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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.

Column 5: Reference numbers in part 3

Reference to sections in part 3 where additional information is given about measuring installations and methods comprising measuring devices, technical requirements, possible problems and errors of measurement, checking of operation and maintenance, redundancy possibilities and additional remarks.

A) Loads

Purpose	**Measuring installation** **Measuring devices** **Measuring methods**	**Requirements** **R** = Reliability **L** = Longevity **M** = Measuring range **P** = Precision	**Remarks**	Reference numbers
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	1.000
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	1.100
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	1.110
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	1.200
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	1.300

B) Indicators of concrete dam behaviour

Purpose	Measuring installation Measuring devices Measuring methods	Requirements **R** = Reliability **L** = Longevity **M** = Measuring range **P** = Precision	Remarks	Reference numbers
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	2.100
	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	2.101
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	2.110
	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	2.111
	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	2.112
	Measurements of angles and distances	See same item under "Displacements along vertical lines"	See same item under "Displacements along vertical lines"	2.101
	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	2.113

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	Reference numbers
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	2.120
	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	2.121
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) ≤ ± 3 mm for measuring stations and important reference points ≤ ± 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	2.130
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	2.140
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	2.150
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 ± 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	2.160

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	Reference numbers
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	2.200
	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	2.201
	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)	2.202
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	2.300
	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	2.301
	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	2.302

C) Indicators of embankment dam behaviour

Purpose	Measuring installation Measuring devices Measuring methods	Requirements **R** = Reliability **L** = Longevity **M** = Measuring range **P** = Precision	Remarks	Reference numbers
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	2.101
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	2.110
	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	2.111
	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	2.112
	Measurements of angles and distances	See same item under "Displacements along vertical lines"	See same item under "Displacements along vertical lines"	2.101
	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	2.113
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	3.101
	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	3.102

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	Reference numbers
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	2.120
	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	2.121
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) ≤ ± 5 mm for measuring stations and important measuring points ≤ ±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	2.130
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	2.140

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**	Reference numbers
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	2.200
	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 <0.05l/s – At the collecting point of the total dam seepage a recorder and alarm signal should be provided for	2.201
	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)	2.202
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:** ±0.2m 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	2.300
	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	2.301
	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	2.302
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	3.301

Part 3: Measuring devices – Measuring methods

Hydraulic loads

Pressure balance

Reference number 1.000–1

1. Measuring device

Instrument for determining reservoir level by measuring the hydrostatic pressure.

2. Appraisal

This is a well-proven instrument. Measurement accuracy and the resolution of the measured values exceed normal requirements for the monitoring of dams. Recent technical improvements have further increased the reliability of this instrument.

3. Possible problems and measurement errors

Deposition of sediment can block the inlet pipe from the reservoir and disturb the measurements. Suspended material in the water can lead to incorrect measurements.

4. Technical requirements

Installation of this instrument should be allowed for at the time of designing the dam. An accurate manometer should be installed for the checking of the pressure balance. The pressure sensing point should not be located in a canal, conduit or pipeline as readings can be affected by the flow velocity of the water (e.g. low level outlet, water intake or weir, etc.).

5. Checking of operation and maintenance

Checks:
- At high reservoir level:
  By measurements from a bench mark or staff gauge.
- At low reservoir level:
  By means of the accurate manometer or using piezoelectric, hydraulic or pneumatic pressure cells.

Maintenance:
- All pipes must be flushed out at regular intervals.

6. Redundancy

With precise manometer possibly with remote transmission, or with pressure measurement cell, staff gauge, light gauge, etc.

7. Remarks

The measurement transmission equipment should be planned in the context of the overall instrumentation of the dam.

Float

Reference number 1.000–2

1. Measuring device

This instrument allows variations of reservoir level to be measured over a limited range, especially at high water levels (during times of flood).
The float is usually connected to a continuous recorder or is equipped for data teletransmission.

