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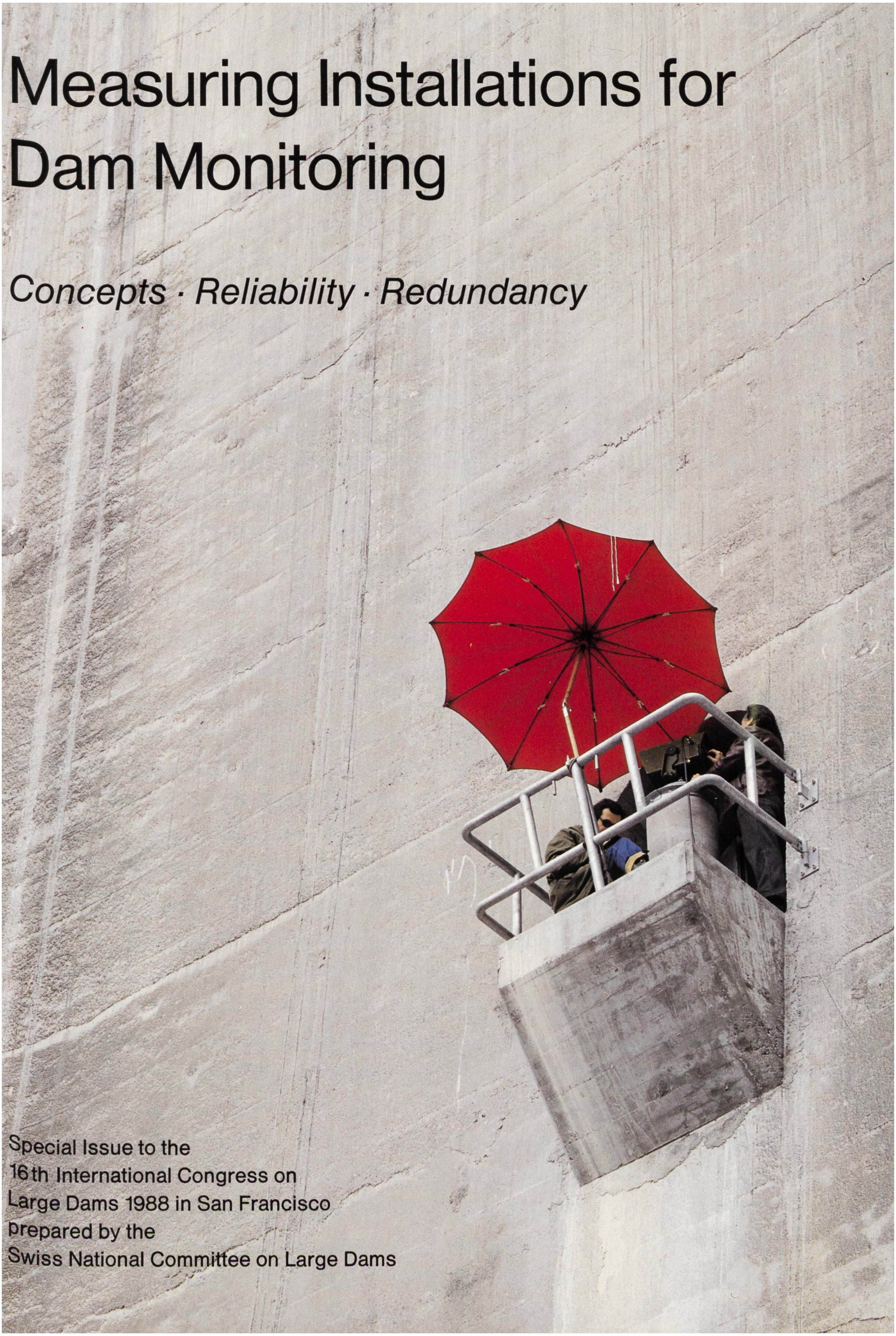
Measuring Installations for Dam Monitoring

Concepts · Reliability · Redundancy



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Preface

Among several hundreds of dams Switzerland has 161 large dams, most of them constructed in the second half of the 20th century. From the beginning of construction of dams in Switzerland, the engineers were at any time conscious of their responsibility. Consequently, importance was attached to dam safety and surveillance of dam behaviour. The first time a dam was provided with more extensive monitoring equipment was during the construction of the 55 m high Montsalvens arch dam in 1920, when instruments for geodetic survey, clinometer and temperature measurements were installed. In 1932 the first plumb-line measurements were performed at the 114 m high Spitallamm arch dam.

In course of time a wide range of measuring instruments was developed in order to meet all requirements of purpose, precision, reliability and longevity. Today specialized manufacturers offer a widespread collection of equipment for dam monitoring. Close cooperation between consulting engineers, dam owners and manufacturers helps to continue the development of suitable instruments to assure dam safety.

