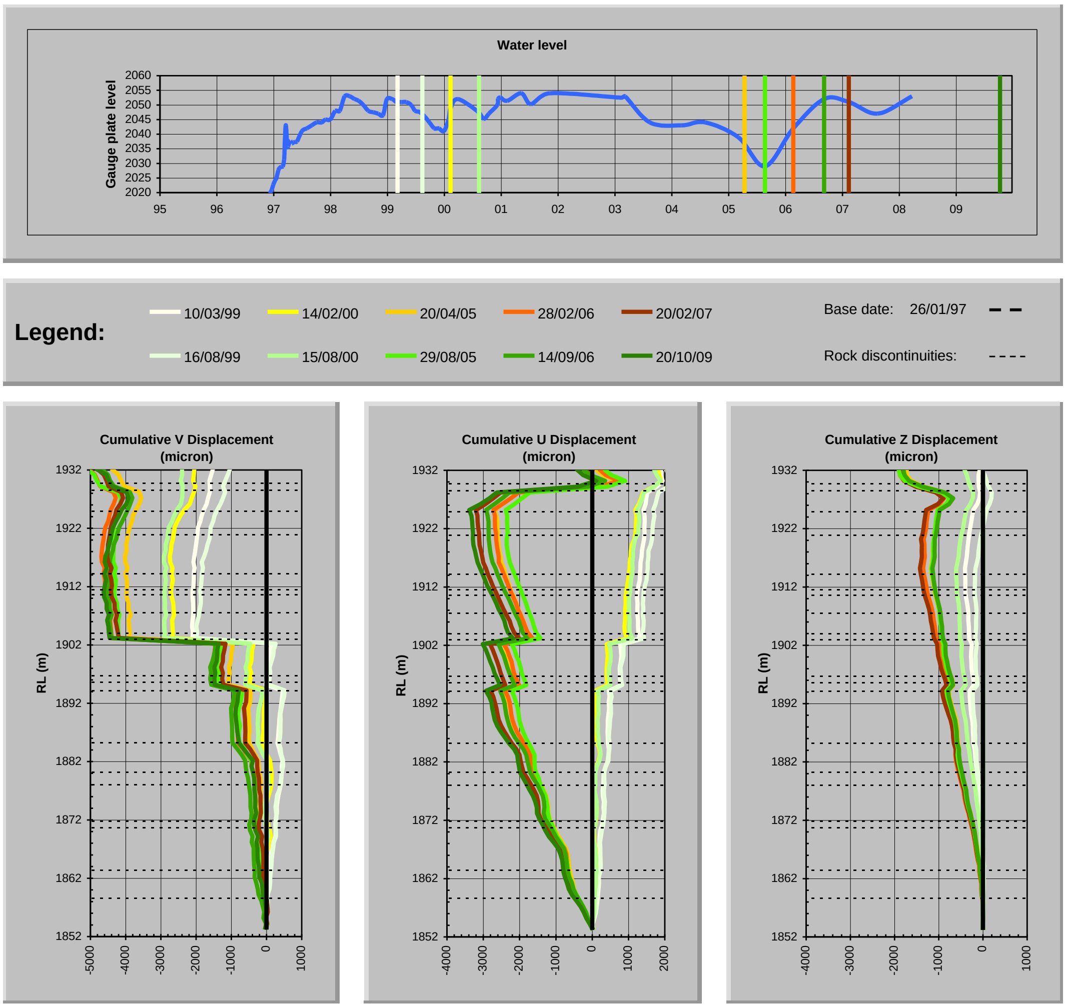


Figure 8.8.2: Cumulative v, u and z components of displacements measured with the instrument over a period of 11 years

References:

Kovari, K. (1985). “Detection and monitoring of structural deficiencies in the rock foundation of large dams.” *15th Int. Congr. Large Dams ICOLD*, Lausanne:

Oosthuizen, C, Naude, PA, Pretorius, CJ ‘Mota, V, and Műller FPJ.(2003) Geodetic Surveying & TRIVEC monitoring system at Katse dam : Value added or waste?. Proceed. 6th Int. Conf. on Field Measurements in Geomechanics, Oslo, Norway.

8.9 Satellite survey by SAR (Synthetic Aperture Radar) and Permanent Scatterers (PS)

Satellite images in the past were used primarily for monitoring the subsidence of large areas. The concept has received a major boost due to the development of new processing technologies, which allow quantitative data of local movement to be obtained with an accuracy and resolution previously thought impossible. The techniques set up in the last few years for radar SAR images acquired by the ESA (European Spatial Agency) satellite, Figure 8.9.1 and the new operational techniques based on Permanent Scatters (PSInSAR) enable accuracies of ± 1 mm in the estimation of vertical displacements.

The normal time interval for a satellite to repeat a pass over a specific target area is approximately 35 days. Satellite images have been available since 1991; thus, it is possible to get historical movement data from archived images.

It is now possible to detect precursor movements which could lead to development of hazard situations such as instability of reservoir slopes. Different applications of satellite SAR to dams, reservoirs and channels have been explored, bringing to light the advantages and the limits of the new technology in dam engineering.

Advantages are:

- Measurement of rate of change in and displacements of selected points with the indicated precision.
- Simultaneous monitoring of extended data.
- Access to an archive with more than 10-15 years of historical data.

Limitations are:

- Extremely high uncertainty of the PS position and density in rural areas or in mountainous regions. (The limitation of interferometry has been overcome through the PS approach. PS physically coincides with structures or with natural elements present in the survey site, such as rocks and stones).
- Many dams are located in high mountainous areas, where the climatic conditions (snow coverage) and vegetation conditions can vary rapidly. These aspects induce false data and consequently a reduction in number of images that can be used. The valley morphologies could reduce the opportunities offered by the use of satellite images.
- Of course, the actual repeat time of the satellite (35 days) makes this ineffective for emergency applications or for issuing alarms in an early warning system.

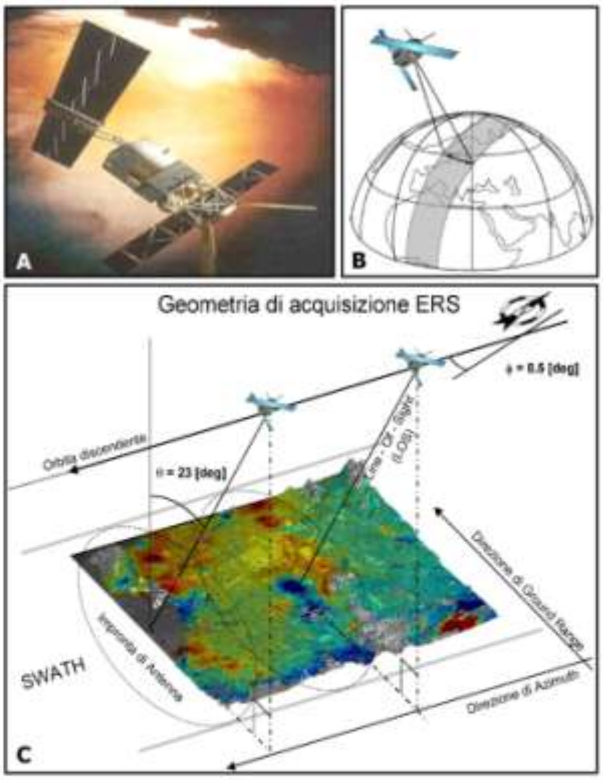


Figure 8.9.1: Acquisition geometry of ERS Satellites

Measurements obtained via satellite SAR can be as accurate as those obtained by other traditional precision monitoring systems, such as leveling, total stations or GPS. This is illustrated by the case study of the hydraulic basin shown in Figure 8.9.2, where the vertical movements derived from SAR images are compared to precision geodetic leveling. The comparison is shown in Figure 8.9.3. The vertical movements determined by leveling are shown by the red and orange lines. The other two lines show the vertical movements derived from the SAR images.

The use of satellite data and in particular the PS techniques provide a powerful tool for monitoring dams and reservoirs. In the future, new European and Canadian satellites will also be available for use.

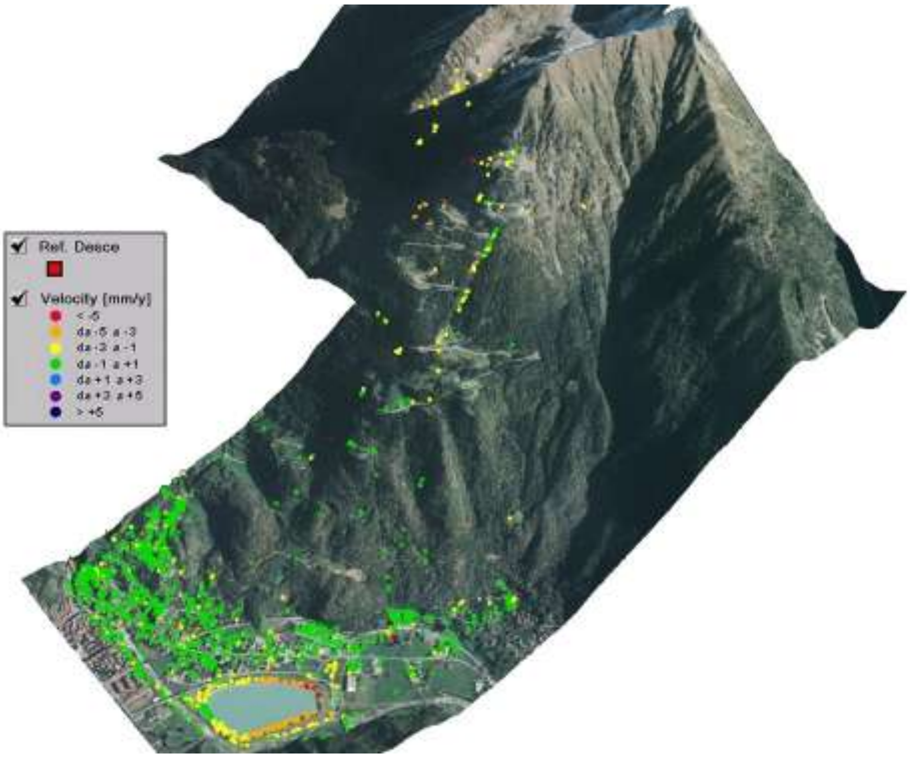


Figure 8.9.2: Layout of Permanent Scatters (PS) and Digital Elevation Model (DEM) together with the hydraulic basin

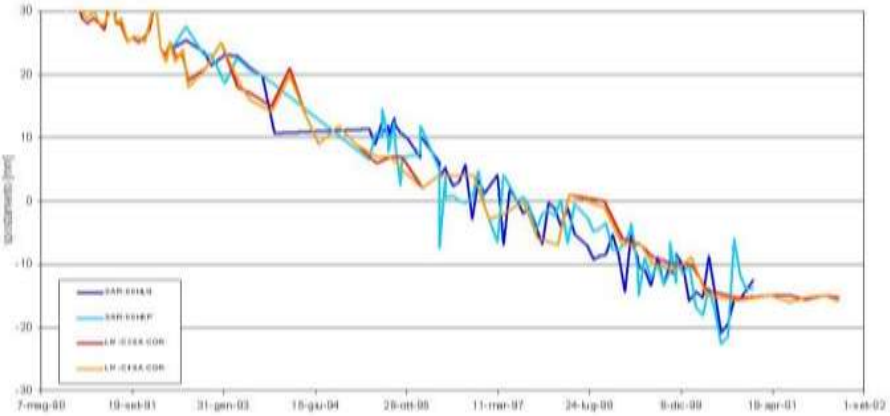


Figure 8.9.3: Comparison of vertical movements (Permanent Scatters and precision leveling) measured along the crest of the hydraulic basin shown in Figure 8.9.2.

8.10 Ground survey by SAR (Synthetic Aperture Radar) – GBInSAR

The technique is based on the use of radar interferometry (Synthetic Aperture Radar) from a ground station located in front position to the dam in order to monitor the structure or alternatively for monitoring reservoir slopes..
The techniques allow the measurement of movements of points on the line of sight. The accuracy of the measurement is a fraction of the wave length, and could be evaluated theoretically equal to 0.1 mm.

For evaluation purposes the technique was used to measure the horizontal displacement, in upstream-downstream direction, of Venina Dam (multi arch dam – 50 m height and 175 m crest length), with respect to traditional measurements (pendulums and survey targets)

Figure 8.10.1: Venina Dam from ground SAR station

Advantages with respect to traditional monitoring:

- It is not necessary to access the area to be monitored, also the installation of targets is not necessary.
- System is independent from the structure to be monitored.
- Surveys can be made also at night.
- Possibility to obtain displacements maps for the whole structure.
- Possibility to install instruments far from the structure (up to about 1 km).
- Possibility to collect measurements in emergency condition in order to monitor in “real time” the phenomenon in evolution (such as landslide).

Limitations:

- Some meteorological conditions or light conditions have an influence on the quality of the measurements.
- The displacements can be measured only in the direction of the line of sight
- The presence of snow during winter period and the vegetation in summer could cause signal disturbances.
- Phase ambiguity: the technology could not evaluate displacements corresponding to multiples of ½ length wave.

- Distortion of the flat image. The phase ambiguity and the distortion could be corrected by the use of a digital model, set up for example by laser scanning technique, and by mathematical algorithm.

The following figure 8.10.2 shows the measured displacements superimposed on a model of the dam structure, in a more practical presentation of the results.