2. Appraisal

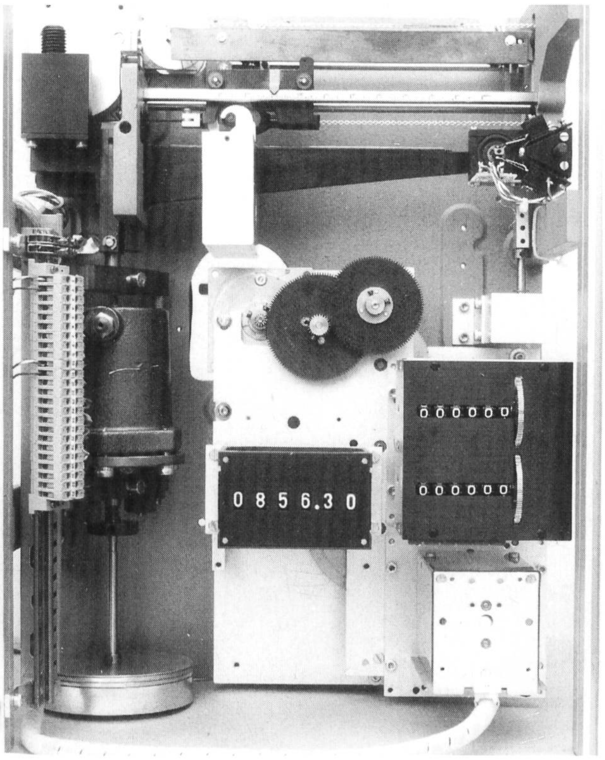
This is a simple and reliable instrument which must, however, be regularly checked. The measuring range is limited.

3. Possible problems and measurement errors

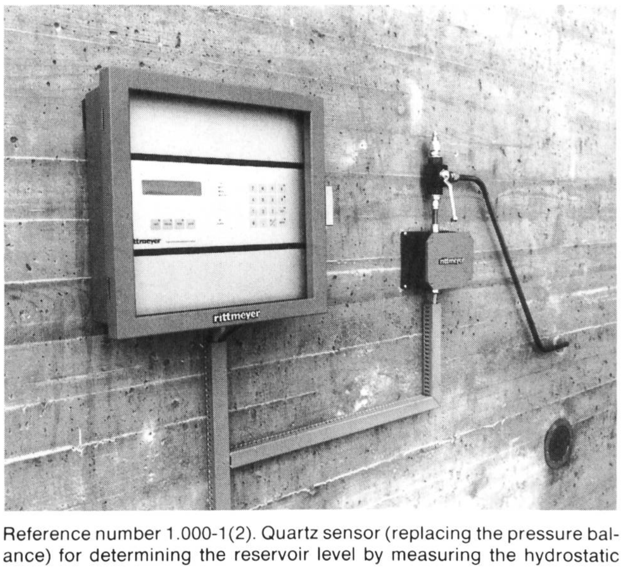
The float can be damaged by floating material or ice. Deposited sediments and floating matter can affect the readings.

4. Technical requirements

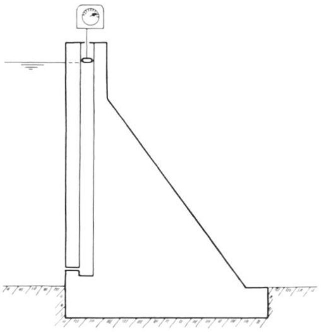
The float must not be located in flowing water or where ice can form (if necessary, it must be provided with heating equipment).
Access for maintenance must be ensured.



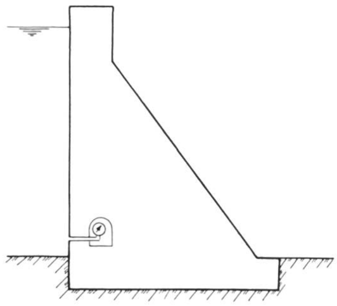
Reference number 1.000-1(1), left. Pressure balance for determining the reservoir level by measuring the hydrostatic pressure.