The Subcommittee on Dam Monitoring of the Swiss National Committee on Large Dams is to be thanked for the preparation of the present paper which marks the purpose and goals of the installation of dam monitoring equipment, and we hope it will be of value to everybody engaged in dam engineering.
Our particular gratitude goes to "wasser, energie, luft – eau, énergie, air", the official periodical of our national Committee, which made it possible to print this special issue edited in honour of the participants at the 16th ICOLD-Congress in San Francisco, June 1988.

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The cover shows the pulpit on the downstream wall of the Gigerwald arch dam serving for the geodetic control of the structure. The owner of the dam is the Sarganserland Power Company Ltd., Switzerland.

Color plate by courtesy of Kern & Co. Ltd., Mechanical, Optical and Electronic Precision Instruments, CH-5001 Aarau, Switzerland.

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National Committee on Large Dams
Committee on Dam Monitoring

Measuring Installations for Dam Monitoring

Concepts, Reliability, Redundancy

Part 1: Concepts

1. Introduction

Any dam is subjected to external loads that cause deformation and permeability of the structure and its foundations. Deformation and seepage are clearly a function of such loads. Any sign of abnormal dam behaviour could possibly threaten dam safety. Loads and the dam's response to them should therefore be carefully monitored for any sign of abnormality as early as possible, and action promptly taken before that abnormality becomes a threat to safety.

Monitoring consists of both measurements and visual inspections, neither being sufficient on their own. Every dam should be equipped with appropriate instrumentation according to the set goals and according to dam type and size as well as to particular site conditions.

As experience in dam engineering grows constantly and measurement techniques become more sophisticated, dam instrumentation should be regularly checked for suitability. It may need to be supplemented or even refurbished altogether.

When designing a dam monitoring system or evaluating an existing one, the following should be borne in mind:

- a dam and its foundations form a whole that is embedded in the surrounding terrain, which may also have an impact;
- an abnormality in dam behaviour may occur either quite rapidly or only gradually;
- in the event of some abnormality, its cause should be identifiable through analysis of the measurement data.

Thus, a monitoring system should be capable of monitoring both short- and longterm behaviour. It should also be capable of distinguishing between behaviour of the dam and that of its foundations and surrounding terrain. To assess behaviour in the short term, analysing relatively few data is usually sufficient, provided that the data are selected in such a manner that they clearly show whether behaviour is normal or not. These main parameters must therefore be checked quite frequently. This will be helped by instruments that are simple to operate, combined with measurement methods producing results that can be easily interpreted.

For the collection and analysis of data on long-term behaviour, including analysis of some detected abnormality, more differentiated measurement methods should be used. Since monitoring in such cases will be less frequent, measurement procedures and interpretation of results may require more sophisticated instrumentation and analysis methods or even the intervention of specialists.

Monitoring data should be available at all times with the required reliability. Any malfunction or interruption in the monitoring may jeopardize dam surveillance as a whole, and raise doubts about safety. Even if defective installations and instruments are replaced immediately, there is some danger of the fixed datum being altered. Continuity of the data series will be lost and long-term analysis made more difficult. Therefore, preference should be given to measuring installations and instruments which are robust and have a long service life. A reduced accuracy is less serious than an interruption in instrument operation. Maintenance and accuracy checks at regular intervals are therefore essential to ensure reliability and longevity.

The measuring range should be extensive enough, so that excessive load cases and/or abnormal behaviour may be recorded, if possible, without restraint. It is precisely such cases that might threaten dam safety and need appropriate countermeasures.

Accuracy of the monitoring data should not be beyond the scope of existing facilities for analysis and interpretation. It is important to remember that knowledge about the theoretical principles affecting dam behaviour is to a certain extent still approximative, and that such principles may be influenced by phenomena (e.g. the impact of seasonal climatic variations on the behaviour of the foundation) that are not quantifiable, for the time being at any rate.

Even if sturdy and easy to operate instruments have been installed, defects and failures cannot be ruled out. Thus, any monitoring system should be sufficiently redundant.

By redundancy we mean keeping parallel but separate sets of instruments and, in addition, facilities for evaluating data by double-checking, using alternative measurement methods (e.g. plumbline-traverses, alignment-triangulation, and settlement gauge-levelling). Of the two, double-checking is preferable, because it invariably provides other helpful data. Its usefulness is, therefore, twofold.

2. External loads

Dam deformation is caused only in part by the reservoir level. Other factors come into play, such as temperatures in concrete dams, and the self-weight of the fill in embankment dams. Earth pressure may also be a decisive factor. In either type of dam, seepage rates depend essentially on the reservoir level and to a lesser degree on precipitations or melting snow. A monitoring system should, therefore, include regular measurements of the reservoir level and of representative temperature and precipitation data.