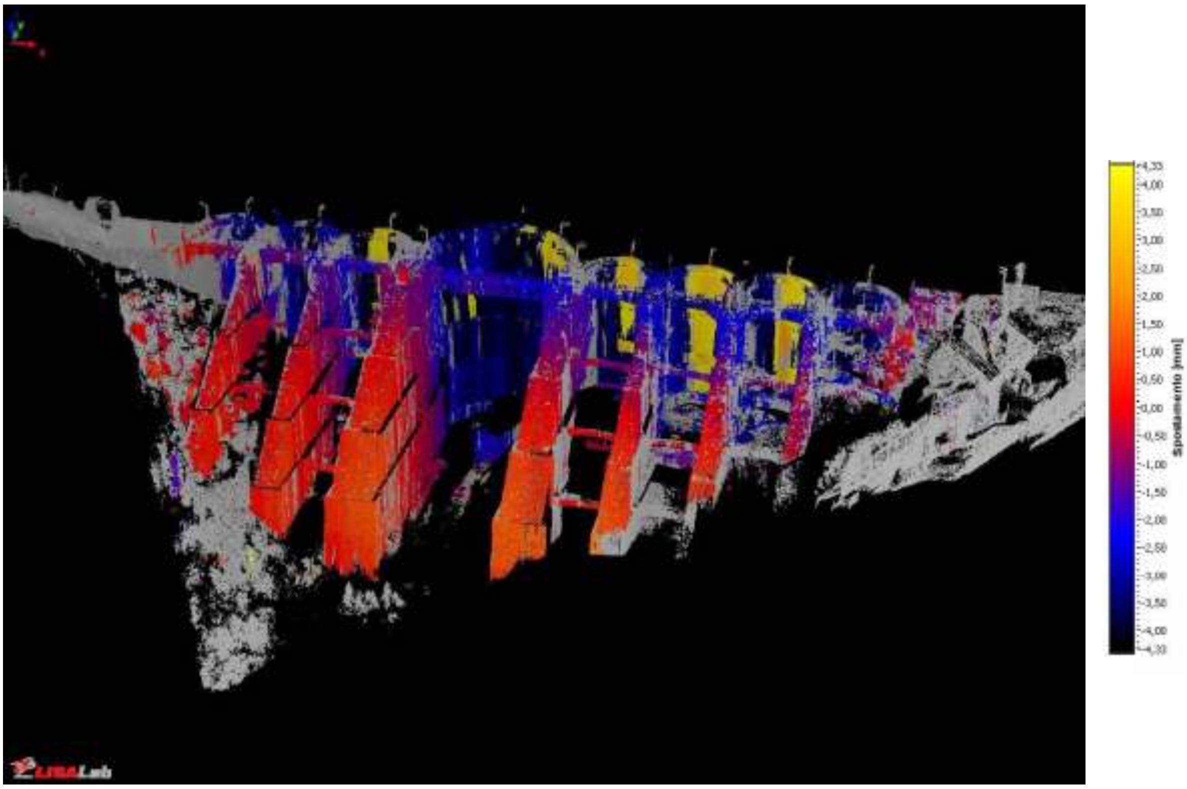


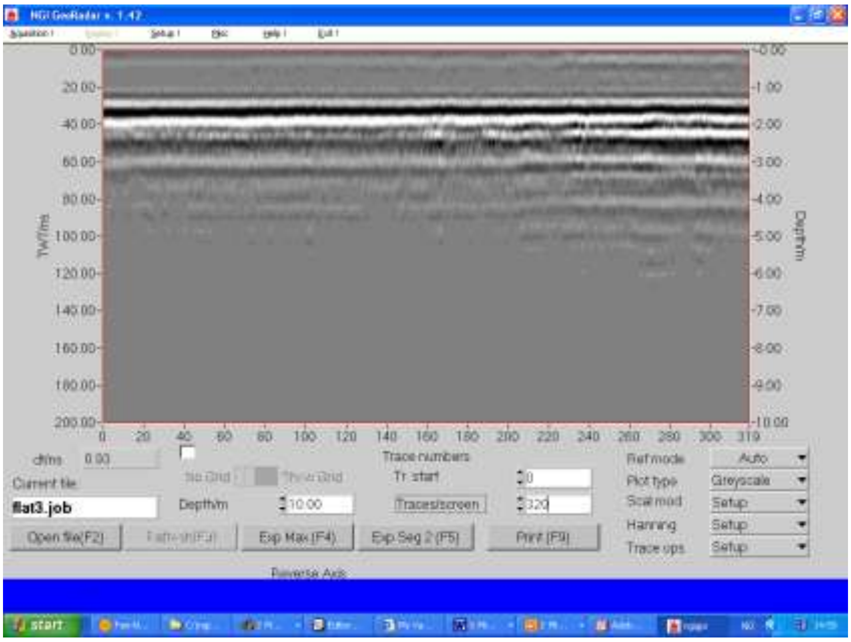
Figure 8.10.2: Venina Dam – Maps of displacements (August 2006 to December 2006). The comparison of dam displacements measured with SAR and pendulums highlights a good consistency and precision of the technology corresponding to ± 0.4 mm.

8.11 Ground penetrating radar

Ground Penetrating Radar (GPR) is a shallow distance geophysics survey tool using electromagnetic waves to develop a *radargram* image of the underground. Conventional GPR uses two antennas, one for transmitting and the other for receiving signals. There are two standard survey modes: (1) Reflection GPR which uses two antennas with a fixed spacing at the surface of the ground or object being investigated and (2) Transmission GPR which is based on signals transmitted through the media under study, for example between two boreholes. The typical detection distance is 0.1 - 30m.

Reflection GPR is a non-destructive method that can perform quick surveys to detect changes in the upper part of the core of an embankment dam. Two antennas with a fixed spacing are moved slowly along the dam axis. Radar signals are transmitted through the ground with the help of the transmitting antenna. The energy of the wave is reflected back towards the surface from zones where the electric or magnetic properties change in the core material. The reflected waves are received by the second antenna. Even though the detection distance is limited, GPR reflection measurements of the top of the core are commonly used for inspecting embankment dams. This is because changes detected in the core material at shallow depths may imply that disturbances have also taken place further down in the core.

Figure 8.11.1 shows the results of a GPR reflection survey of a 150 m long section of an embankment dam with a clay core. The left vertical scale TWT/ns is the Two Way Travel time in nanoseconds and the right vertical scale shows the travel distance in meters. From the figure one can see that there are no strong and sudden changes in reflection patterns; this indicates that the core is homogeneous.



dt/ns 0.00

Current file flat3.job

Depth/m 10.00

Tr start 0

Traces/screen 320

Ref mode Auto

Plot type Greyscale

Scal mod Setup

Hanning Setup

Trace ops Setup

Figure 8.11.1: GPR reflection survey of the top of the core of an embankment dam.

GPR reflection measurements have many advantages. For instance, the GPR survey is non-destructive and can be carried out very quickly. The antennas do not have to be in contact with the ground surface. The survey speed can be as fast as 2-3 km/hour. Equipment and analysis procedures are under constant improvement. For an experienced operator, the interpretation of the survey results can be made on site without further data processing. Hence the GPR survey is very low cost. It is also repetitive, since the radar signal is generated by the hardware electronics, and is always the same for measurements taken at different times.

Reflection GPR is based on detecting changes in arrival time and energy of electromagnetic signals reflected from a media. Transmission GPR on the other hand is based on detecting changes in the propagation speed of electromagnetic signals through a media, for example between a transmitter antenna and a receiver antenna embedded in the ground. Transmission GPR is commonly used for cross-hole GPR tomography, i.e. to obtain a 2- dimensional image of the changes in propagation speed between two adjacent boreholes. GPR tomography has been used to locate shear zones in soil and rock, detect defects in concrete structures and to detect voids in karst formations as illustrated in Figure 8.11.2. The method has also been used to monitor distribution of grout on projects where remedial grouting is used to control leakage through embankment dams.

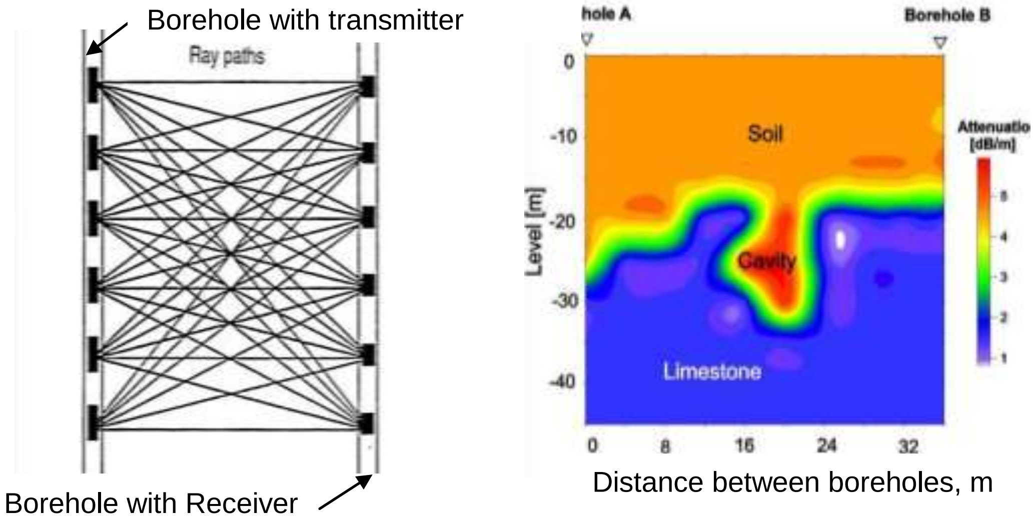


Figure 8.11.2: ***Example of GPR tomography between two boreholes in a karst formation.***

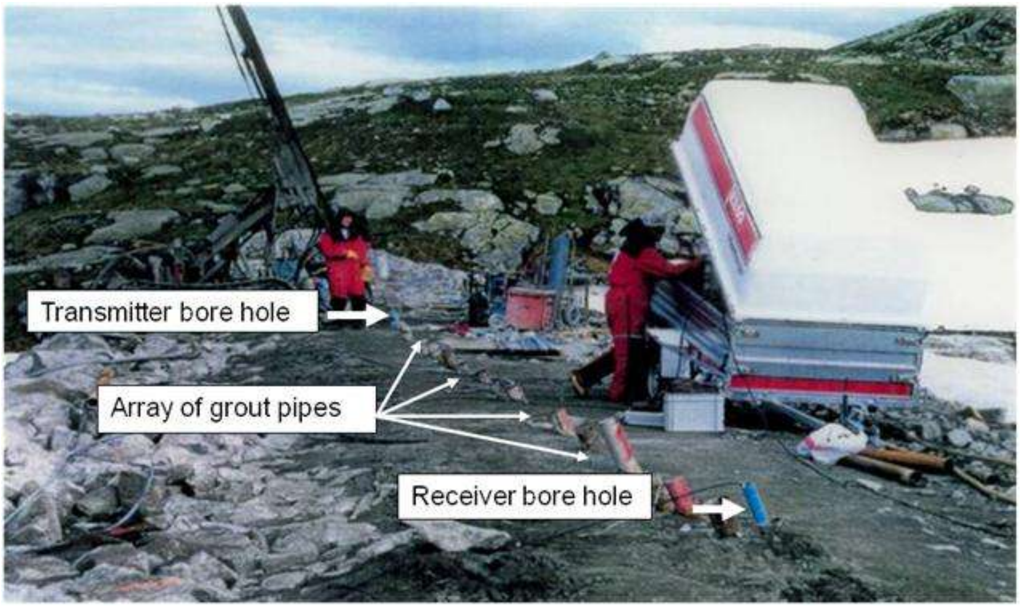


Figure 8.11.3: ***GPR set-up for monitoring remedial grouting of the core of a small embankment dam with a moraine core.***

8.12 Seepage measurement using Self Potential

Self-potential measurements (SP) have long been considered interesting for dam seepage investigations. The main reason is the methods' theoretical capability to detect fluid flow through the streaming potential mechanism, which generates electric potential variation in response to fluid flow through porous media.

The fluid flow causes a mechanical displacement of the electric charges that are loosely bound to the mineral surface (the so called electric double layer). The movement of electric charge causes an accumulation of charges downstream and depletion upstream. In most cases in nature the charges bound to the mineral surface are positive so that the downstream or outflow areas acquire a positive charge. Consequently upstream or influx areas become negatively charged. This charge separation creates electric potential differences that can be observed using common SP survey techniques.

The streaming potential generated SP-anomaly observed on an embankment dam depends on the following parameters: the cross-coupling coefficient, the hydraulic boundary conditions and the electric resistivity. The first two parameters define the primary driving convection current sources. The strength and location of these sources together with the resistivity distribution define the self-potentials in the ground.

Measuring SP is done using a pair of non-polarizing electrodes and a high impedance voltmeter. Installation of the electrodes in the dam is similar to the installations needed for resistivity measurements (see section 8.13). Factors that must be considered minimized or corrected for include: electrode polarizations effects, telluric disturbances (natural time varying potentials that are not related to the anomalies sought in an SP survey, often with amplitudes exceeding these), electrode drift, external electrical noise (power lines, electric equipment etc.).

SP has been used primarily for investigation but can also be used for long-term monitoring using permanently installed electrodes. SP can then detect changes over time in the state of the dam.

SP measurements are normally taken along several lines parallel with the longitudinal axis of the dam. Inflow areas will be shown as positive anomalies; while outflow areas will be seen as negative anomalies. Figure 8.12.1 shows, for example, the SP values along three measuring lines at an embankment dam. SP values depend also on the resistivity of the soil; therefore, measurements of both parameters are recommended. The result from the two measurement methods can be combined and plotted together as shown on Figure 8.12.2 which indicates two leakage pathways through the dam.