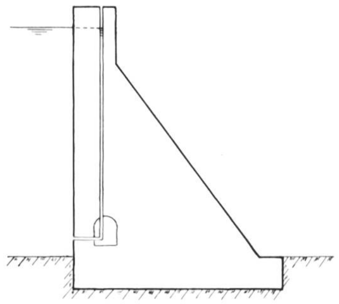
Reference number 1.000-1(2). Quartz sensor (replacing the pressure balance) for determining the reservoir level by measuring the hydrostatic pressure.



Reference number 1.000-2. Float to measure the reservoir water level.



Reference number 1.000-4. Manometer to measure the hydrostatic pressure corresponding to the reservoir water level.



Reference number 1.000-5. Acoustic or light gauges to measure the reservoir water level.

Special damping equipment should be provided to counteract the effects of sudden water level variations caused by waves.
Provision must be made for flushing the measurement shaft.

5. Checking of operation and maintenance

It must be checked that the mechanical parts of the instrument can move freely.
The agreement of the actual and indicated water levels must be periodically checked.

6. Redundancy

Staff gauge, which is also used for calibration of the instrument.

Reference number 1.000-3. Staff gauge. Calibrated metal scale to determine reservoir water level.

Staff gauge

Reference number 1.000–3

1. Measuring device

This is a calibrated, wood or metal scale with decimeter or centimeter divisions. Certain models are also provided with equipment to record the maximum water level reached.

2. Appraisal

This is a very simple way of determining the reservoir level by direct reading. It allows variations of reservoir level to be followed visually, e.g. in the event of floods.
The staff gauge can be installed vertically or inclined.

3. Possible problems and measurement errors

When the surface of the reservoir is disturbed by waves the water level can only be measured approximately. The staff gauge can be damaged by floating matter. The color and markings of the staff gauge can fade or peel off.

4. Technical requirements

The staff gauge must be located where it will not affect the flow of water, and away from the zone of influence of a hydraulic structure as this can result in incorrect readings. The staff gauge must be easily visible and access to it must be assured at all times. The staff gauge must be provided with markings which can be accurately read at all times, and if necessary must be illuminated.

5. Checking of operation and maintenance

The staff gauge must be regularly checked to ensure that it is correctly fixed and not damaged. Regular cleaning and if necessary repainting are necessary.

6. Redundancy

Not necessary.

7. Remarks

If need be a staff gauge can be installed downstream of the dam to allow measurement of the tailwater level and determination of the corresponding discharge.

Manometer

Reference number 1.000–4

1. Measuring device

A connecting pipeline from the reservoir transfers to the manometer the hydrostatic pressure corresponding to the reservoir level (figure 1.000–4).

2. Appraisal

A simple and reliable instrument of limited accuracy which can be installed for instance as redundancy for the rough checking of pressure balance.

3. Possible problems and measurement errors

Blockage, icing up, and entry of air into the pipeline. Jamming of the mechanical parts of manometer.

4. Technical requirements

The instrument and connecting pipeline must be located in a frost-free position. Flushing and removal of air from of the pipeline must be possible. The pressure sensor must not be located in a zone influenced by the flow through in- or outlets (pressure tunnel, bottom outlet, etc.).

5. Checking of operation and maintenance

Periodic flushing of the pipeline. Periodic checking of the equipment. It is recommended that a replacement manometer be provided for rough checks.

6. Redundancy

The installation of similar equipment at other locations or from case to case other instruments such as staff gauge, acoustic gauge, light gauge or electrical pressure measurement cells, etc.

Acoustic or light gauges

Reference number 1.000–5

1. Measuring device

The water level in a vertical shaft or pipe connected with the reservoir is determined by means of a weighted sensor. This is suspended on a graduated cable and the position of the water surface is indicated by a whistle (which sounds as the air is driven out of the submerging sensor), or by the illumination of a lamp, often with an additional buzzer (which operate when an electric circuit is closed by the conductive water) (figure 1.000–5).