Generally, *reservoir levels* are today measured with pressure balances. Double-checking is essential. This can be done for instance by installing a manometer on either an existing or new pipe connected to the reservoir. The measuring range should extend at least as far as the dam crest, because it is important to know extreme values of the water level, for an immediate judgement of flood risk as well as the subsequent assessment of peak inflows.

Temperature measurement is required to determine the impact of temperature variations on concrete dam deformation on the one hand, and on the other, to determine whether precipitations consist of rain or snow, or whether the snow-melting period has begun (which the ambient air temperature at the dam site will indicate). Where daily temperature readings cannot be guaranteed, it is recommended to install a temperature recorder or, at least, a thermometer indicating maximum and minimum values. Here, a double check is not strictly necessary, since other temperature measurement methods can always be used in case of failure. Assessing the impact of temperature on concrete dam deformation will be helped by installing a sufficient number of thermometers at various locations within the dam. Use may then be made either of temperature gauges embedded in the concrete, or thermometers inserted in drillholes. Redundancy would consist of a greater number of gauges than strictly necessary.

Precipitation gauging, essential near any embankment dam, is recommended practice for concrete dams as well. Daily readings are adequate. Although the gauge need not

be located right at the dam site, it should not be too far removed from it. If daily readings cannot be guaranteed, a rainfall recorder may be used. A redundancy is not essential in this instance, since data can always be obtained from other gauging stations further away.
Earth-pressure-gauging, to determine the overall stress on critical structural elements, may be useful in particular cases of embankment dams or debris check dams. Interpretation of results is, however, problematical.

3. Deformation

Dam deformation patterns vary according to type of dam, foundation conditions and external loads. Due to the differences in construction materials the behaviour of concrete dams is completely different from that of embankment dams. In concrete dams, deformation is mainly elastic, depending on reservoir water pressure and temperature variations. Permanent deformation may, however, be caused by the subsoil adapting to the new loads, concrete aging or foundation rock fatigue. In such cases, deformation is without danger for so long as it does not exceed some critical value. The case of earth dams is altogether different. Deformation here is to a large extent permanent. Under the impact of the self-weight of the embankment and the hydrostatic pressure of the reservoir water, the fill material (and the foundation if consisting of soil) continues to settle – albeit at a decreasing rate – for decades after construction. In addition, permanent horizontal deformation of the embankment are due to reservoir water pressure and are mainly perpendicular to the embankment centerline. Actual elastic deformation is slight, and not typical of earth dam behaviour.
In view of the difference between concrete and embankment dam behaviour, a monitoring programme cannot be organized in the same way for both types. In concrete dams, monitoring is essentially a matter of observing behavioural trends in both elastic and plastic deformation. The work consists of comparing effective (i.e. measured) deformation to the predicted normal behaviour, assessed through analysis or some other method. In embankment dams on the other hand, permanent deformation trends should be closely monitored for any sign of abnormality. Deformation values vary considerably according to type of dam: they are expressed in millimeters and centimeters in concrete dams, and centimeters or decimeters in the case of embankment dams.
Deformation of a dam and its foundations may be determined by measuring the *spatial displacement of selected control points* from reference points, themselves controlled in position. If the reference points are located inside the dam, only relative deformation values will be recorded. Absolute displacement values are obtained if the reference points are located outside the dam (in the foundation or surrounding terrain) and beyond the region that may be affected by the dam or the reservoir. Although relative data are adequate for routine monitoring, assessing permanent deformation requires absolute data, so that a monitoring system confined to the interior of a dam would be inadequate in this case. Ideally, in concrete dams, the reference points should be located in the rock foundation at a depth unaffected by the reservoir. In that event, absolute data could be obtained by frequent use of simple measurement devices. Fixed reference points located in the vicinity of the dam but outside the range of its impact are, moreover, essential to identify behavioural trends in the surroundings of the dam. Thus, monitoring arrangements in the dam plane should be supplemented by and connected to a vast triangulation network and levellings. Thus, monitoring dam deformation according to set goals requires a spatial, i.e. *three-dimensional measuring installation.*
The monitoring of dam or foundation deformation will be helped if *displacements* are measured at points *along both horizontal and vertical lines* (measurement along lines) extending as far as possible into the foundation and including it. Redundancy – essential in this case – is then achieved by measuring the displacements at the points intersecting the orthogonal lines of this network, using various methods.
If a dam includes inspection galleries and shafts, deformation values along vertical lines can be obtained by using plumb-lines (both hanging and inverted) and along horizontal lines by traverses, both methods being standard practice. Where there are neither galleries nor shafts (as in embankment, thin arch and small gravity dams), the same result can be achieved by an orthogonal network of survey targets on the downstream face. These targets are sighted by angle measurement (combined with optical distance measurements if required) from reference points outside the dam. The geodetic measurement of deformation does have one disadvantage, however. Because it is costly and can be performed by specialists only, it cannot be performed frequently. In routine but more frequent monitoring – of short-term behaviour – the work may be confined to observing trends at selected points (usually, along the crest but occasionally along vertical lines) by simple angle measurement or by an alignment supplementing the measuring installation. The settlement of an embankment dam can easily be monitored by levelling of the crest. Here, redundancy is not essential since levelling can easily be repeated. However, it is essential to extend levelling to some distance beyond the abutments. Alternative measuring methods to assess deformation of an embankment should include settlement gauges, hose levelling devices or extensometers.
Measuring lines may be extended into the foundation by inverted plumb-lines and extensometers (preferably multi-rod extensometers aimed in 2, preferably 3 directions to detect spatial displacements). In some cases use may also be made of a sliding micrometer, preferably incorporating an inclinometer, to determine not only strains but also inclinations. Where there are exploratory and drainage galleries, traverses may be extended into the abutments. Redundancy may be dispensed with if plenty of foundation and abutment-gauging instruments are available.