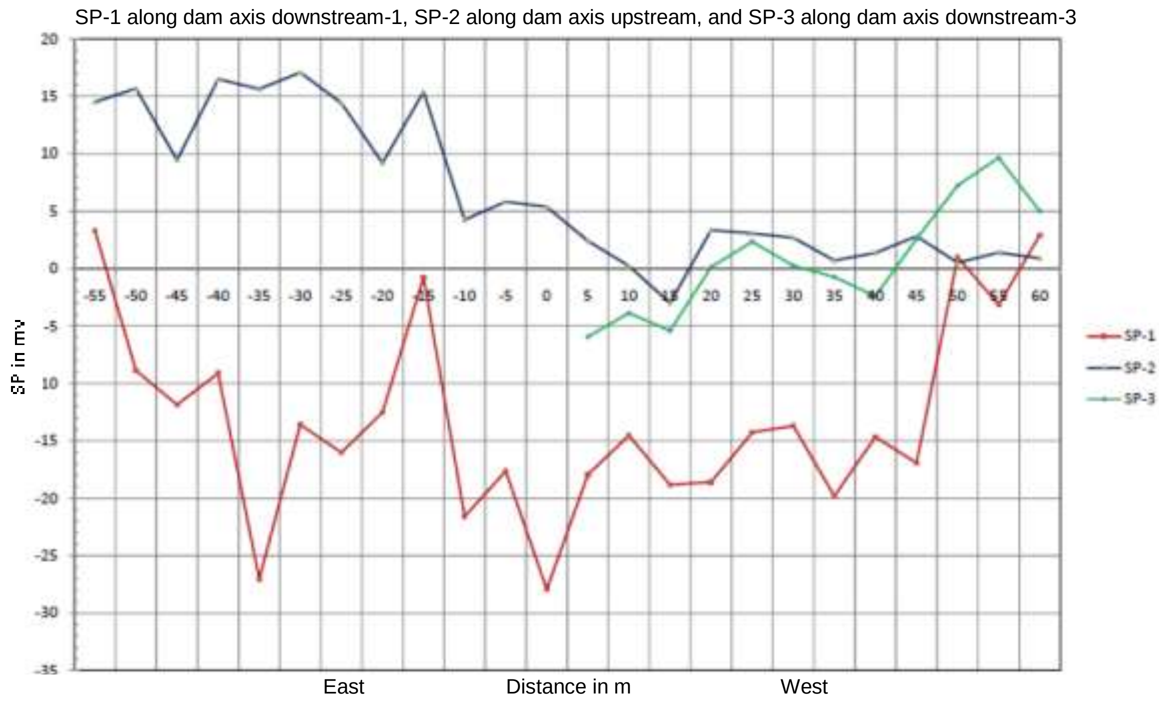


Figure 8.12.1: Results from SP-measurements along three lines at an embankment dam

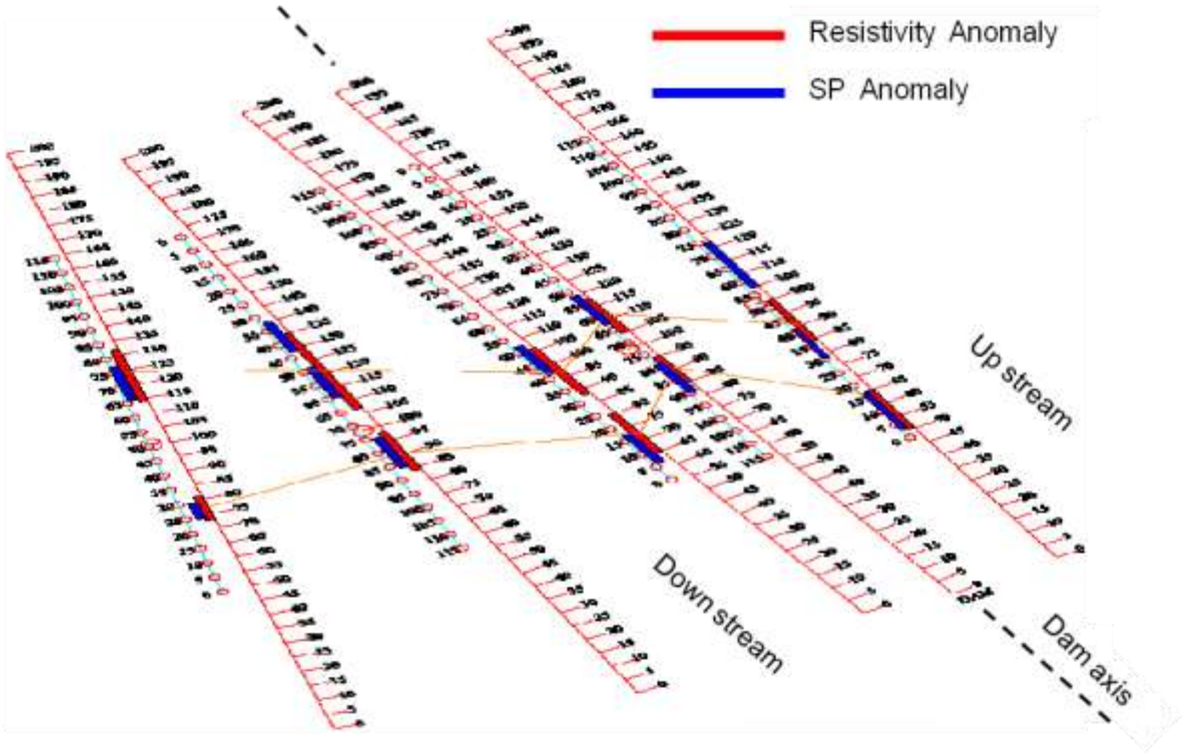


Figure 8.12.2: Presentation of SP - and resistivity anomalies along five lines at an embankment dam

References:

Corwin, R. F., (2005) Investigation of Geophysical Methods for Assessing Seepage and Internal Erosion in Embankment Dams: Self-Potential Field Data Acquisition Manual, CEATI Report No T992700 0205B/1, Canadian Electricity Association, Burnaby, British Columbia, Canada.

Sheffer, M., (2007) Investigation of Geophysical Methods for Assessing Seepage and Internal Erosion in Embankment Dams: Interpretation of Self-Potential Data for Dam Seepage Investigations, CEATI Report No T992700 0205B/3, Canadian Electricity Association, Burnaby, British Columbia, Canada.

8.13 Resistivity measurements

The resistivity method is an established geophysical method with a broad range of engineering and environmental applications. In the resistivity method an electrical current is introduced into the ground and the resulting potential distribution is measured. Since electrical resistivity of soils and rocks correlates with other soil and rock properties such as clay content, groundwater conductivity, soil porosity and degree of water saturation, useful information on the condition of the dam can be inferred. It has been applied numerous times on embankment dams, mainly for seepage investigations, dam status control and investigations of known defects.

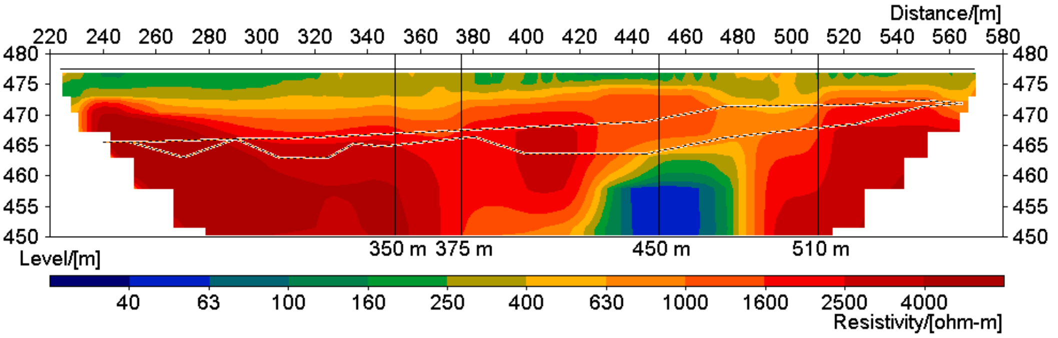
The method can be applied in two ways. Firstly, resistivity investigations as a one time survey may detect spatially anomalous zones along the dam, and can be used to investigate suspected structural weaknesses. Secondly, long-term resistivity monitoring make use of the seepage-induced seasonal variation inside the embankment to detect anomalies not only in space, but more importantly in time, by studying deviations from the time-variation pattern. The second approach is more powerful as repetition of measurements provides additional evaluation possibilities for seepage analysis. However, the monitoring approach is also more demanding as installations are necessary as well as long-term instrumentation.

The use of the resistivity method on embankment dams can be challenging and the anomalies are often small. Significant effort must then be made to achieve sufficient measuring accuracy. There are also many complicating factors for interpretation, such as for instance complex dam geometry, plentiful noise sources, rather small signals and reservoir level fluctuations. Advantageous factors for the method include it being non-destructive, the possibility to cover large volumes, the possibility to install on existing dams and the sensitivity of the method to changes in material properties and seepage flow among others.

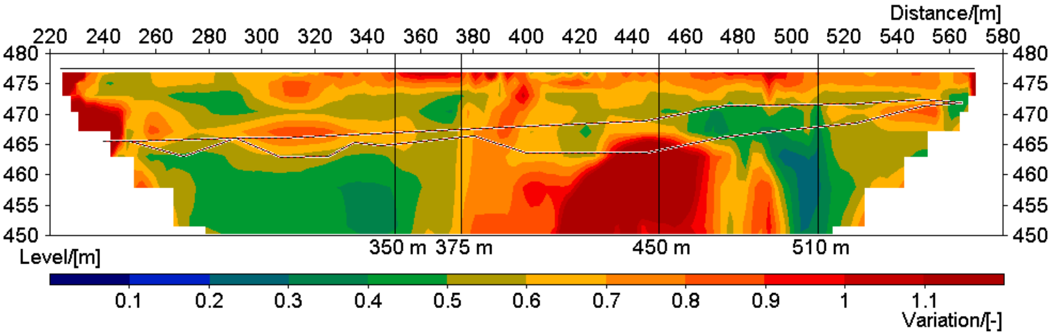
Standard resistivity surveying equipment may be used for dam investigations. For repeated measurements it is advisable to leave the electrodes in the ground between measurements. It is essential to make sure that good electrode contact is provided, especially in the case of permanent installations where the contact can often not be improved after installation works are completed. Processing of resistivity data includes data quality assessment, inverse numerical modeling and presentation and analysis of the results. Data quality is preferably checked in the field, typically by examining the pseudo section. Standard inversion packages may be used for data processing of 2D-measurements. Interpretation should be made with as much reference data as possible.

The monitoring approach is based on the principle that the resistivity in an embankment dam varies seasonally, mainly due to variations in temperature and ion content of the water in the reservoir. This causes resistivity variation in the dam depending on the seepage flow rate. This implies that areas in the dam with larger seepage may stand out as areas with larger seasonal resistivity variation, and increasing seepage may be noticed as increasing variations. Moreover, material change due to washout of fines may be detectable through resistivity measurements implying that trends of changing resistivity over time may relate to internal erosion.

In regards to practical aspects of performing resistivity measurements on dams, it is most common to perform 2D-measurements using an array of electrodes placed along a line. The complex geometry of the dam leaves two options, i.e. measurements where the survey line is placed along the dam, usually along the dam crest, or measurements where the survey line crosses the dam axis. The latter is often difficult to conduct in practice but whenever possible, it is a good complement providing detailed information in a specific part of the dam. Using a survey line along the dam is the most straightforward option and provides information on a larger part of the dam, although less detailed. The final choice of survey design should always depend on site-specific conditions.



(a), Average resistivity measured over a 4.5 year interval



(b), Relative variation in resistivity (ρ_{max} - ρ_{min})/(ρ_{median})

Figure 8.13.1: Measured resistivity distribution (a) and variation (b) along the longitudinal axis of the 32 m high zoned rockfill Sãdva dam in Sweden

References:

Dahlin, T., Sjödahl, P. and Johansson, S. (2008) Investigation of Geophysical Methods for Assessing Seepage and Internal Erosion in Embankment Dams: A Guide to Resistivity Investigation and Monitoring of Embankment Dams, CEATI Report No T992700 0205B/4, Canadian Electricity Association, Burnaby, British Columbia, Canada.

Johansson, S. and Sjödahl, P. (2009): A Guide for Seepage Monitoring of Embankment Dams using Temperature Measurements, CEATI Report No T062700-0214, CEATI International Inc., Montreal, Quebec, Canada, www.ceati.com.

Sjödahl P, Dahlin T, Johansson S (2009) Embankment dam seepage evaluation from resistivity monitoring data. Near Surface Geophysics 2009 (7): 463-474.

9 Data management

9.1 General

In a dam monitoring system, the management of data, including all procedures beginning with the data acquisition and ending in the data analysis, interpretation and reporting, is accomplished in two main steps:

- The first one, consisting of the data processing (set of operations including the data checking, reducing and storage, and the execution of numerical and graphical outputs)
- The second one, consisting of the subsequent analysis and interpretation of the dam behavior and including also the reporting of the corresponding results.

9.2 Data acquisition and processing

9.2.1 General Features

Manual data collection is the traditional way used at most dams in the world, and in any case it is complementary to an automatic monitoring system, if installed.

The data, including the visual inspection is collected by personnel reporting the data of the device, and is recorded on paper forms. The same approach could be considered for measurement recording on a palmtop or a personal computer directly during the collection.

Regarding data acquisition and processing, the following actions must be mentioned:

- Collection of data at: (1) fixed time intervals, and/or (2) controlling for consistent conditions at the damsite (e.g. temperature; reservoir level, etc.);
- Collection of data in the case of particular events such as a seismic event or other particular predefined conditions;
- Collection of data by explicit request;
- Check of data in order to increase the reliability of the measured values, which may signal a possible malfunction of the instruments;
- Data storage and periodic back-up;
- Periodic display and printing of data and other results of the data processing, showing in different ways the data trends
- Management of anomalies, particularly those resulting from exceeding allowable limits, triggering corresponding alarm signals;
- Display of the location of the different measurement points; and
- Easy access to the data reduction equations and to other logic programs and sets of specific instrument constants that are included in the data reduction portion of the system (though control of who has access to altering these needs to be appropriately controlled).

9.2.2 Data Validation and related actions

The data reduction is the calculation of the engineering quantities from the sensor readings. This calculation is to be preceded by a preliminary check of the raw values (following the execution of functional tests on measurement equipment), that involves comparing the actual values with two limits corresponding to the instrument’s measurement range.

The data checking shall be made on the engineering quantities, on a sensor by sensor reading basis, by comparing each value with the two limits of the allowable ranges predefined by the dam safety engineer. This range may be "statically" or "dynamically" established.

In the first case, the limits define a fixed (at least during a certain period of time) range within which, under normal circumstances, values should fall. This range will be the smallest possible that the knowledge about acceptable value variations permits. For dams having some years of operation under a reasonably wide variation of load combinations, the corresponding history of data values enables the definition of acceptable intervals by taking into account the limit values already observed. During the first filling of the reservoir and during the first period of operation those limits can be established on the basis of the data obtained in the physical and/or analytical models established in the design (such as, for example, those regarding the values obtained for the more severe normal load combinations).

In the second case, the difference between an actual recorded value and the value calculated by means of a predefined behavior model is compared with the predefined allowable range. These models, the calculation of the expected values taking into account the load condition at the time of the reading, as well as the determination of the allowable ranges, will be dealt with in Section 9.3.

Whatever the case, the dam safety engineer is to define the value of the difference between the actual values and the closer limit value from which the situation is considered abnormal (regarding the instrument performance, or regarding the dam behavior if the instrument has not suffered any disturbance), which will emit an alarm signal. Obviously, the ability to define the above mentioned ranges as well as the alarm values for each data sensor is essential. In fact, due to the large amount of data usually produced by dam monitoring measurements, it is important to screen incoming data and to alert reviewers of any values that exceed the predefined limits.