2. Appraisal

This is a simple, reliable and very precise instrument for all ranges of water level. It can be used for instance as redundancy for the pressure balance.

3. Possible problems and measurement errors

Blockage, icing up of the connection to the vertical shaft or pipe.

4. Technical requirements

A frost-free position for the connection and the vertical shaft or pipe.

Flushing of and removal of air from the connecting pipe and the vertical shaft or pipe must be possible.

The connecting pipe must be of sufficient capacity.

The connecting pipe must not be located in a zone influenced by the flow through in- or outlets (pressure tunnel, bottom outlet, etc.).

5. Checking of operation and maintenance

The connecting pipe and the vertical shaft or pipe must be periodically flushed.

6. Redundancy

The same equipment in another position.

Improvised direct sounding of the reservoir (this is difficult or impossible when the reservoir is frozen) or from case to case other instruments such as staff gauge, electrical pressure measurement cells, etc.

Air temperature

Thermograph

Reference number 1.100–1

1. Measuring device

The thermograph allows the continuous measurement and recording of the ambient temperature. The readings are plotted on a band of paper fixed to a drum. The duration of the recording is from 7 to 31 days according to the speed of rotation of the drum. The clockwork is either wound up by hand or operated by a battery.

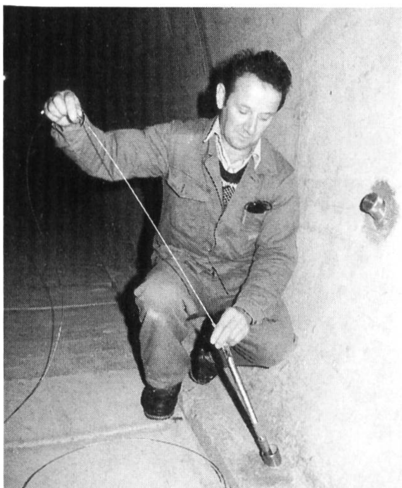
2. Appraisal

The instrument functions without any problems as long as it is well installed and maintained.

It's ability to attein the desired accuracy of ±1 °C is not absolutely certain.

3. Possible problems and measurement errors

Direct exposure to the sun's rays or currents of air distorts the recordings. Running out of ink can lead to a loss of part



Reference number 1.110-2. Engineer introducing a thermometer in a borehole to measure internal temperature of concrete or roc.

Reference number 1.200. Pluviometer (center of the photograph) integrated in a meteorological field station.

of the recordings. Interruption of the recordings due to lack of power (winding up of the clockwork not carried out or battery discharged). Breakdowns due to windblown snow are not uncommon.

4. Technical requirements

The thermograph must be installed, if possible, in a small housing with easy access (particularly in winter). The location of the thermograph must be representative of the ambient temperature of the zone of the dam. The thermograph must not be installed in a location susceptible to heating by the sun or to the heat from air exhausts.
The thermograph must be complemented by a maximum/minimum thermometer.

5. Checking of operation and maintenance

Maintenance of the instrument is carried out in accordance with the manufacturer's instructions (changing the paper, ink, etc.).
A continual comparison of measurements must be made by means of a maximum/minimum thermometer.
When the band of paper is changed, the clockwork must be rewound, as it will only continue to function for a further 30% to 50% of the duration of the next recording.

6. Redundancy

This is obtained with the maximum/minimum thermometer.

7. Remarks

Modern electronic instruments exist which enable the direct processing of the measured values.

Thermometer

Reference number 1.100–2

1. Measuring device

Measurement of the air temperature can be made by means of a standard commercial capillary thermometer. A maximum/minimum thermometer is particularly well suited, because in addition to the current temperature, it also indicates the lowest and highest temperature during the period of measurement.

2. Appraisal

The measurement is simple and is made by direct reading.
Defective thermometers are easily replaced.

3. Possible problems and measurement errors

Direct exposure to the sun's rays or currents of air can distort the measurement of the air temperature.