4. Seepage

Every reservoir entails seepage through the dam structure and its foundation, even if there is a grout curtain. In concrete dams, seepage is usually slight and confined to permeable areas of the concrete, as well as along joints and at the contact between rock and concrete. But any unusual rise in the seepage rate is a danger warning. Seepage flows cause uplift pressure, which should be carefully monitored in concrete dams in view of its considerable impact on stability. In embankment dams, seepage flow through the embankment is similar to that in the foundation, since construction materials (including those used for the impervious core, if any) are more or less pervious. Seepage through and underneath the embankment causes pore-water and uplift pressure, which has a crucial impact on stability. Seepage should therefore be carefully monitored, because any abnormal rate may indicate a development within the embankment or the foundation that may be a serious threat to safety.

The *total seepage rate*, in either type of dam, will indicate whether seepage as a whole may be considered normal. Gauging may be either volumetric (using a calibrated container and a stopwatch) or by using a gauging weir or flume. Since both methods are simple and reliable, redundancy is not necessary. As far as possible, however, *partial seepage rates* (i.e. those occurring in selected, isolated zones) should be monitored. If an abnormality is detected, the critical zone will be all the more easy to identify, as will the search for the cause of the seepage.

In embankment dams constructed from soluble or easily erodable materials – or founded on such materials – it is recommended to monitor *turbidity*, at least at regular intervals if not constantly. This should be followed by periodic *chemical analysis* of the seepage water. In this way useful data can be obtained for assessing the stability of the embankment and foundation materials, and of the grout curtain in particular.

The pattern of seepage and *pore-water pressures* – especially in the foundation and the impervious core – has a significant impact on the normal behaviour of embankment dams. Since pore-water pressures should not exceed design values, they must be carefully monitored, possibly by pressure cells. The greater the number of measurement profiles and number of cells per profile, the more useful the data obtained will be. This method, redundant in itself, is highly advisable in view of the considerable failure rate of pressure cells.

Although recent experience shows that the installation of pressure cells, even in existing embankment-type dams, is possible, refurbishing is not always feasible. In such cases seepage will have to be monitored by gauging the *phreatic line* in selected points. This may be done by using standpipe piezometers, in which the piezometric level is checked (e.g. by a light or acoustic gauge). Since gauging the phreatic line provides a redundancy with regard to pore-water pressure measurements, and its evolution is an important behavioural indicator, standpipe piezometers should be standard equipment in any embankment dam and should be installed in several cross sections.

Seepage underneath a concrete dam causes *uplift pressures* that act against the – stabilizing – effect of the dam's self-weight. Although such pressures are usually controlled by a grout curtain and also, in some cases, by drainage holes, the effectiveness of both should be checked, and uplift pressures carefully monitored, except in cases where the dam would continue to be safe even under the most extreme uplift pressures. Since foundation conditions are heterogeneous (fracturing), uplift pressures should be measured in as many cross sections as possible and at several points between the upstream and downstream face, to monitor the decrease in uplift pressures. Although measurements taken at the rock-concrete contact are usually adequate, it may be advisable, in exceptional cases, to gauge the pressure at various depths. To measure uplift pressure at the rock-concrete interface, piezometers connected to a manometer have proved to be highly reliable, accurate and robust. Since seepage rates are frequently low despite high pressure levels, true pressure readings may not be obtained for quite some time (several days or months). To avoid incorrect gauging, the piezometers should be kept under constant pressure. Readings can be distorted or interrupted, either by clogging of the piezometer intake or the connecting pipe, or by some defect in the pressure transducer. Thus, a drop in the pressure reading should never be viewed with too much optimism. Pressure gauging deep inside the foundation may be performed using pressure cells and standpipe piezometers connected to a manometer. However, since failure in uplift pressure-gauging instruments cannot be ruled out, redundancy is essential. This can be achieved by installing a larger number of measuring devices than is strictly necessary, and/or by a double set of instruments at each observation point.