It is hardly likely that all data collected from the same instrument will fall in the predefined allowable ranges, even when there are no changes in the dam behavior. Therefore, the occurrence of a sequence of values falling outside the predefined interval, but not exceeding the alarm values, must be followed by:

- A specific and careful analysis in case those values maintain or increase the deviation from the allowable range. This analysis must be precise and carried out in the shortest possible time if similar increases in deviations also occur for other instruments;
- The qualification of such data (values), if subsequent data returns to values within the allowable range, in order to indicate that such data is questionable and needs to be explained.

As the dam behavior has not changed, at least significantly, as is "proved" by the data returning to normal values; the qualified data may correspond to erroneous measurements due to some external factors or to valid measurements corresponding to situations not envisaged when establishing the allowable ranges.

9.2.3. Data Storage

It is advisable to design and use a database that contains the monitoring data selected to be stored.

By taking into account the new capabilities of modern computers, this approach has almost no limits. Although data may be stored in separate files - one file for each sensor - it is better to build a "solid state" database. The operation of that database is to be governed by specific rules allowing for a better approach when establishing relationships between all the relevant variables. Data portability must also be considered as a primary factor.

The data to be stored can be either the raw values only, the engineering quantities only, or both. The fact that when the raw values are not engineering quantities, they are meaningless means, the option of storing only the engineering quantities may be adopted. However, as it is relatively easy and practically inexpensive to reprocess batches of data if changes in data reduction programs or computational procedures are desired, the option of storing raw values may be preferred. The recommended option is to store both quantities, namely: the engineering quantities, which are to be used for the subsequent operations, such as analysis and the raw data, which are only to be used whenever a need arises to recover this data. The cost of electronic storage of data is now so low that storage of all data is a reasonable option that should be considered.

Not all data, whatever the type, needs to be permanently stored, especially when the frequency of the automatic data acquisition is significantly greater than the one corresponding to the manual acquisition. In fact, if the software ensures that all data eventually corresponding to a changing of the dam behavior will be adequately detected and duly identified, only representative data may be permanently stored. However, when using an automated measurement system, it is advisable that all collected data also be stored, but in temporary files. These files could be subsequently transferred to a mass storage device (e.g. a tape or recordable CD-ROM) to release hard disk space and for redundancy. For example, if the data is typically collected every hour, the data storage may be organized by creating the following temporary archives:

- One archive to store all data collected during a month; and
- One archive to store one value per day, during a year (the value corresponding to a predefined hour, for instance, at 2:00 in the morning, in order to avoid daytime thermal disturbance.

Whenever the structure is very sensitive to temperature variations, it is advisable to create specific archives containing more frequent pertinent data in order not to affect the statistical processing involving temperature function analysis.

These temporary archives are to be replaced by the next similar ones, unless something unusual happens, as for example, if the established allowable limits have been exceeded. In this case, the temporary archives can only be deleted after the diagnosis of the problem by means of an action from the dam safety engineer. The permanent archive would be for storing only the significant data for the phenomena under consideration, for example, one data set per week (the value corresponding to a predefined hour and day of the week, for example, 2.00 in the morning of every Wednesday, except when temperature variations are especially important, in which case, the above note must be taken into consideration).

The raw data and even the engineering quantities are by themselves often meaningless. This is the reason why the dam safety engineer, or the monitoring personnel at the dam site, in case the corresponding software is available locally, need to see in the computer display or in plots, sequences of the engineering quantities and/or chronological diagrams or any other type of graphical representation of data showing the evolution of these quantities usually plotted versus time and reservoir level, and whenever justified, environmental temperature. The software must then produce, on a routine basis and at the request from the system operator, lists and diagrams showing the data evolution. The software shall be flexible enough to permit, in an easy and in a user-friendly way when requested by the system operator, changing the format of the printed outputs or displays (for instance, change the scales of the diagrams) or to produce specific printed output or displays.

9.2.4. Archive Entry and Editing of Data

Even with an automatic monitoring system there should be facilities to permit manual data entry in order to cope with situations such as the automatic system check, and the possibility of system being out of order, or system failure. The manual data entry must be automatically followed by the full reduction of data to engineering quantities. The same criteria for scanning allowable ranges and alarm values described above would be applied to manually entered data as well.

The use of portable measuring devices equipped with data storage, that allow the direct feed of measurement records to archive, or the use of portable devices (lap-top type) allowing the recording, the immediate validation of the measured (by a manual measuring device) data and the direct feed of these records to the archive makes the manual operations easier and more reliable. It is important that the operator (user) of the system must have the capability to define new types of sensors and update the inventory of project instrument types in a straightforward manner.

A well planned data management system should provide the reviewer with all the information needed to assess whether an instrument reading is accurate or it just reflects malfunction of a sensor, or it might be related to field conditions at the time of reading.

9.2.5. Management of Alarms and Anomalies

One of the most important requirements of the systems is to allow for rapid (the "speed " depending on the frequency of the data collection) detection of any anomaly, particularly those concerning the dam behavior that would impact on the monitored physical quantities.

Therefore, mixed with some real behavior problems, there will be a number of false alarms requiring a careful analysis. This justifies that the alarms emitted by the automatic system will be exclusively technical alarms, i.e., emitted only to the safety control agents (culminating in the highest responsible, the dam safety engineer).

An alarm concerning only a sensor reading, despite needing a quick and careful assessment, will correspond usually to an equipment anomaly or to a situation not covered by the hypothesis supporting the establishment of the allowable limits. A completely different situation corresponds to the emission of alarms concerning not only several instrument readings but also several successive readings. Despite the possibility of being also a consequence of an anomaly affecting equipment that controls these instruments, the alarms' coincidence and continuity require a thorough check.

This check may include (i) performance of a special test on the sensors' performance specifically requested by the system operator or by the dam safety engineer, (ii) taking a series of supplementary readings followed by its processing and analysis, and (iii) conducting a visual inspection of all possible aspects, features, and places where some evidence of possible behavior disturbances may be apparent (particular attention shall then be paid to the increase of depths and water pressures, to joint displacements, to new cracks or leakage, to the turbidity of seepage waters, to settlements, etc.). In the case of such a situation occurring, it is absolutely necessary to carry out all recommended tasks until a convincing explanation is reached. Since the kind of actions to be implemented in confirming the occurrence of an anomaly in the dam behavior, that possibly might affect its safety, is not specific to the automatic monitoring systems, they are out of the scope of this bulletin.

9.3. Data analysis

The data analysis consists of the management of the previously stored data (monitoring data, material properties, geometric characteristics of the dam, external connections of the body of the dam, etc.) in order to obtain the things that are needed by the dam safety engineer to interpret the dam behavior.

A typical example of data analysis is represented by the so-called behavior models. By assuming a certain generalization, the same designation may also refer to the functional relationships between observed effects and the corresponding actions resulting from the application of methods of quantitative analysis. These methods may be classified as statistical, deterministic or hybrid methods and the resulting "models" classified accordingly. Other examples of preliminary data analysis include the determination of averages or moving averages and the execution of Fourier analysis.

As regards the behavior models, the software is to include the models to be used in the data checking that is done on a routine basis (usually those resulting from the application of quantitative analysis methods) and the procedures to define new models for replacing the existing ones or for supporting a more comprehensive interpretation of the dam behavior.

When the data checking is made by means of behavior models, the allowable range may be established on the basis of the standard deviation ("s") of the differences ("d") between the measured values obtained during two or three years of normal operation and the corresponding values obtained by means of the forecast model. The limits of the allowable range may be fixed as equal to twice the standard deviation (assuming that the distribution follows a normal law and then that approximately 95% of the d's values will fall in the interval ±1.96s - 2s).

Other intervals may also be established, on the basis of the same standard deviation (for instance, "d" falling outside the interval ±2s but within the interval ±3s, etc.) to which different signals will be associated, permitting the perception of how much the dam behavior is away from the "normal" behavior. If the value of "d" falls outside a certain range previously defined by the dam safety engineer, a careful analysis must be done.

Similar to the data processing, the data analysis is to be performed not only at the processing center but also at the dam site. Usually developed up to a preliminary state only, compatible with the technical background of the monitoring personnel, the analysis performed at the dam site aims at the verification, in a simple way and as soon as possible, of possible evolutionary behavior trends. The execution, at the dam site, of such analysis will not only facilitate the task of the dam safety engineer but also may contribute to a more reliable safety control. In fact, the monitoring personnel introduce a human judgment at the dam site that can identify, in due time, possible automatic monitoring system (if any) failures as well as events needing urgent corrective actions. In these cases, the monitoring personnel will alert the dam safety engineer.

9.4. Behavior models

As we have seen, interpretation of the measurements requires a comparison of the currently computed data with reference values, or their transformation into standard conditions, and an account taken of the influence of all the variations that occur in the dam's environment.

It follows that it is necessary to establish a procedure, a mathematical model, to work back from the environmental conditions to the aforementioned reference values.

This model will be able to rely on experience of the past (statistical model), on a logical mathematical formalization of the law that the dam is thought to obey (deterministic model), and, lastly, on both of those considerations together (hybrid model).

In each case, it is therefore a question of establishing a link between a group of variables considered as the "causes" of behavior, imposed by the dam environment, and another group of variables considered as the "effect" characterizing the structural response of the dam to these actions. This link being sought through a statistical correlation procedure for the models of that name; starting from our knowledge on the geometry of the installation, of the acting loads and of the physical and rheological properties of the materials and foundations, in the case of deterministic models; and lastly, in the case of "hybrid" models, the first type of procedure is used for certain components of the effects in question and the second type for other components.

Among the "cause" quantities, we would above all include the reservoir water level and the external or internal temperature (or the season of the year, if temperatures are not measured). The "affect" quantities include displacement, dilatation, water leaks, piezometric pressures, effective stresses, etc. The measurements of these values must be taken at the same time.

9.4.1. Statistical Models

In order to establish a statistical behavioral model, it is necessary to have available chronological series of data in respect of the "cause" and "effect" quantities that are as complete and homogeneous as possible.

The well-known statistical analysis of the correlations (analysis of variance, covariance, etc.) will then enable one to:

- ascertain whether a functional link can be detected at a given level of statistical significance
- if so, estimate the most probable functional correlation parameters.

A by-product of the analysis will be the definition of the distribution of the deviations of the "effect" of quantities observed and their reference values as given by the correlation model established. In general, the performance and reliability of the results of statistical models (and deterministic models, as well) is higher in the case of concrete dams. The result of statistical and deterministic models should not be used without first doing a critical review of their reliability.

9.4.2. Deterministic Models

A scheme is established of the installation and its foundations, which is represented as a solid of known geometrical shape possessing more or less well-known physical and rheological properties, and subjected to external actions (hydrostatic pressure, thermal variations), defined in a suitable way. A procedure for analyzing the structure – for example, finite element - will then enable one, in principle, to relate the "reference" response of the dam to any external action. It must be noted that in the case of fill dams, the effect of all the previous history of the dam, including the construction stages, must be taken into account as their behavior is very dependent on the loading history.

It is necessary to perform more detailed computations (finite element analyses, for example) only once, at the beginning, for all the "unit" functions. The responses to real load cases are then given, on the often admissible assumption that behavior is linear, by linear combination of the elementary load cases. This is a simplified assumption which is normally acceptable for concrete dams. On the contrary, for fill dams, it is necessary to resort to more general hypothesis, that are however, more cumbersome to translate into practical application. Consequently, the reliability of results often is higher for concrete dams than for fill dams, since the definition of material properties and behavioral relationships typically can be done with more confidence and accuracy.

To put this procedure into practice, it is necessary to have available the measurement data concerning the water level of the reservoir and the temperature (at least, the air and water temperatures), as well as information on the thermal and rheological characteristics of the material.

A procedure needs to standardize these characteristics, based on comparison of the "forecasts" of the model with the corresponding values observed over a sufficiently long period of time (without the influence of initial disturbances).

9.4.3. Hybrid Models

Recourse is sometimes had to models of this type in cases where data exists (for example, water-level measurements) which is needed for estimating an effect component, but in which there is no data that is indispensable for estimating other components (for example, the temperature of the concrete is not measured, nor even that of the air and the water, so that a deterministic model cannot be supplied with the thermal effects).

In this case, a statistical estimate of a seasonal component - in other words, only a periodic time function - may suitably accompany a deterministic model of the elastic deformation of the body of the dam due to variation in the hydrostatic load.

9.4.4. Neural network models

Neural network systems, on the other hand, do not require any understanding of the behavior of the system being represented. Instead, they simply rely upon an ability to match patterns, without needing an underlying model to explain how or why the system produces particular output from the given input. One key advantage of artificial neural networks is the ability to cope naturally with noisy input, both in the training phase and when applied to new data. It is important that the results from neural network models be validated by dam engineering experts.

The effort to build up and run neural network systems is high in comparison with other types of models. Therefore, at the present time, this approach is generally viewed to be more of a possible future alternative that is being researched and developed.

9.4.5. Critical Remarks on the Three Types of Model

To establish a valid statistical model, it is necessary to have available a sufficient number of observations, taken in a sufficiently varied range of "cause" quantities. The model will not, therefore, be able to be used for control until after an adequate or a sufficient amount of observation data is collected. It will, therefore, be unavailable for "control" during the first filling of the reservoir, which is the most critical phase in the life of the dam. On the other hand, the model does make it possible to analyze all kinds of measurement made on all types of dams, and is convenient to show the evolution over a period of time of an installation's performance.

It is, therefore, well suited for "control" during operation of the dam. Moreover, it is both easy and quick to set up such a model, that calls for no previous knowledge of the geometry of dam or of the properties of the material - such as, elasticity modulus and Poisson ratio for the concrete and rock, the thermal capacity of the concrete and the rock, and the physical and rheological properties of the soils and terrains.

A good deterministic model is the only one that allows obtaining certain reference values indispensable for safety control during the first reservoir filling. However, the properties of the materials used in the body of the dam are not known with complete certainty. The same applies, with much more uncertainty, to the materials forming the foundation. For each state of "cause" quantity and for each "effect" quantity, it is therefore only possible, at the beginning of the installation's life time, to define a fairly wide "reference interval", but not a "reference value", characterizing normal behavior.