4. Technical requirements

For measurement of the air temperature, the range of measurement must be some 35°C below and above the average ambient temperature.
The thermometer must not be installed in a location susceptible to heating by the sun or to the heat from air exhausts.
Make allowances for some replacement thermometers.

5. Checking of operation and maintenance

The accuracy of the readings must be verified from time to time by comparison with the readings of a replacement thermometer.

6. Redundancy

By means of the replacement thermometers.

7. Remarks

By virtue of the installation of supplementary thermometers in different locations, the air temperature can be determined in the whole zone of the dam.

Water temperature

Thermometer

Reference number 1.100–3

1. Measuring device

A special thermometer is used consisting of a thermometer placed inside a metal protection tube with a perforated water reservoir. The thermometer is lowered to the desired depth by means of a metric tape, and the reading is taken after raising it.

2. Appraisal

The measurement is simple and is made by direct reading.
Defective thermometers are easily replaced.

3. Possible problems and measurement errors

The thermometer must be left long enough at the required depth (several minutes) in order that the water in the perforated reservoir reaches the surrounding temperature. Taking a correct measurement is a matter of rapidly withdrawing and reading the thermometer in order to limit the change of temperature.

4. Technical requirements

The range of measurement of the thermometer must be between 0°C and +30°C (standard commercial thermometers reach +50°C).
Thermometers which indicate extreme values are very useful.
The thermometers must have a certain inertia so that they do not react too quickly to external influences (changes in water or air temperatures, rays of the sun) when they are withdrawn from the water.
Allow for a replacement thermometer.

5. Checking of operation and maintenance

The accuracy of the measurements should be verified at some time or another by comparing readings with the replacement thermometer.

6. Redundancy

By means of the replacement thermometers.

7. Remarks

The water temperature can otherwise be taken by means of an electric sensor placed in the water or fixed to the upstream face of the dam (see reference number 1.110–1). With a fixed installation of the electric sensor, transmission of the measured data is possible.

Concrete temperature

Electric thermometers

Reference number 1.110–1

1. Measuring device

The instruments placed in the concrete for measuring the temperature are based on the following principles:
Resistance thermometer: a change in temperature causes a change in the resistance of a metal wire placed in the sensor. Readings are taken with a Wheatstone bridge.
Thermocouple: two wires of different metals are soldered together at their ends; one end is placed in the concrete at the point of measurement and the other end is outside. When a temperature difference occurs between the two soldered ends, an electric current is induced which can be measured from the exterior.
Vibrating wire thermometer: a change in temperature modifies the natural frequency of a vibrating wire excited by a

magnet located in the sensor. A wire of comparison located in the measuring instrument enables the temperature to be determined.

2. Appraisal

These measurements are reliable and easy to carry out. Failure of some of the sensors is possible.

3. Possible problems and measurement errors

Failure due to over voltage caused by atmospheric conditions.
Corrosion of the electric connection points of the instrument.
In the course of time, the zero point of the instrument can be displaced.
Incorrect connections of the cables are possible with many of the measuring bridges.

4. Technical requirements

The required range of measurement lies between −10°C and +60°C, at the time of installation in the fresh concrete, −10°C and +40°C for a later installation.
The quality of material chosen for the sensors and the cables is very important (mechanical resistance, electrical shielding).
The cables must not include spliced joints between the sensors and the terminal boxes.
Use only reliable sensors.
The measurements must not be interrupted over many years.
The reading instruments (possibly centralised) which are capable of storing the recorded data facilitate the transfer to a computer.

5. Checking of operation and maintenance

The measuring instruments (measurement bridge, etc.) must be checked periodically.
The electrical connection points require periodic maintenance (corrosion).

6. Redundancy

The installation of a sufficient number of sensors provides a certain degree of redundancy.

7. Remarks

The electrical sensors can also be placed in open boreholes to facilitate their replacement in the event of damage.
Measurement with electrical sensors is suitable for the remote transmission of data.