In cases where the foundation is being drained, *drainage water discharge* should be monitored. Any fall in the flow rate may indicate clogging in the drainage system. Gauging may be either volumetric or by using a gauging weir, both methods being reliable enough not to require redundancy.

The discharge of any *spring* located downstream of the dam should be carefully monitored. Any variation in the discharge may indicate some abnormality in the seepage. But here again, volumetric and/or gauging weir methods are sufficiently reliable not to require redundancy.

Part 2: Measuring installations and methods

Explanations to the tables

Column 1: Purpose

This column indicates the measurement data required, grouped by loads and reactions (indicators of concrete and embankment dam behaviour).

Column 2: Measuring installation, measuring devices, measuring methods

The most suitable and commonly used instruments/methods to obtain the required data are listed in this column.

Column 3: Requirements

The requirements to be fulfilled by the instruments/methods are defined as follows:

R – high *reliability* is required for the data which are indispensable for the proper monitoring of a dam and which must be available at all times.

L – for important data it is necessary to use – together with sufficient redundancies – *long-lived* measuring equipment, whenever its refurbishing, the replacement of parts or the establishment of relations to previous measurements are exceptionally time-consuming or impossible.

M – *measuring ranges* must be wide enough to cover exceptional loads or unexpected behaviour.

P – the required *precision* must cover all errors of the complete measuring installation and procedure (inaccuracy of the instruments and their centering as well as effects of temperature, embedding materials, frictions, wear, zero-point deviations, non-linearities etc.).

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.

Column 4: Remarks

This column includes important indications and details or characteristics of measured data and equipment.

A) Loads

Purpose	**Measuring installation** **Measuring devices** **Measuring methods**	**Requirements** **R** = Reliability **L** = Longevity **M** = Measuring range **P** = Precision	**Remarks**
Water level			
Hydraulic loads	**Pressure balance** **Float** **Staff gauge** **Manometer** **Light gauge** **Acoustic gauge**	**R:** very high **L:** nil **M:** above crest level **P:** ± 10 cm **Redundancy:** absolutely necessary	Important measurement Range must also cover the flood levels
Temperatures			
Air and Water External thermal load Influence on snow melt	**Thermograph** Continuous recording of temperature variation **Thermometer** Min., max. and instantaneous temperature	**R:** nil **L:** nil **M:** – 30°C to + 40°C **P:** ± 1°C **Redundancy:** desirable; necessary for thermograph	These instruments can easily be replaced
Concrete Internal thermal loads (as they directly influence concrete deformation)	**Electrical thermometer** **Thermometer placed** in boreholes	**R:** very high **L:** very high **M:** – 10°C to + 60°C **P:** ± 1°C **Redundancy:** 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
Rainfall			
Rainfall in the dam area influence on water percolation	**Rain gauge**	**R:** moderate **L:** nil **Redundancy:** not necessary	Such measurements are not absolutely necessary in the immediate vicinity of the dam
Earth pressure			
Essential structural parts subject to embankment loads	**Earth pressure cell**	**R:** moderate **L:** high **M:** total overburden (0 to 3 N/mm²) **P:** ±5% of **M** **Redundancy:** not necessary	The deformation modulus of the instrument must be adjusted to the type of embankment material Interpretation and results are problematic

B) Indicators of concrete dam behaviour

Purpose	Measuring installation Measuring devices Measuring methods	Requirements **R** = Reliability **L** = Longevity **M** = Measuring range **P** = Precision	Remarks
Deformation of dam and foundation			
Displacements along vertical lines extending into the rock for comparison with measuring results observed during previous periods, as well as with the assumptions and results of the structural analyses	**Plumbline, inverted plumbline;** measuring device in two directions, with optical sighting of the plumbline wire; the wire serves as vertical reference axis	**R** and **L:** very high **M:** max. calculated deflection +50% **P:** ±0.2 mm resp. ±1% of **M** **Redundancy:** absolutely necessary by means of: – spare measuring device – calibrating station for the measuring device – combination with triangulation, traverse, alignments and extensometers	– Well-tried and precise device – Short measuring time – Teletransmission possible; measuring device must not influence the plumbline position
	Angular measurements and electro-optical distance measurements from stations located downstream of the dam	Requirements to be determined from case to case **Redundancy:** absolutely necessary; possible displacements of the measuring stations must be checked periodically by triangulation or inverted plumbline	– Well-tried but exacting measuring methods to be used only where the installation of plumblines is not possible – Measurements require favourable weather conditions – Precision depends upon distance and refraction
Displacements along horizontal lines extending into abutments and valley sides	**Wire alignment** measuring device in one direction with optical sighting of the wire, which marks a vertical reference plane	**R** and **L:** very high **M:** max. calculated deflection +50% **P:** ±0.2 mm resp. ±1% of **M** **Redundancy:** absolutely necessary by means of: – spare measuring device – calibrating station for measuring device – combination with triangulation, plumblines and extensometers	– Equivalent to plumblines; precision independent from length of wire – Applicable only to straight structures – Max. length limited by quality and weight of the wire
	Levelling	**R** and **L:** moderate **P:** ±1 mm **Redundancy:** necessary according to circumstances in combination with triangulation; groups of reference points must be provided on both valley sides	– Well-tried and simple method when modern instruments are used
	Optical alignment	Requirements to be fixed from case to case **Redundancy:** absolutely necessary in combination with triangulation and plumblines	– Well-tried and simple method otherwise, same remarks as for angular measurements
	Measurements of angles and distances	See same item under "Displacements along vertical lines"	See same item under "Displacements along vertical lines"
	Traverse	Requirements to be fixed from case to case **Redundancy:** absolutely necessary in combination with triangulation and plumblines	– Very exacting measurement; attachment to triangulation and plumblines is absolutely necessary