For certain quantities (for example, water leakage flow); it is not common to formulate deterministic models. Only statistical models can, therefore, be used. Likewise, deterministic models cannot give an overall picture of the behavior of fill dams, at present. Moreover, it has already been noted that no model is, in fact, purely deterministic, and the most probable physical and rheological constants values are provided by statistical analyses, even for deterministic models.

9.4.6. Tolerance limits

Lastly, a statistical analysis of the deviations between model forecasts and the corresponding observations are, in any case, necessary for definition of the width to be given to the "tolerance interval" of those deviations. By this we mean that it will only be possible to assign an alarm value to those deviations if they exceed, by a statistically significant amount, the natural variability of the distribution of the deviations observed under "normal" conditions over a suitably long period.

Obviously, this criterion is to some extent arbitrary, and means that the alarm threshold for the deviations cannot yet - desirable though it might be - be associated with rational considerations in respect of hazard and cost.

9.5. Data Reporting

The data management software should have the capability of producing standard reports with a repetitive format. The reports would be generated on a monthly and annual basis. Ad hoc reports should also be possible, where the user defines the format and the instruments to be reported.

A special procedure for visual inspection reports should be considered. In this case, the database must include tables specifically designed for that type of information including the possibility of increasing or changing the topic list. Reports can be made by both summarizing the topics for each date or by analyzing the evolution of a specific topic with time.

9.6. Data Interpretation

The data interpretation consists of the evaluation of the dam safety condition not only on the basis of the results produced by the measurements but on the whole set of entities related to the dam, namely the dam body, its appurtenant features and their foundations, environment, etc., and also including past knowledge and experience, physical laws, specific models, regulations requirements, etc.

Specialized software, based on artificial intelligence (AI) techniques, for carrying out on-line interpretation of dam behavior and for evaluating, explaining and filtering alarms generated by the data analysis have already been implemented and tested with considerable success. In order to take full advantage of an automated monitoring system, trends on new technology development tools towards a better understanding and control of dam safety will necessarily resort to the AI techniques. The most common AI techniques so far used in the field of the safety control activities are (i) the expert systems and (ii) neural network systems.

Expert systems depend upon the existence of expert knowledge or heuristic regarding the behavior of the system in question. This implies that the expert has some understanding of the system, which may be expressed in terms of a model. A key feature of an expert system is to tell a user "how" a conclusion has been reached, by outlining the data and sequence of rules which led the reference engine to that conclusion.

The two technologies in many ways represent complementary approaches: the logical, cognitive and mechanical nature of expert system approaches, and the numeric, associative, self-organizing, biological nature of neural network system approaches. A good approach for the data processing systems (DPS) would include a neural network for the data processing, having the instrument signals as input and filtered data as output for an expert system aiming at the data analysis and interpretation.

So far, the implementation of artificial intelligence techniques allowed for the automatic execution of a certain type of data interpretation, even though not dispensing with the intervention of the dam monitoring engineer, especially when the results of the application of such techniques indicate the possible occurrence of an abnormal situation. Regardless of how developed artificial intelligence techniques become, complete reliance on “black box” solutions is inadvisable. Appropriately trained structural and geotechnical experts should always be employed in reviewing and interpreting monitoring data, utilizing AI techniques and input to benefit the process as appropriate to the situation.

When sufficiently reliable input data is available, artificial neural networks can also be used to predict future measurements or to establish allowable range limits for the measurements.

9.7. Software available

The standard mode software is the software that performs the data processing, analysis, interpretation and reporting. The other one is the so-called Supervisory mode software necessary to activate or to reactivate the system, to supervise it, to control, to check and to maintain the system, and to establish the local and the remote communications, etc.

As regards the standard mode software; there is already considerable experience in some countries, usually developed on the basis of the previous experience obtained in dealing with similar matters within the scope of the manual data acquisition. However, some developments are underway in specific subjects, as for example, those concerning data basis techniques, behavior models and expert systems.

Although it will be very useful to any entity that envisages the automation of the monitoring activities to have the possibility of using commercialized software that makes it possible to carry out, in a general way, the automatic procedures involved in the data processing, analysis and reporting, and even, if possible, in the data interpretation; use of such software will entail extensive and thorough work that will certainly be necessary to adapt that software to each particular dam.

All software should be thoroughly checked for accuracy by manual methods before being employed.

10. Dam documentation management

Efficient management and surveillance of dams, like any other major civil engineering structure, needs permanent and immediate availability of all relevant updated information on its design, its construction and its operation.

All dam owners have a responsibility to manage documents and records that provide documentary evidence of the safe operation and maintenance of these facilities, according to their national regulations and/or updated state of the art.

Dam records are of enduring value and are a critical part of the owners and operator’s archives, which constitute the institutional memory for these very long lasting facilities.

Nowadays, document management begins with the conversion of paper or other documents into digitized images or files that can be easily organized and quickly retrieved, indexed and archived. This operation should be carried out under the supervision of highly experienced dams engineers, geologists and hydro-mechanical personnel, to classify available information by speciality, importance, conservation period etc.

There are many ways that documents and records may be efficiently filed and maintained. Some characteristics of effective filing systems include:

- well-designed file structures
- well-established procedures regarding what gets filed and how the files are managed

- well-defined roles and responsibilities for maintaining the files

When applied to dam documentation, classification systems may be made according to the following criteria:

- Documents stage: Design, construction and operation;
- Documents contents: survey, design, construction, operation, expertise;
- Documents type: text, drawing, presentation, picture, video, audio;
- Dam components: dam (wall), foundation, reservoir, ancillary works, navigation, powerhouse, …etc;
- Dam specialty: earth works, concrete works, grouting, hydro-electromechanical, monitoring, etc.;
- Documents date: chronology of documents production.

A classification system for the documentation and records of dams is presented in Table 10.1.

It is worthy that management of dam documentation includes the preparation and updating at regular intervals of a "briefcase" containing all relevant information, easily transportable. This information may be available on digital form along with a hard copy of frequently used documents. It is advised to cover the following items:

- Synoptic description of the dam and its appurtenant works.
- Main drawings (20 to 30) on A3 format: layout, excavation, geology, ancillary works, foundation treatment, instrumentation, hydro-electromechanical equipment,
- Description and justification of design options, updated according to adaptations introduced during construction or operation,
- History of the dam since its first impoundment, with a chapter on any eventual issue or item requiring special attention.
- End of construction reports, especially those related to quality control.
- Latest report on instrumentation data analysis and site visit inspection.
- Note on any eventual large repair works carried out or on hold.
- Maintenance instructions
- A comprehensive list of references presented by topic (general studies, drawings, monitoring, equipment …etc.)
- Any eventual expertise reports
- Photos and videos during construction and under operation
- Reservoir bathymetry and hydraulic balance (to be updated each 2 years and after any major hydrological event)
- Executive summary of environmental impact and economical studies.
- Names and phone numbers of persons to be contacted for each specific event.

The ‘briefcase’ should be placed under the responsibility of an Engineer and permanently updated particularly for monitoring data analysis, periodic inspection visits, repair or maintenance works and bathymetry.

The most convenient way for gathering, retrieving and updating dam documentation may be achieved using a geographical information system. It needs however an important effort to build, and is therefore more justified for the time being for very large dams.

Ensuring the long-term integrity and continuous availability of data and important documents is a critical issue, considering threats associated with fire, power outages, software changes with time, and hardware changes with time. Important considerations include developing and maintaining reliable back-up systems, regularly updating software file systems, and preserving data and important documents in more than one form (paper copies, electronic files, including different types and methods of electronic files, etc.).

Table 10.1 Classification system for dam documents and records

Class One	**Class Two**	**Class Three**
Dam Site Survey Data	Topography / bathymetry	Classify by scale and by year
	Investigations - Geology	Classify by work
	Hydrology / Climatology	Classify by year
Design Documents	Geotechnical / Geomechanical	Classify by specialty and date
	Hydraulics calculations and model	Classify by work and by date
	Design documents	Classify by design report, drawing, date
Construction Documents	Construction drawings and calculation notes	Classify by works, drawings,
	Final reports	Classify by works
	Quality control	Classify by item, date
	Reports, during construction	Classify by item, date
Operation Manual	Dam operation manual	Classify by item
	Operation and maintenance reports	Classify by work and by date
	Inspection and checking records	Classify by work and by date
Monitoring Documents	Monitor equipment drawings and description	Classify by instrument type and by date
	Original records	Classify by instrument and date
	Engineering data	Classify by instrument and date
	Monitoring reports	Classify by work and date
Special Records	Reservoir stability slopes	Classify by zone and by year
	Large floods	Classify by year
	Earthquake and other special events	Classify by year
Inspection Reports	Regular inspection reports	Classify by works and by date
	Yearly inspection reports	Classify by works and by year
	Special Safety inspection reports	Classify by works and by year
Safety Appraisal	Construction safety appraisal reports	Classify by first storage, complementary and special items

Reports	Safety analysis reports once every 5 year	Classify by report date

11. Assessment of condition and behavior of dams

11.1 General

After all the expense and hard work of putting in place monitoring systems for a dam, then collecting data and information (perhaps using automated methods for some or all of the instruments), and then storing and managing the collected data and information, the payoff comes in being able to accurately and confidently assess the condition, performance, and behavior of the dam. Such assessments are of three basic types:

- General understanding of dam behavior
- Generic performance assessment
- In-depth, failure-mode-based performance and program assessment.

Each of these assessment types are discussed in the sections below.

11.2 Understanding of dam behavior

Instrumentation data can allow checking/verifying of actual performance against performance expectations assumed during the design process for a dam. Instrumentation data can also add to the profession's understanding of the behavior and performance of dams. The data is particularly valuable when information from a number of different dams can be assembled and analyzed. Examples of the knowledge that can be gained include:

- The patterns of water pressure dissipation at a damsite, such as moving through the core of an embankment dam, moving from the upstream side to the downstream side of a grout curtain or seepage cutoff feature, etc.
- The patterns of the dissipation of excess construction pore water pressures in the core of an embankment dam.
- Embankment settlement performance.
- Foundation settlement performance, with consideration of the differing types of materials that might be present (jointed v. unjointed bedrock, dense v. loose overburden material, etc.).
- Deflection performance of concrete arch dams, considering reservoir levels and temperature loadings.
- The effectiveness of measures used to control heat of hydration temperatures in mass concrete.

The actual measured performance of dams can be compared to the predicted values from analytical methods and models, which promotes increased understanding of the dam in question, and can also result in improvements to the analytical methods and models.

Information regarding the actual measured performance of dams can aid practitioners in dam engineering to develop an improved understanding of the behavior and performance of dams, which presumably will result in improved designs and evaluations in the future.

11.3 Generic performance assessment

Some aspects of a performance assessment for a dam do not necessarily require an in-depth knowledge of the dam and damsite. Instead, having a solid background regarding dams and dam performance in general can allow important conclusions to be developed from an assessment that is generic (not site-specific). Table11.1 below gives some examples.

Table 11.1 Generic performance assessments. (Assumes normal operating conditions – not post-earthquake or flood loading conditions)

Performance Information	Possible Significance
Embankment Dam	
New seepage area, increased flow from an existing seepage/wet area, or anomalous increases in a monitored drain flow	New or increased seepage emerging at the toe of the dam, on the abutments, on the downstream slope of the dam, or in areas downstream of the dam could be of great concern because it could relate to initiation/development of a seepage-related potential failure mode. Similarly, an increase in any of the monitored seepage/drain flows would indicate changed seepage conditions at the damsite that could possibly relate to initiation/development of a seepage-related failure mode. Close monitoring of the dam should be instituted, and the situation should be promptly investigated.
Evidence of material transport by seepage flow	This is a direct indication of possible seepage erosion or piping. Small amounts of sediment or small seepage rates that are constant could indicate the potential failure mode is just initiating/developing. Muddy seepage that is rapidly increasing is very serious and dam failure could follow quickly.
Anomalous water pressure data	Unusual piezometer water pressure readings (not consistent with historical performance) could indicate changed seepage conditions/performance of the dam and/or foundation and should be promptly investigated. Such data would be of most concern when occurring in conjunction with other evidence of changed seepage conditions (new seepage or wet areas, changes at existing seepage or wet areas, anomalous increases in monitored drain flows, etc.)
Sinkholes, or unusual embankment settlements or deformations	Sinkholes could be due to subsurface removal of embankment or foundation material by seepage flow. Similarly, unusual settlements or deformations could indicate subsurface material is being removed by seepage flow. It should be noted that sinkholes or unusual settlements or deformations could also be related to other occurrences or situations at the dam (unrelated to a potential seepage-related failure mode). However, sinkholes or unusual settlements or deformations of the dam embankment should be taken seriously and investigated quickly.

Performance Information	Possible Significance
Transverse crack (upstream-downstream direction)	This does not mean that a seepage-related failure mode is necessarily underway, but only that increased attentiveness to this possibility is warranted. Changes in the seepage performance of the dam (including monitoring of embankment and foundation water pressures) provide the best indication of whether a seepage-related failure mode may have initiated. Close monitoring of the dam should be performed during reservoir filling above the current reservoir level.
Longitudinal crack (parallel to the axis of the dam)	This could be due to sliding instability of the dam, which would be of great concern. This also could be due to embankment settlement, perhaps due to differing rates of consolidation for adjacent zones in the embankment. In any event, the dam should be closely monitored for at least a few days to ensure that no continuing sliding movements are occurring.