Thermometer

Reference number 1.110–2

1. Measuring device

The internal temperature of the concrete can be determined simply by means of a standard commercial capillary thermometer. This is introduced into a vertical or inclined borehole, or in a tube cast in the concrete, such that the reading can be taken at the required depth. The thermometers are either attached to a string or to a rod at one end and are withdrawn from the borehole for reading.

2. Appraisal

The measurement is simple and is made by direct reading. Defective thermometers are easily replaced.

3. Possible problems and measurement errors

The circulation of air and water in the boreholes or tubes should be avoided. The openings of the boreholes or tubes must be closed with stoppers. At the time of measurement, the thermometer is rapidly withdrawn and read in order to limit the change in temperature.

4. Technical requirements

Standard commercial thermometers of different sizes can be used with a range of readings within −10°C and +30°C (...+60°C) and with an accuracy in the order of ±0,5°C.
The boreholes for the measurements must be situated at some distance from conduits and openings (shafts, galleries). A sufficient number of points of measurement should always be allowed for.
Make allowances for replacement thermometers.

5. Checking of operation and maintenance

The accuracy of the measurement must be verified from time to time by comparison with the replacement thermometers.

6. Redundancy

By means of the replacement instruments.

Precipitations

Pluviometer, rain gauge

Reference number 1.200

1. Measuring device

Instrument used in the monitoring of a dam to measure precipitations falling in the vicinity of the dam. The results of the measurements enable the meteorological conditions to be taken into account in the interpretation of the discharge of seepage and drainage water as well as the water pressure in the foundations, which are both influenced by the level of the groundwater table.

2. Appraisal

The pluviometer totaliser is a very simple volumetric measuring instrument, readings being taken, as a rule, every 24 hours. For this application, a high level of accuracy is not necessary.

3. Possible problems and measurement errors

Wind during rain and freezing or evaporation of collected precipitations.

4. Technical requirements

The location must be representative, with easy access at all times. If necessary, the pluviometer must be equipped with a heater to avoid freezing.

5. Checking of operation and maintenance

Normal maintenance according to the manufacturer's instructions.

6. Redundancy

This is not necessary.

7. Remarks

The above text is only valid for use of the pluviometer in the context of dam surveillance.
A pluviograph can also be used in place of a pluviometer.

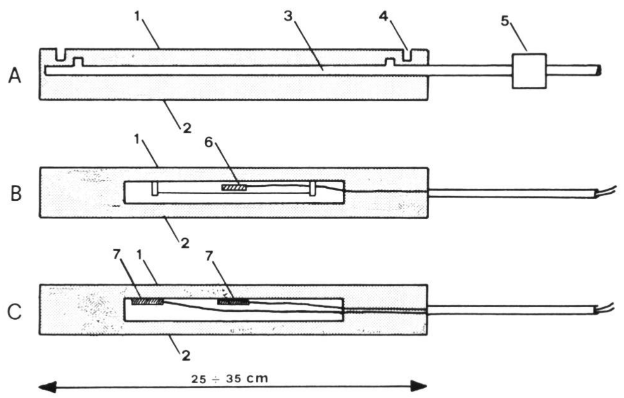
Earth pressure

Earth pressure cell

Reference number 1.300

1. Measuring device

A flat round plate (diameter 25 to 35 cm) for measuring the total stresses in a fill dam (earth pressure plus pore water



Reference number 1.300. Earth pressure cells. (A) Hydraulic cell, (B) Diaphragm cell with vibrating wire transducer, (C) Diaphragm cell with resistance strain gauges; 1 Active face, 2 Inactive face, 3 Liquid filled cavity, 4 Grooves to increase flexibility, 5 Pressure transducer, 6 Vibrating wire transducer, 7 Resistance strain gauges [*Dunnicliff* 1988].

pressure) perpendicular to the plate. Various systems exist for transmitting the measured values (electric, hydraulic, pneumatic), and depend on the transmission distance and manufacturer. Connection with the terminal cabinet for the reading of the measured values is by means of a cable or flexible tubes. Pore water pressure measurement cells must be installed at the same time if the effective earth pressure alone has to be determined.