B) Indicators of concrete dam behaviour (continuation)

Purpose	Measuring installation Measuring devices Measuring methods	Requirements R = Reliability L = Longevity M = Measuring range P = Precision	Remarks
Deformation of dam and foundation (continuation)			
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, L** and **M:** to be fixed from case to case **P:** ±0.5 mm **Redundancy:** not always necessary; can be achieved by: – installing extensometers in several comparable locations – subdividing the full length in several parts – combination with inverted plumbline or levelling	– Placing of anchors and grouting of the protective sleeves are critical operations – Teletransmission possible
	Sliding micrometer differential length variations **Sliding micrometer with inclinometer** differential deflections, partly combined with sliding micrometer **Deflectometer** global or partial respectively differential deflections (chain of deflectometers)	Requirements to be fixed from case to case **Redundancy:** not necessary	– 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 to observe their movements – Measurement and interpretation time consuming
Spacial displacements of individual points of the dam and its surroundings	**Triangulation/trilateration** combined from case to case with: – traverses and levellings – electro-optical distance measurements – optical plumbing, plumblines – alignments, extensometers	**R** and **L:** very high **P:** (three times the expected mean error) $\leqslant \pm 3$ mm for measuring stations and important reference points $\leqslant \pm 5$ mm for other points **Redundancy:** absolutely necessary by means of: – superabundant measuring points and elements – combination with other measuring installations	– The geodetic survey network must cover a large area to enable the long term observation of the structure as well as of its surrounding area and checking possible displacements of reference points for other measurements (redundancy) – Exacting measurement which can be carried out only at long intervals; requires provision of reduced measurements for rapid appraisals – All data and indications on measuring and evaluation methods to be filed safely
Movements of cracks and joints at accessible places – expansions – sometimes shear movements	**Micrometer** **Deformeter** **Dilatometer** **Deflectometer**	**R** and **L:** according to purpose **M:** 10 mm **P:** ±0.05 mm **Redundancy:** according to purpose	– Measurements in gallery walls or recesses are often not representative for the behaviour of the whole mass – Adequate check-marks can often replace a measuring device – Teletransmission possible
Local rotations in the vertical plan (inclinations)	**Clinometer** – with a level and a micrometer – with direct display (electronic)	**R** and **L:** high **M** and **P:** according to purpose **Redundancy:** this measurement is recommended only if combined with other measuring installations such as plumblines for instance	– Near to cavities results are often influenced by stress concentration and transfer effects – Results may be improved by short chains of measuring stretches
Local specific deformations to check stresses	**Electric deformeters embedded in concrete** combined with temperature measurements	**R** and **L:** high **M:** – deformations 2 mm/m – temperature $-10°C$ to $+50°C$ **P:** – stress ± 0.2 N/mm² – temperature $\pm 0.2°C$ **Redundancy:** necesssary by means of – superabundant instruments – other types of instrument for comparison	– Frequent instrument failures – Behaviour often influenced by local material conditions at the instrument site – Analysis of the records problematic

B) Indicators of concrete dam behaviour (continuation)