Concrete Dam	
New cracks in concrete, or extension or widening of existing cracks	Pattern cracking typically is not of great immediate concern, but cracks that appear structural in nature (significant length, linear or semi-linear, diagonal, etc.) would be. The appearance of such structural cracks could be a direct indication that a portion of the dam, or dam and foundation, has displaced slightly, or is about to displace (crack occurred due to high stresses in concrete). This situation should be taken very seriously and immediately investigated/studied. Structural failure of the dam could occur very suddenly, at any time, with essentially no additional warning or precursors of failure.
Offset at a contraction joint	The appearance of an offset at a contraction joint could be a direct indication that a portion of the dam, or dam and foundation, has displaced slightly. This should be taken very seriously and immediately investigated/studied. Structural failure of the dam could occur very suddenly, at any time, with essentially no additional warning or precursors of failure.
Anomalous plumbline or structural measurement point data	If not accompanied by new structural cracking of the dam, or offsets at contraction joints, then apparently the indicated movements have not been sufficient in magnitude as yet to lead to stress sufficient to cause cracking or joint movements. However, this data directly indicates structural distress and should be promptly investigated/studied. If accompanied by new structural cracking of the dam or offsets at contraction joints, this data should be taken very seriously as structural failure of the dam could occur very suddenly, at any time, with essentially no additional warning or precursors of failure.
Increased uplift pressure	This would be of concern, and the situation should be promptly investigated/studied. If decreased drain flows accompany the increased pressures, this would indicate possible drain plugging, and efforts to clean the drains should be undertaken as soon as is practicable. If increased drain flows accompany the increased pressures, this could indicate higher water pressures in the foundation and/or abutments, which would decrease safety factors relative to sliding-related potential failure modes.
Decreased uplift pressure	This would be a positive, though unexpected development. Obviously checks would need to be made to be sure that the uplift pressure gauge(s) were functioning properly.
Increased flow from a foundation drain	This would be of concern, particularly if accompanied by an increase in uplift pressures, and should receive a prompt and thorough investigation. It is possible that this could be due to higher water pressures in the foundation and/or abutments, which would decrease safety factors relative to sliding-related potential failure modes.
Decreased flow from a foundation drain	This would be of concern, particularly if accompanied by increased uplift pressures, as this would indicate possible drain plugging. Efforts to clean the drains should be undertaken as soon as is practicable.

The ability to make generic performance assessments is very important because in many situations, full information about a dam is not available. In fact, full information is really never available. Foundation exploration is always limited to some degree, so there will always be geological unknowns. Similarly, there will always be construction unknowns. How exact is the match between the actual constructed dam and the design drawings? Consequently, engineers are almost always going to need to make generic assessments because having full knowledge of everything we would like to know is almost never the reality.

11.4 Failure-mode-based performance and programme assessment

To do a thorough, comprehensive assessment of a dam's condition and behavior, it is beneficial to begin by identifying the potential failure modes for the dam. Defining the greatest dam safety "threats" provides a useful context for proceeding with a comprehensive evaluation of the dam, and a useful basis for organizing one's thinking about the dam's behavior.

The process of identifying the potential failure modes for a dam is a significant endeavour about which much has been written in recent years. In a nutshell, available information and analyses for the dam are gathered, as are people familiar with the dam (representing operating personnel as well as all applicable technical disciplines), and an intensive, site-specific discussion regarding possible ways the dam could fail is conducted. Often, a follow-on activity to developing the list of potential failure modes for a dam is to make qualitative or quantitative estimates of the risks associated with each of the potential failure modes, so as to promote improved understanding of them, and to allow prioritization of efforts in managing a dam safety program for a collection of dams.

With a good understanding of the dam's potential failure modes, attention can then turn to whether there is evidence from the visual and instrumented monitoring program for the dam of possible initiation/development of any of the potential failure modes. The table below illustrates the association between several sample potential failure modes, and evidence associated with their possible initiation/development:

Table 11.2. Potential failure modes and possible evidence of associated initiation/development

Potential failure mode	Evidence of possible initiation/development
Embankment dam	
Seepage-related failure leading to breaching of the dam embankment (regarding a seepage path that has been identified to be of concern)	Direct Evidence: Evidence of sediment transport by the seepage flow (discolored seepage water, sediment deposits in stilling pools behind weirs, sediment deposits along seepage flow paths, etc.) Indirect Evidence: Sinkholes or depressions in the area of the flow path. New seepage areas or wet areas, or increasing seepage flows with time in the area of concern.

Potential failure mode	Evidence of possible initiation/development
Post-earthquake seepage-related failure due to flow through a new earthquake-caused transverse crack through the dam embankment that results in breaching of the dam embankment	Post-Earthquake Direct Evidence: Evidence of sediment transport by seepage flow through the new crack (discolored seepage water, sediment deposits along the path of the new seepage flow, etc.). Post-Earthquake Indirect Evidence: Evidence of a major transverse crack through the dam embankment. Changed seepage flows at the downstream slope/downstream toe area (compared to baseline data/information collected prior to the earthquake). Evidence of major earthquake-caused embankment damage/deformations.
Concrete Dam	
Structural failure due to loss of foundation support for the dam due to movement of a block of abutment rock	Direct Evidence: Newly apparent structural cracks (significant length, linear or semi-linear, diagonal, etc.) in concrete, or extension or widening of existing structural cracks. Offsets at a contraction joint. Anomalous deformations of the dam indicated by surveyed measurement points, plumbline data, or other instrumentation data. Indirect Evidence: Evidence of anomalously high abutment water pressures (such as from abutment piezometers, the development of new seepage in areas higher than has ever been observed before, etc.). Unusually high and sustained reservoir levels. Increased uplift pressures in the vicinity of the area of concern. Increased or decreased flow from foundation drains extending into the abutment area of concern.
Spillway	
Erosion in the channel downstream of the spillway that undermines the spillway foundation, and initiates a headward erosion process that eventually leads to complete loss of the spillway and uncontrolled reservoir releases	Direct Evidence: Unusual flow patterns within the spillway structure that is consistent with displacements or loss of floor slabs. Indirect Evidence: Unusual flow patterns in the downstream channel. Evidence of erosion of material in the downstream flow channel (unusually discolored water, material deposits in downstream slackwater areas, etc.).

The distinction in Table 11.2 above between direct and indirect evidence is important. Direct evidence is “conclusive” evidence of initiation/development of the potential failure mode, assuming that the evidence is what it purports to be (i.e. it is not associated with instrument reading mistakes, etc.). With indirect evidence, the information is consistent with possible initiation/development of the potential failure mode, but there could be other circumstances, unrelated to initiation/development of the potential failure mode, that could also lead to the appearance of the same evidence. For example, a sinkhole in the toe area of an embankment dam could be due to subsurface removal of material by seepage flow and stoping to the ground surface, or it could be due to an old exploration drill hole that was improperly backfilled, a subsurface void (not created by seepage flow) that has collapsed, etc.

A careful failure mode by failure mode assessment of whether there is any evidence of possible initiation/development of each of the potential failure modes forms the foundation for a thorough dam safety assessment of a dam's condition and behavior. Coincident, and in conjunction with this, an assessment of the monitoring data along the lines indicated in section 11.2 above for conformance with generally expected behavior patterns, provides a comprehensive assessment of a dam's condition and behavior.

Upon conclusion of such an assessment, it would be prudent to make an assessment of the future monitoring program for the dam. Are there any key monitoring parameters that relate to possible initiation/development of any of the identified potential failure modes that are not currently being monitored, but should be? If so, what additional monitoring installations should be provided? Are there any instruments that are currently being monitored that are not providing useful information relative to (1) possible initiation/development of potential failure modes, or (2) a general understanding of the dam's condition and behavior needed for a comprehensive dam evaluation? If so, should they be placed on standby or abandoned? Are the monitoring frequencies for the instruments and for the routine visual inspections appropriate, or should they be adjusted in light of the risks of development of the identified potential failure modes? Adjusting the instrumented and visual routine monitoring program for the dam to the current issues and information needs promotes not only effectiveness, but also efficient use of funds available for monitoring activities.

12. Assessment of dam safety monitoring programme

The following form and format has been developed as an aid for assessing the effectiveness of an organization's routine dam safety monitoring efforts for a dam or a collection of dams. The first column includes the elements and sub-elements associated with an effective program. The second column is used to document (briefly) the approach currently being used to address the element or sub-element. The third column is for "self-assessment" of the methods/approaches currently being used to address the element or sub-element. If the third column assessment reveals an element or sub-element to be an area that is in need of significant improvement, then the fourth column is a place to list possible solutions to the problems noted (for presentation to and consideration by management, as applicable).

Table 12.1 Typical assessment form for the assessment of a dam safety monitoring programme

Dam safety monitoring program assessment form
Organisation: ____
Assessment performed by: __________________Assessment date: ___________

Elements associated with an effective routine dam safety monitoring program (maximum points for this element or sub-element)	Approach currently being used	In need of significant improvement?	Additional tools, processes, etc. needed
1. Monitoring program is appropriately defined and communicated to operating personnel			
a. Monitoring program, including monitoring frequencies and ranges of expected performance, is developed using potential failure mode analysis and risk analysis (7)			
b. Monitoring program requirements are concisely defined/presented (for ease of use and understanding) (4)			
c. Monitoring program requirements, including ranges of expected performance, are provided to operating personnel (3)			
2. Monitoring work is performed on schedule (13)			
3. Monitoring work is performed by appropriately trained and qualified personnel			
a. Personnel have a good general understanding of the basic principles of dams and dam safety (3)			
b. Personnel have a good general understanding of the design issues and dam safety concerns regarding their dam(s) (4)			
c. Personnel have a good understanding of how to properly obtain instrument readings and perform routine visual inspections (4)			

4. Monitoring work is performed properly			
a. Instrument readings are properly obtained and routine visual inspections are properly performed (4)			
b. Personnel have access to appropriate information and “tools” to allow effective “initial evaluations” of the data to be performed at the time instrument readings are obtained (4)			
c. Instrument readings are checked as they are obtained for anomalies, and re-checked as appropriate (5)			
5. Monitoring results are being properly reported			
a. Monitoring data are promptly transmitted (5)			
b. Anomalous visual observations and/or instrument readings are “immediately” reported, when appropriate (7)			
6. Monitoring data are evaluated in a timely fashion (9)			
7. Monitoring data are evaluated by appropriately trained and qualified personnel			
a. Personnel have a good understanding of the principles of dam design and analysis (5)			
b. Personnel have a good understanding of the design issues and dam safety concerns regarding their dam(s) (6)			
8. Monitoring data are properly evaluated.			
a. Personnel have access to appropriate computer tools and information to allow effective evaluations to be performed (5)			

b. Personnel effectively assess the data for anomalies, including undesirable gradual data trends (6)			
c. Personnel appropriately alert other personnel when anomalous data are noted (6)			
Total Points (100 is maximum)			

Below is an example showing use of the assessment form relative to Sub-Element 1.c.

Monitoring Program Assessment Form (MPAF) Example Use of MPAF for Sub-Element 1.c.			
Elements and Sub-Elements (Maximum Points)	Approach Currently Being Used	In Need of Significant Improvement?	Additional Tools, Processes, Etc. Needed
1. Monitoring program is appropriately defined and communicated to operating personnel: c. Monitoring program requirements, including ranges of expected performance, are provided to operating personnel (3)	The "Schedule of Periodic Monitoring (L-23)" and the "Ongoing Visual Inspection Checklist (OVIC)" are incorporated in the Standing Operating Procedures (SOP) document for the dam.	Yes. Currently SOPs often have out-of-date information. (0)	• An expedited procedure for getting L-23s and OVICs incorporated in SOPs (within 90 days) could be required. • A component could be added to the Facility Reliability Rating (FRR) associated with the SOP having the current L-23 and OVIC. (The FRR is a quantitative rating method for scoring the current status of all efforts for a dam - operational, maintenance, dam safety, etc.)

While some of the information in the above table is a bit cryptic, it illustrates the use of the form by one organization with respect to one sub-element.

In some situations, it may be desirable to have the ability to develop quantitative ratings using the above form. These might include tracking progress and improvements made over time in a particular program, and/or allowing rough comparisons to be made regarding the programs of different entities. To accommodate the potential desire for quantitative ratings, weighting factors were developed for each of the sub-elements and for the elements themselves that have no sub-elements. These appear as numbers in parenthesis in the boxes in the first column of the form.

If everything about the routine dam safety monitoring program is perfect, then the full amount of the weighting factor is the total of the scores for each element and sub-element, and a total score of 100 is achieved. Where problem areas are identified, appropriate reductions are made in the various weighting factors (down potentially to a score of zero for that element or sub-element), and then each of the element or sub-element scores are summed to achieve a score that would fall somewhere between 0 and 100. It is very important to note that a relatively high score on the rating form could be computed, yet an ineffective monitoring program could exist. For an extreme example of this, dam operating personnel may not be doing any of the required monitoring work, so Element 2. would get a score of 0 (out of 13), but the total score could still reach 87, which gives the impression of a pretty good situation, even though no monitoring work is actually being done. It is also very important to note that the above form can be very effectively used to identify problems and develop lists of possible solutions without employing the quantitative rating approach. However, to reiterate, the ability to develop quantitative ratings may be a useful capability to have in some circumstances.

Using the above assessment form to take stock of the effectiveness of a routine dam safety monitoring program should occur at least once every 5 years, though performing such an assessment at least every 3 years would be more preferable and desirable.

13 Prioritisation of maintenance, remedial and upgrading monitoring systems

13.1 General

Several decision making models are available for the prioritisation of dam engineering related works as a whole, which can be used specifically with respect to monitoring systems. There are basically two groups of methodologies, vis-à-vis deterministic- and probabilistic. The probabilistic (cost-effectiveness) methodologies are more rigorous and therefore more time consuming. The following “dimensions” are added to the evaluation process:

- Condition indexes is one of the more promising deterministic methods, where the condition of “facilities” are compared with “standardised” values. These indices must be developed for or adjusted to the country specific (and even local specific) conditions. This may be time consuming and costly. There may be a temptation to use the indices of other countries. The end result of these analyses is a list of ranked alternatives.
- The major disadvantage of the probabilistic methods is that these analyses are subjected to the bias of those who perform the analyses. In essence probabilities are added in the decision-making process with these methodologies. Probabilities are calculated for various aspects such as useful life expectancy of the dam, the efficacy of existing surveillance system as well as the probability of various potential failure modes. The cost and potential benefit of the status quo (do nothing) option is compared with other alternatives on a probabilistic basis. Finally a list of alternatives, “ranked” on the basis of “additional value added versus cost of added value”.

The deterministic methodologies are less rigorous and relatively easy to perform. The two methodologies are not mutually exclusive and may be combined to benefit from the best of both. The optimal solution may therefore not necessarily be the maintenance and/upgrading to the state of the art.

13.2 Probability based methods

ICOLD issued in 2005 Bulletin 130 titled Risk Assessment in Dam Safety Management: A Reconnaissance of Benefits, Methods and Current Applications. The probabilistic methods for prioritization of any dam engineering related works are clearly discussed in this bulletin and in related literature.

13.3 Condition index methods

The monitoring system is one of the elements pertinent to the safety analysis of the dam and it is necessary to check it from time to time and to modify or improve it in relation to the total project condition.

One of the methods that permit one to do this analysis is to establish condition indexes, which enable one to obtain tools to prioritize, schedule, and classify by order of importance all types of maintenance or improvement actions.