Purpose	Measuring installation Measuring devices Measuring methods	Requirements R = Reliability L = Longevity M = Measuring range P = Precision	Remarks
Seepage through dam and foundation			
Quantity of seepage and drained water (by zones and in total)	**Volumetric measurements** with calibrated container and stopwatch resp. by volume displacement (for example by means of a calibrated rod in boreholes inclined downwards)	**R** and **L**: moderate **M:** max. expected discharge +100% **P:** ±0.05 l/s resp. ±5 to 10% of **M** **Redundancy:** not necessary	– Method limited to moderate discharges up to 10 l/s; the container's filling time must be at least 10 s
	Weir, measuring flume sometimes with recorder **sonar gauge**	**R** and **L**: high **M:** max. expected discharge +100% **P:** ±5% of **M** **Redundancy:** not necessary	– 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
	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** and **L**: high **M:** max. expected discharge + 100% **P:** ±5% of **M** **Redundancy:** necessary by means of other measuring devices of additional gauges	– Simple means for a periodical check of the indications must be provided for (manometers, weirs, free flow measuring flume)
Pressure of the water circulating in the foundation (uplift and water pressure in rock joints)	**Open borehole/standpipe (piezometer)** Gauging of the water level by a cable line with light or acoustic signal	**R:** nil **L:** high **M:** total length of borehole **P:** ±0.2 m resp. ±1% of **M** **Redundancy:** necessary; installation of piezometers in groups	– Borehole cased watertightly down to the pressure measuring area; protection of head of borehole against penetration of surface waters, mud, stones, etc. – Ensure permanent aeration
	Closed borehole Pressure indication by high precision manometer	**R** and **L**: high **M:** total height between manometer and dam crest **P:** ±0.5 m resp. ±1% of **M** **Redundancy:** 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 max. pressures even if they need a long time to build up – Periodical venting of pipes required – Periodical check of manometers absolutely necessary
	Pneumatic, hydraulic or electrical pressure cells installed in individual boreholes or at several levels in the same borehole	**R** and **L**: high **M:** total height between cell and dam crest **P:** ± 0.5m resp. ± 1% of **M** **Redundancy:** necessary; provision of a great number of cells or disposition in groups	– Central reading of pressure cells spread over a large area possible – Hydraulic measures possible only if the measuring station lies below the minimum pressure level – Careful selection of the filter type in order to avoid its early clogging – Placing of cells exacting expecially if several of them must be installed in the same borehole

C) Indicators of embankment dam behaviour

Purpose	Measuring installation Measuring devices Measuring methods	Requirements **R** = Reliability **L** = Longevity **M** = Measuring range **P** = Precision	Remarks
Deformation of dam and foundation			
Displacements along vertical lines for comparison with measuring results of previous periods	**Angular measurements and electro-optical distance measurements** from stations located downstream of the dam	Requirements to be fixed from case to case **Redundancy:** absolutely necessary; possible displacements of the measuring stations must be checked periodically by means of triangulation	– Well tried but exacting measuring methods – Measurements require favourable weather conditions – Precision depends upon distance and refraction
Displacements along horizontal lines extending into abutments and valley sides	**Wire alignment** measuring device in one direction with optical sighting of the wire, which marks a vertical reference plane	**R** and **L**: very high **M:** max. calculated deflection +50% **P:** ±1 mm resp. ±1% of **M** **Redundancy:** absolutely necessary by means of: – spare measuring device – calibrating station for measuring device – combination with triangulation and extensometers	– Precision independent from length of wire – Applicable only to straight structures – Max. length is limited by quality and weight of the wire
	Levelling	**R** and **L:** moderate **P:** ±1 mm **Redundancy:** necessary according to circumstances in combination with triangulation; groups of reference points must be provided on both valley sides	– Well-tried and simple method when modern instruments are used
	Optical alignment	Requirements to be fixed from case to case **Redundancy:** absolutely necessary in combination with triangulation	– Well-tried and simple method Otherwise, same remarks as for angular measurements
	Measurements of angles and distances	See same item under "Displacements along vertical lines"	See same item under "Displacements along vertical lines"
	Traverse	Requirements to be fixed from case to case **Redundancy:** absolutely necessary in combination with triangulation	– Very exacting measurement; attachment to the triangulation is absolutely necessary
Settlements due to dead weight and hydraulic loads	**Vertical settlement gauge**	**R** and **L**: high **M:** 50–100 m **P:** ±5 cm (construction phase) ±1 cm (operation, after reinstallation) **Redundancy:** necessary with levelling	– Pipe elements <6 m – Verticality during placing to be checked carefully – Difficulties with inclined systems – Electrical gauges – Combination with pipe-inclinometer possible
	Hose levelling device	**R** and **L**: high **M:** a few meters **P:** ±1 cm **Redundancy:** 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 – Deaeration of the measuring fluid necessary

C) Indicators of embankment dam behaviour (continuation)