There are three types of condition indexes developed for embankment dams, concrete storage facilities and spillways. Later developments will undoubtedly make it possible to compare and classify the three types of condition indexes to establish a ranking list for the maintenance actions that would apply to various types of facilities.

The ranking, through condition indexes are relative to each other, and does not yet provide an absolute threshold beyond which maintenance action would be compulsory. As shall be seen, this possibility exists and can easily be achieved through identification of values that are acceptable or not for the condition indexes.

The Condition Index Methodology could appear to resemble a risk analysis method. However, although this methodology refers to potential failure mechanisms, early warning signs, and defence groups, it is free of the fastidious and sometimes controversial probabilities linked to chains of events.

The principle underlying the methodology is that a facility, of whatever type, is comprised of an organization of various components that are identified as defence groups that counter the various adverse conditions to which the facility is or can be exposed.

Deterioration of a defence group can initiate a failure mechanism due to the inability to resist an adverse condition to which it is subjected. The condition of the defence group is thus measured and assessed based on specific events or appropriate measurements.

The steps in the index condition methodology are summarized in figure 13.1.

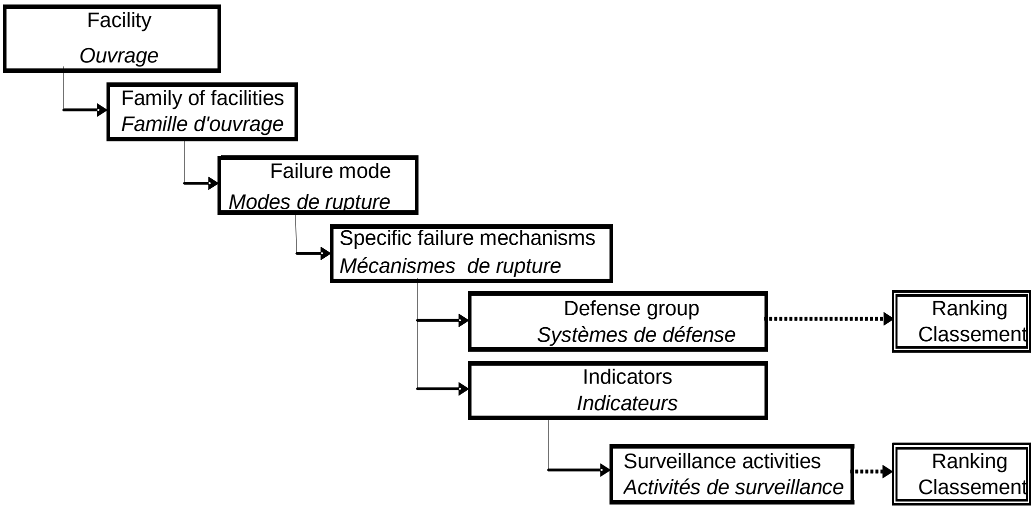


Figure 13.1 Flow diagram of the Condition index Methodology

a) Family of facilities

For a given facility, the family in which it can be classified is identified. The methodology effectively identifies the families of facilities that have similarities and operate similarly.

b) Failure Modes

For each family the failure modes to be retained and which are applicable are preset. For example, for embankment facilities, this includes overtopping, piping, surface erosion, or mass movement. For concrete gravity dams, it includes sliding in the dam, sliding in the foundations, and sliding at the dam/foundation interface.

c) Specific Failure Mechanisms

As with the families of facilities and since the probable failure modes are pre-established with predetermined probability percentages, the specific failure mechanisms are also identified. The probability percentages are similarly suggested based on expertise and known experience in this matter. Some failure modes are linked to one or several failure mechanisms. Certain links are impossible. A table is then set up, for each family of facilities, proposing the various modes of failure and their probability percentage. The combination of the failure mechanisms and modes enables one to identify the relative importance of each specific failure mechanism.

d) Defence Groups

Based on the same goal of standardizing pre-established tables and suggested values, tables propose the identification of defence groups. In the same manner, these defence groups are linked to importance or probability percentages, with the failure mechanisms identified and evaluated in the previous step.

The relative importance of each defence group is then obtained to counter the specific failure mechanisms that could bring about a probable failure mode for a type of facility in a pre-established family.

e) Condition of defence groups

In order to evaluate defence systems, tables are created and suggested so as to evaluate their condition. The well-known approach (REMR – Repair Evaluation Maintenance and Rehabilitation) was taken as a general concept (excellent, good, fair, marginal, bad, unacceptable) with value ranges on a 1 to 100 scale.

f) Classification of defence groups

In this stage, the classification of the different defence systems is obtained using the following formula:

$PR_{DS} = (I_{dam}) \times (I_{DS}) \times (100 - CI)$

where PR_{DS}: Priority ranking - Priority classification of the defence system; I_{dam}: Importance of dam - Value obtained in dam classification according to the applicable requirements (governmental or owner); I_{DS}: Importance of defence system; and CI: Condition index for defence system.

This priority classification can be presented as a list or a table for overall review. Efforts and resources can thus be allocated to maintenance activities that require priority intervention. In the different stages above, it is observed that the specific path followed to identify priorities to be given to the various maintenance actions on different facilities among a whole facility plant. It is also possible to follow this methodology, using the same systematic and pre-established approach, to evaluate and prioritize the surveillance activities or devices.

g) Surveillance indicators

Tables are developed and used with the same Condition Index Methodology to make links between specific failure mechanisms and the indicators (or events) in these mechanisms (or in their triggering). The tables are developed for the different families of facilities mentioned above. Thus, the relative importance of the indicator is achieved using the rules that govern the mechanism-indicator relationships.

h) Relative importance of the surveillance activity or system

Another series of tables establishes the possible or probable relationships (with their relative importance) between the indicators related to the specific failure mechanisms and the surveillance activities or devices. Here again, as before, rules suggest, limit, and establish the relative probabilities (in %) of each.

$PR_{AD} = (I_{dam}) \times (I_{DS}) \times (100 - CI_{DS})$

where PR_{AD} : Priority ranking of activities and monitoring devices; I_{dam}: Importance of the dam. Value obtained in dam classification according to the applicable requirements (governmental or owner); I_{DS}: Importance of defence system; and CI_{DS}: Condition index for defence system.

i) Surveillance priorities

Applied to a facility, a family of facilities, or an overall facility plant, this methodology makes it possible to classify, prioritize, and assign a relative importance to all surveillance activities and monitoring devices.

It also makes it possible to determine if addition of an instrument or removal of one (aging for example), can help to meet the primary goals of countering or detecting any failure modes early.

The systematic approach established using accepted practices and the expertise of dam safety specialists provides a more rational tool than the many piecemeal recommendations that are difficult to compare with each other and that have no link with the potential failure modes of facilities being studied.

References:

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14. Concluding remarks

14.1 General

ICOLD Bulletins are guidelines and not instruction manuals. This bulletin and the best of other guidelines or manuals cannot provide for every field condition that may affect the results. Every dam and site condition must therefore be evaluated on its own merits. Sometimes one must consciously depart from these guidelines. The practice of copying an existing instrumentation lay-out (even one from a reputable engineer) is not advisable. Each dam is unique and no one size fits all.

14.2 Other Relevant Guidelines

Technical committees of ICOLD have produced several bulletins on instrumentation of which the following are relevant:

Bulletin 60 (1988) Dam monitoring, General considerations. This bulletin was an update and merger of Bulletins 21 (1969) & 23 (1972). The bulletin covers monitoring purposes, planning instrumentation systems, measurements and instruments, installation, frequency of measurements and geodetic methods for the determination of movements of dams

Bulletin *68 (1989) Monitoring of dams and their foundations, State of the Art,* was produced in the format of 11 National Committee Reports. (approximately 60 dams).

Bulletin 87 (1992) Improvement of existing dam monitoring, covers 12 case histories from 7 countries.

Bulletin 118 (2000) Guideline for Automated Dam Monitoring Systems, covers all aspects of the automation of monitoring systems for dams and their foundations.

Bulletin 138 (2008) General approach to dam surveillance was the first bulletin of the present committee and aimed at introducing dam owners, managers and non-specialists into the basic elements of dam safety surveillance.

14.3 Institutional memory

The importance of institutional memory in the monitoring and evaluation of the behavior of dams should not be under-estimated. Visual inspections are one of the important means to develop institutional memory of the dam and its instruments. The loss of the “living” memory of staff that was directly involved with the installation is a loss for ever and cannot be re-generated. This risk may be mitigated by a well structured visual inspection programme.

For dam operators and their immediate supervisor’s diligence, dam safety experience (especially of the particular dam) and a positive attitude are essential. The level of education (formal and informal) plays a major role in the success rate. Over-qualified personnel, as a rule, are less effective. Supervisors for dam operators should ideally also have progressed through the ranks.

ANNEXURE

The following tables have been produced by the Swiss National Committee of ICOLD.

The abbreviations, used in the tables, to list typical requirements of the particular devices and/or monitoring/measuring methods are:

R: Reliability required of the data which is indispensable for the proper monitoring of a dam and which must be available at all times.

L: Lifespan of measuring equipment goes hand in hand with sufficient redundancies for the monitoring of essential data.

M: Measuring ranges must be wide enough to cater for unforeseen conditions such as exceptional loads or unexpected behavior.

P: The required precision must cover all errors of the complete measuring installation and procedure (inaccuracy of the instruments and their calibration as well as effects of temperature, material coatings, friction, wear, zero-point deviations, non-linearities etc.).

Re: Redundancy means both the (independent) duplication of a measuring device or the possibility to check or reconstruct a measurement by means of another measuring installation.

	Purpose	**Equipment Measuring device Measurement methods**	**Requirements** **R** = Reliability **L** = Longevity **M** = Measuring range **P** = Precision **Re** = Redundancy	**Remarks**
1. LOADS AND EFFECTS FROM SURROUNDING ENVIRONMENT				
Hydraulic and Sediment Loads				
	Water Level	**Pressure Balance**	**R**: very high **L**: low **M**: up to above the crest/parapet level **P**: ± 10 cm **Re**: Necessary	Important measurement. Range must also cover the flood levels. Possibility to set-up automatic measurements and to record data with most devices.
		Float		
		Staff Gauge		
		Manometer		
		Sonar Gauge		
		Pressure Gauge		
		Acoustic		
		Light Gauge		
	Sedimentation Level Deposits in the reservoir and in front of the intake shaft; Loads of the sediments.	**Measurement of water depth**	**R**: moderate **L**: nil **M**: On all height **P**: ± 0.2 … 0.5 m **Re**: not necessary.	Also to measure scouring depth.

Temperatures				
	Air and water Temperature External thermal load. Influence on snow melts.	**Thermograph** Continuous recording of air temperature variations.	**R**: moderate **L**: moderate **M**: -30°C to +40°C **P**: ± 1°C **Re**: necessary.	These instruments can be easily replaced. With possibility to set-up automatic measurements and to record data.
		Normal Thermometer Minimum, maximum and instantaneous values.	**R**: moderate **L**: moderate **M**: -30°C to +40°C **P**: ±1°C **Re**: advised.	These instruments can be easily replaced.
		Electric Thermometer	**R**: moderate **L**: moderate **M**: -30°C to +40°C **P**: ±1°C **Re**: advised.	These instruments can be easily replaced. With possibility to set-up automatic measurements and to record data.
	Concrete Temperature Internal thermal loads (as they directly influence concrete deformation).	**Normal Thermometer** In boreholes.	**R**: very high **L**: very high **M**: -10°C to +60°C **P**: ± 0.5°C **Re**: necessary: foresee enough instruments.	A measuring range up to + 60°C is only necessary during the construction period. When installed later a range up to + 30°C is sufficient. With possibility of recorded automatic readings.
		Electric Thermometer	**R**: very high **L**: very high **M**: -10°C to +60°C **P**: ± 0.5°C **Re**: necessary ; provide enough instruments	A measuring range up to + 60°C is only necessary during the construction period. When installed later a range up to + 30°C is sufficient. With possibility to set-up automatic measurements and to record data.

	Purpose	Equipment Measuring device Measurement methods	Requirements **R** = Reliability **L** = Longevity **M** = Measuring range **P** = Precision **Re** = Redundancy	Remarks
	Temperature of the concrete, **Water circulation in the embankments,** **Modification of the temperature due to seepage**	**Fibre optic temperature gauges**	**R**: very high **L**: very high **M**: -10°C to +60°C **P**: ± 0.5°C **Re**: necessary.	A measuring range up to + 60°C is only necessary during the construction period. When installed later a range up to + 30°C is sufficient. Embankment: a measuring range up to + 30°C is sufficient; tarmac surfaces up to + 60°C. Relatively easy Installation. With possibility to set-up automatic measurements and to record data.

Rainfall				
	Rainfall in the dam area Influence on water percolation.	**Rain Gauge** **Accumulator** **Pluviometer**	**R**: moderate **L**: low **M**: Total rainfall in the measuring interval **P**: ± 10% **Re**: not necessary.	Such measurements are not absolutely necessary in the immediate vicinity of the dam. With possibility to set-up automatic measurements and to record data.
Pressure				
	Constraints in embankments and in concrete	**Earth Pressure cell**	**R**: moderate **L**: high **M**: Total overburden (0 to 3 N/mm^2) **P**: ± 5% of **M** **Re**: not necessary.	Rarely used. The deformation modulus must be adjusted for the embankment material. Interpretation and results problematic. With possibility to set-up automatic measurements and to record data.
		Tele-pressure cell	**R**: moderate **L**: high **M**: total of constraints (0 to 10 N/mm^2) **P**: ± 5% of **M** **Re**: not necessary.	Very rarely used. Interpretations and results can be problematic. With possibility to set-up automatic measurements and to record data.
Dynamic Loads				
	Recording of seismic activities	**Seismometer** Recording of the movements of the support over time (speed and acceleration). **Accelerometer** Recording of the accelerations over time.	**R**: high **L**: medium **M**: ± 1g (a_{max}) **P**: $\Delta a \leq 0.03$ mg (≥ 16 Bits); $\Delta t \leq 0.005$ sec **Re**: necessary.	Foresee 3 component instruments Install at least 3 instruments (at crest level, foundation level and in the free-field). Application and interpretation of results to be done by specialists.