Purpose	Measuring installation Measuring devices Measuring methods	Requirements **R** = Reliability **L** = Longevity **M** = Measuring range **P** = Precision	Remarks
Deformation of dam and foundation (continuation)			
Settlements and displacements along lines global measurements on long stretches or differential measurements along chains of short stretches	**Rod or wire extensometer** with one or more rods (wires)	**R, L, M**: to be fixed from case to case **P:** ±1 mm **Redundancy:** not always necessary; can be achieved by: – installing instruments in several comparable locations – subdividing the full length in several parts – combination with alignment or levelling	– Placing of anchors and grouting of the protective sleeves are exacting operations – Teletransmission possible
	Pipe-inclinometer, deflectometer gobal or partial, respectively differential deflections (chain of deflectometers)	Requirements to be fixed from case to case **Redundancy:** not necessary	– Electrical plumbline probe in standpipe with guide grooves – Precision highly dependent upon guiding system – Placing and grouting of the guiding sleeves are exacting operations – Recommended for the localization of discontinuities (cracks and/or joints) and to observe their movements – Measurement and interpretation time consuming
Spacial displacement of individual points of the dam and its surroundings	**Triangulation/trilateration** combined from case to case with: – traverses and levellings – electro-optical distance measurements – optical plumbing – alignment, extensometers – vertical settlement gauges	**R** and **L:** very high **P:** (three times the expected mean error) $\leqslant \pm$ 5 mm for measuring stations and important measuring points $\leqslant \pm$10 mm for other points **Redundancy:** absolutely necessary by means of: – superabundant measuring points and elements – combination with other measuring installations	– The geodetic survey network must cover a large area to enable the long term observation of the structure as well as of its surrounding area and checking possible displacements of reference points for other measurements (redundancy) – Exacting measurement which can be carried out only at long intervals; requires provision of reduced measurements for rapid appraisals – All data and indications on measuring and evaluation methods to be filed safely
Movements of cracks and joints at accessible places – expansions – sometimes shear movements	**Micrometer** **Deformeter** **Dilatometer** **Deflectometer**	**R** and **L**: according to purpose **M:** 10 mm **P:** ±0.05 mm **Redundancy:** according to purpose	– Measurements in gallery walls or recesses are often not representative for the behaviour of the whole mass – Adequate check-marks can often replace a measuring device – Teletransmission possible

C) Indicators of embankment dam behaviour (continuation)

Purpose	Measuring installation Measuring devices Measuring methods	Requirements **R** = Reliability **L** = Longevity **M** = Measuring range **P** = Precision	Remarks
Seepage through dam and foundation			
Quantity of seepage and drained water (by zones and in total)	**Volumetric measurements** with calibrated container and stopwatch resp. by volume displacement (for example by means of a calibrated rod in boreholes inclined downwards)	**R** and **L**: moderate **M:** max. expected discharge +100% **P:** ±0.05 l/s resp. ±5 to 10% of **M** **Redundancy:** not necessary	– Method limited to moderate discharges up to 10 l/s; the container's filling time must be at least 10 s
	Weir, measuring flume sometimes with recorder **Sonar gauge**	**R** and **L**: high **M:** max. expected discharge +100% **P:** ±5% of **M** **Redundancy:** not necessary	– 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 alarm signal should be provided for
	Measurements 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** and **L**: high **M:** max. expected discharge + 100% **P:** ±5% of **M** **Redundancy:** necessary by means of other measuring devices or additional gauges	– Simple means for a periodical check of the indications must be provided for (manometers, weirs, free flow measuring flume)
Pressure of the water circulating in the dam (core and shells) and in the foundation (uplift and pore-water pressure)	**Open borehole/standpipe (piezometer)** Gauging of the water level by a cable line with light or acoustic signal	**R:** nil **L:** high **M:** total length of borehole **P:** ±0.2 m resp. ±1% of **M** **Redundancy:** necesssary; installation of piezometers in groups	– Borehole cased watertightly down to the pressure measuring area; protection of head of borehole against penetration of surface waters, mud, stones, etc. – Ensure permanent aeration – Operating availiability checked by flushing operations
	Closed borehole Pressure indication by high precision manometer	**R** and **L:** high **M:** the total hight between manometer and dam crest **P:** ±0.5 m resp. ±1% of **M** **Redundancy:** necessary; installation of piezometers in groups	– Well-tried method – Pipes and connections to the manometers must be watertight – Do not relieve pressure artificially, to allow the observation of max. pressures even if they need a long time to build up – Periodical venting of pipes required – Periodical check of manometers absolutely necessary
	Pneumatic, hydraulic or electrical pressure cells installed individually in the embankment or in boreholes or at several levels in the same borehole	**R** and **L**: high **M:** total height between cell and dam crest **P:** ±0.5 m resp. ±1% of **M** **Redundancy:** necesssary; provision of a great number of cells or disposition in groups	– Central reading of pressure cells spread over a large area possible – Hydraulic measures possible only if the measuring station lies below the minimum pressure level – Careful selection of the filter type in order to avoid its early clogging – No splicing in cables and pipes – Cables and pipes are threatened by differential settlements
Detection of physical or chemical alterations (erosion, dissolution)	**Turbidimeter**	**R** and **L**: high **M:** 0–500 ppm **P:** ±1 ppm **Redundancy:** necessary; analysis of water samples in laboratory	– Indicates amount of dissolved or suspended materials – A protected location is important – Calibration by means of laboratory analysis of seepage water