	Purpose	Equipment Measuring device Measurement methods	Requirements **R** = Reliability **L** = Longevity **M** = Measuring range **P** = Precision **Re** = Redundancy	Remarks
2.	**RESPONSE DEFORMATIONS AND DISPLACEMENTS (DAM AND SURROUNDINGS)**			
Geodetic Measurements				
	Measurements of Spatial Displacement of individual points Including the influence of the surroundings.	Triangulation From case to case combined with: • Traverses and levelling • Electro-optical distance measurements • Optical pendulums, pendulums • Alignments • Extensometers.	**R:** very high **L:** very high **P:** requirements to be fixed on a case by case basis **R**: absolutely necessary by means of overabundant measuring points Combination with other measurement methods	The geodetic survey network must cover a large area and enable the long-term observation of dam deformations and its surroundings as well as control of possible displacements of the reference points of other measuring devices (redundancy). Precise measurement which can be carried out only at long intervals. Requires provision of reduced measurements for rapid appraisals of the deformations. All data and indications on measuring and evaluation methods to be filed.
		Measurements assisted by satellite (GPS) In relation with terrestrial measurements (consolidation of triangulation network) and terrain movements.	**R, L, P**: requirements to be fixed on a case by case basis **Re:** Necessary; with repetitive measurements or other measuring methods.	Precision depends on the length of the measurements and the satellite set-up. Possibility of automatic measurement and recording.
		Photogrammetry For terrain and glacier movements.	**R, L:** requirements to be fixed on a case by case basis **P:** ± 0.2 m **Re:** not important.	Generally, bird’s eye photos; terrestrial photos also possible Long lasting quality of the photos is necessary. Photogrammetry can also be used to record deposits in the dam.
		Laser-Scanning Complete scanning of the surface of an object.	**R, L, P:** requirements to be fixed on a case by case basis **Re:** not important.	Modern measuring methods that can easily replace photogrammetry.

	Deformations along horizontal or vertical lines Extending into abutments and valley sides.	Levelling	**R:** very high **L:** very high **P:** requirements to be fixed on a case by case basis **Re:** according to circumstances; necessary in combination with triangulation.	Well-tried and simple method when modern instruments are used. Groups of reference points must be set-up on both banks.

	Purpose	Equipment Measuring device Measurement methods	Requirements **R** = Reliability **L** = Longevity **M** = Measuring range **P** = Precision **Re** = Redundancy	Remarks
	Deformations along horizontal or vertical lines Extending into abutments and valley sides.	Simple Angular Measurements and electro-optical distance measurements From stations located outside.	**R**: very high **L**: very high **P**: requirements to be fixed on a case by case basis **Re**: possible by means of repetitive measurements or triangulation.	Well-tried but precise measuring methods to be used only where installation of pendulums is not possible Measurements require favourable weather conditions. Precision depends upon distance and refraction. Measuring stations to be regularly controlled by triangulation.
		Optical alignment	**R, L, M, P**: requirements to be fixed on a case by case basis **Re**: absolutely necessary in combination with triangulation and pendulums.	Well-tried and simple method. Measurements require favourable weather conditions. Precision depends upon distance and refraction.
Instruments				
	Deformations along horizontal or vertical lines Extending into abutments and valley sides.	**Pendulum, Inverted pendulum** Measuring device in two directions, with optical sighting of the pendulum wire. The wire serves as vertical reference axis.	**R**: very high **L**: very high **M**: maximum calculated deflection + 50% **P**: ± 0.2 mm **Re**: absolutely necessary by means of - Spare measuring device - Combination with triangulation, traverse, alignments, extensometers.	Well-tried and precise device. Short measuring time. Instrument control station. Tele-transmission possible; measuring device must not influence the pendulum position.

	Purpose	Equipment Measuring device Measurement methods	Requirements **R** = Reliability **L** = Longevity **M** = Measuring range **P** = Precision **Re** = Redundancy	Remarks
		Hose levelling device	**R**: high **L**: high **M**: a few meters **P**: ± 1 cm **Re**: necessary with a settlement gauge and levelling	Communication tubes with direct reading on the glass standpipe; three tubes per measuring point. Very accurate; somewhat clumsy; sensitive to frost. Degassing of the measuring fluid necessary.
	Variations in length	**Distometer / Distinvar**	**R**: high **L**: high **M**: 10 cm for the distometer 5 cm for the distinvar **P**: ± 0.2 mm **Re**: Necessary; by means of geodetic measurements or metric tape.	Precise measurement of distance in galleries and in the terrain. The distometer enables measurement in a given direction; the distinvar can only measure horizontally. In case of a reading outside the measuring range, the wire can extend or retract itself.
	Variations in length and deflections along boreholes Global measurements on long stretches or differential measurements along a chain of short stretches.	**Rod or wire extensometers** With one or more rods (wires).	**R**: high **L**: high **M**: 10 to 50 mm **P**: ± 0.2 mm **Re**: not always necessary. can be achieved by: - Installing extensometers in several comparable locations - Subdividing the full length in several parts - Combination with inverted pendulum or levelling	Placing of anchors and grouting of the protective sleeves are critical operations. Possibility of automatic measuring and recording.
		Rod extensometers for embankment dams With one or more rods.	**R**: high **L**: high **M**: 10 to 30 cm **P**: ± 1 mm **Re**: not always necessary. can be achieved by: - Installing extensometers in several	Placing of anchors and grouting of the protective sleeves are critical operations. Possibility of automatic measuring and recording.

			comparable locations - Subdividing the full length in several parts	

	Purpose	Equipment Measuring device Measurement methods	Requirements **R** = Reliability **L** = Longevity **M** = Measuring range **P** = Precision **Re** = Redundancy	Remarks
	Variations in length and deflections along boreholes Global measurements on long stretches or differential measurements along a chain of short stretches.	**Fibre-optical extensometers** With one or more rods.	**R**: very high **L**: very high **M**: 1 to 2% of the measured part **P**: ± 0.2 mm **Re**: not always necessary. Can be achieved by installing extensometers in several comparable locations.	Relatively easy installation. Possibility of automatic measuring and recording.
		Borehole Micrometer Differential length variations	**R**: high **L**: high **M**: expected deflection +100% **P**: ± 0.2 mm for length variations, ± 0.02 mm/m for rock deflections, ± 0.2 mm/m for soft terrain deflections **Re**: According to the aim.	Precision highly dependent on the instrument guiding system. Certain devices give very accurate and reliable results. Placing and grouting of the guiding sleeves is a critical operation. Recommended for the localization of discontinuities (cracks and/or joints) and sliding surfaces and to observe their movements. Measurement and interpretation are time consuming.
		Borehole Micrometer with inclinometer Differential deflections combined with borehole micrometer.		
		Inclinometer Differential deflection in boreholes		
	Variations of local rotations In vertical plan.	**Clinometer** On settlement benchmark and micrometer with electronic display. **Tiltmeter** With electronic display.	**R**: high **L**: high **M**: 20 mm/m **P**: 0.02 mm/m **Re**: this measurement is recommended only if combined with other measuring installations such as pendulums or	Near to cavities results are often influenced by stress concentration and transfer effects. Results may be improved by short chains of measuring stretches. Possibility of automatic measuring and recording for the tiltmeter.

			levelling.	
	Movements of cracks and joints On the surface, expansions and shear movements.	**Micrometer** **Deformeter** **Dilatometer** **Deflectometer**	**R**: moderate **L**: high **M**: 10 mm **P**: ± 0.05 mm **Re**: According to the aim.	Measurements in gallery walls or recesses are often not representative for the behaviour of the whole mass. Possibility of automatic measuring and recording.

	Purpose	Equipment Measuring device Measurement methods	Requirements **R** = Reliability **L** = Longevity **M** = Measuring range **P** = Precision **Re** = Redundancy	Remarks
	Specific deformations To check stresses in the concrete.	**Electric deformeter embedded in concrete** Combined with temperature measurements.	**R**: high **L**: high **M**: Specific deformation 2 mm/m, Temperature –10°C to +50°C **P**: Extension 0.02 mm/m, Temperature ±0.2°C **Re:** necessary by means of - Over abundant instruments - Other types of instruments for comparison.	Frequent instrument failure. Behaviour often influenced by local material conditions at the instrument site. Analysis of the records problematic. Possibility of automatic measuring and recording.
		Fibre-optic embedded in concrete		

	Purpose	Equipment Measuring device Measurement methods	Requirements **R** = Reliability **L** = Longevity **M** = Measuring range **P** = Precision **Re** = Redundancy	Remarks

3. RESPONSE SEEPAGE AND LEAKAGE				
Water quantity				
	Quantity of seepage and drained water By zone and in total.	**Volumetric measurements with calibrated container and stopwatch** Or by volume displacement (for example by means of a calibrated rod in boreholes inclined downwards)	**R**: moderate **L**: moderate **M**: maximum expected discharge + 100 % **P**: ± 5 % of **M** **Re**: repetitive measurements.	Method limited to moderate discharges up to 10 l/s; The container's filling time must be at least 20 seconds.
		Weir **Measuring Flume** With scale, sonar gauge, pneumatic scale, pressure cell.	**R**: high **L**: high **M**: maximum expected discharge + 100% **P**: ± 5% of **M** **Re**: by volumetric measurements.	Deposits must be removed periodically. Not recommended for discharges < 0.05 l/s. At the collecting point of the total dam seepage a recorder and an alarm signal should be provided for. Possibility of automatic measuring and recording.
		Measurement of flow in pipes e.g. in pipes of drainage water pumps Venturimeter (measurement of the pressure differential) - Sonar or magneto-inductive Measurement (measurement of the velocity of flow)	**R**: high **L**: high **M**: maximum expected discharge + 100% **P**: ± 5% of **M** **Re**: by volumetric measurements in different locations.	Simple means for a periodical check of the indications must be provided for (manometers, weirs, and free flow measuring flume). Possibility of automatic measuring and recording.
		Measurement of flow in partially empty pipes Sonar or magneto-inductive Measurement (measurement of the velocity of flow)	**R**: high **L**: high **M**: maximum expected discharge + 100% **P**: ± 5% of **M** **Re**: by volumetric measurements in different locations.	Simple means for a periodical check of the indications must be provided for (manometers, weirs, and free flow measuring flume). Possibility of automatic measuring and recording.

Measurements of Hydraulic pressure in the rock and in soft terrain				
	Pressure of the water in the rock Pressure of the water circulating in the foundation (uplift ; water pressure in rock cracks)	**Piezometers: open systems** Gauging of the water level by a cable line with light or acoustic signal.	**R**: moderate **L**: high **M**: total length of the borehole **P**: ± 0.05 m **Re**: necessary; installation of piezometers in groups.	Watertight borehole cased down to the pressure measuring area; protection of head of borehole against penetration of surface waters, mud, stones, etc. Ensure permanent aeration

	Purpose	**Equipment Measuring device Measurement methods**	**Requirements** **R** = Reliability **L** = Longevity **M** = Measuring range **P** = Precision **Re** = Redundancy	**Remarks**
	Pressure of the water in the rock Pressure of the water circulating in the foundation (uplift ; water pressure in rock cracks)	**Piezometers: closed systems** Pressure indication by means of a manometer or electrical gauge	**R**: high **L**: high **M**: Total height between manometer and dam crest **P**: ± 0.5 m resp. ± 1% of **M** **R**: necessary; installation of piezometers in groups.	Well tried method. Pipes and connections to manometers must be watertight. Do not relieve pressure artificially to allow the observation of maximum pressures even if they need time to build up. Periodical venting of pipes required. Periodical check of manometers absolutely necessary. Possibility of automatic measuring and recording.
		Piezometers: pressure cells (pneumatic or electrical) Installed in boreholes : one or more cells per level	**R**: high **L**: high **M**: Total height between manometer and dam crest **P**: ± 0.5m resp. ± 1% of **M** **Re**: necessary by means of a large number of cells or an installation in groups.	Central reading of pressure cells spread over the depth. Careful selection of the filter type in order to avoid its early clogging. Placing of cells exactly especially if several of them must be installed in the same borehole. Possibility of automatic measuring and recording.

	Water pressure on soft terrain Pressure of the water circulating in embankment dams (core, shoulders) and in the foundation (uplift; interstitial pressures)	**Piezometers: open systems** Gauging of the water level by a cable line with light or acoustic signal.	**R**: moderate **L**: high **M**: total length of the borehole **P**: ± 0.05 m **Re**: necessary; installation of piezometers in groups.	Watertight borehole cased down to the pressure measuring area; protection of head of borehole against penetration of surface waters, mud, stones, etc. Ensure permanent aeration Good functioning of the device checked by rinsing.
		Piezometers: closed systems Pressure indication by means of a manometer or electrical gauge.	**R**: high **L**: high **M**: Total height between manometer and dam crest **P**: ± 0.5 m resp. ± 1% of **M** **Re**: necessary; installation of piezometers in groups.	Well tried method. Pipes and connections to manometers must be watertight. Do not relieve pressure artificially to allow the observation of maximum pressures even if they need time to build up. Periodical venting of pipes required. Periodical check of manometers absolutely necessary. Possibility of automatic measuring and recording.
Physical and chemical properties of the waters				
	Recording of physical and chemical modifications (Erosion, dissolving)	**Turbidity meter**	**R**: high **L**: high **M**: 0 to 500 ppm **P**: ± 1 ppm **Re**: necessary by means of analysis of water samples in lab.	Determination of dissolved or suspended materials. A local shelter is important. Calibration after analysis in the laboratory of seepage water. Possibility of automatic measuring and recording.
		Chemical analysis	**R**: high **L**: none **M**: depending on expected values **P**: depending on expected values **Re**: not necessary.	To be done at long intervals. Main characteristics to be determined by specialists.

	Purpose	**Equipment Measuring device Measurement methods**	**Requirements** **R** = Reliability **L** = Longevity **M** = Measuring range **P** = Precision **Re** = Redundancy	**Remarks**
4.	**STRUCTURAL INTEGRITY**			
	Geophysical methods Determining geophysical characteristics of dams and underground terrain.	Seismic reflection Seismic refraction Geo-electric Electromagnetic Geo-radar Geomagnetic Gravimeter Tomography Seismic Ultrasound Infrared reading Diagraphy Tracers	**R, L, M, P**: requirements to be fixed on a case by case basis **Re**: necessary; depending on the case by means of - boreholes - samples - tests - Other geophysical methods.	Application and interpretation of results to be done by specialists.