2. Appraisal

The hydraulic and pneumatic systems are sensitive to temperature variations. With the hydraulic system the measurement chamber must be located at a lower level than the lowest measurement cell in the body of the dam so that the build-up of pressure can be observed from the start of the placing of fill. The evaluation of the measurement results is often problematic. Nevertheless, the system allows the stress development trend to be followed. The pneumatic system is only suitable for pressures up to 3 MPa and for flexible tubes not longer than 500 m.

3. Possible problems and measurement errors

The tubes can be damaged during placing or as a result of differential settlement between adjacent zones of different material.

Cables can be damaged if insufficiently protected against voltage surge.

Problems can arise if the instrument is placed in non-homogeneous material.

4. Technical requirements

The measurement cables must be protected against excessive stresses and must not be spliced between the measurement cell and the measurement chamber. When placing the flexible tubes for the hydraulic system care must be taken to avoid negative pressures. The electrical cables and flexible tubes should be laid in narrow trenches and protected at all times against damage by construction machines.

5. Checking of operation and maintenance

The tubes of the hydraulic and pneumatic systems must be flushed at least once a year, with water or gas, respectively. The reading instruments for these systems must be very carefully maintained.

6. Redundancy

The installation of two different systems (for instance electrical and pneumatic) is possible but not necessary in any case. However, at least two instruments should always be installed at anyone location.

7. Remarks

When installing the instrument great care must be taken to ensure the homogeneity of the surrounding earth material.

Earth pressure measurement cells with microclinometers allow measured readings to be corrected to take account of the rotation of the cell as a result of deformation of the fill material.

Deformations along vertical lines

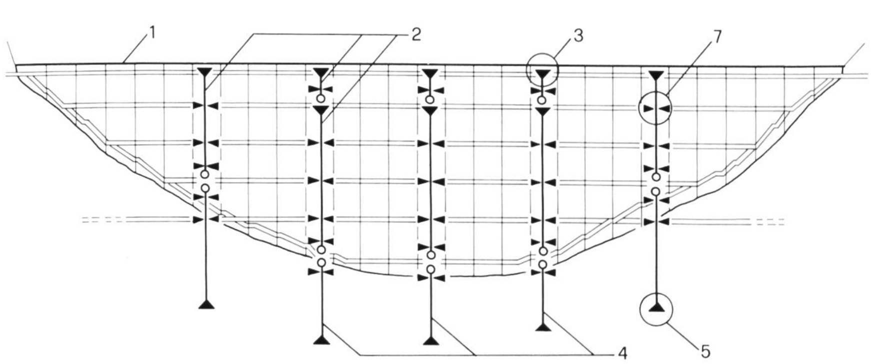
Plumb line / Inverted plumb line

Reference number 2.100

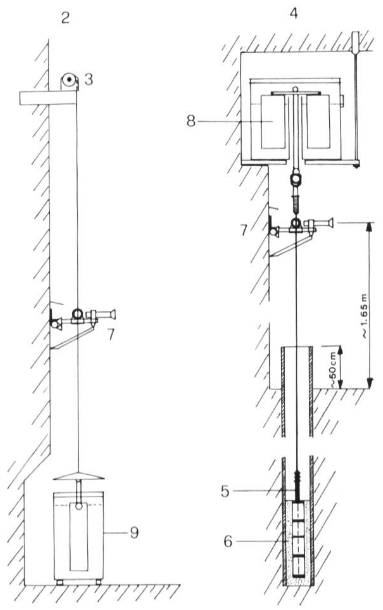
1. Measuring device

The plumb line consists essentially of a suspended wire which is accurately centred and tensioned by a weight. In order to dampen any possible oscillation of the plumb line, the weight is enclosed in a tank filled with oil or water.

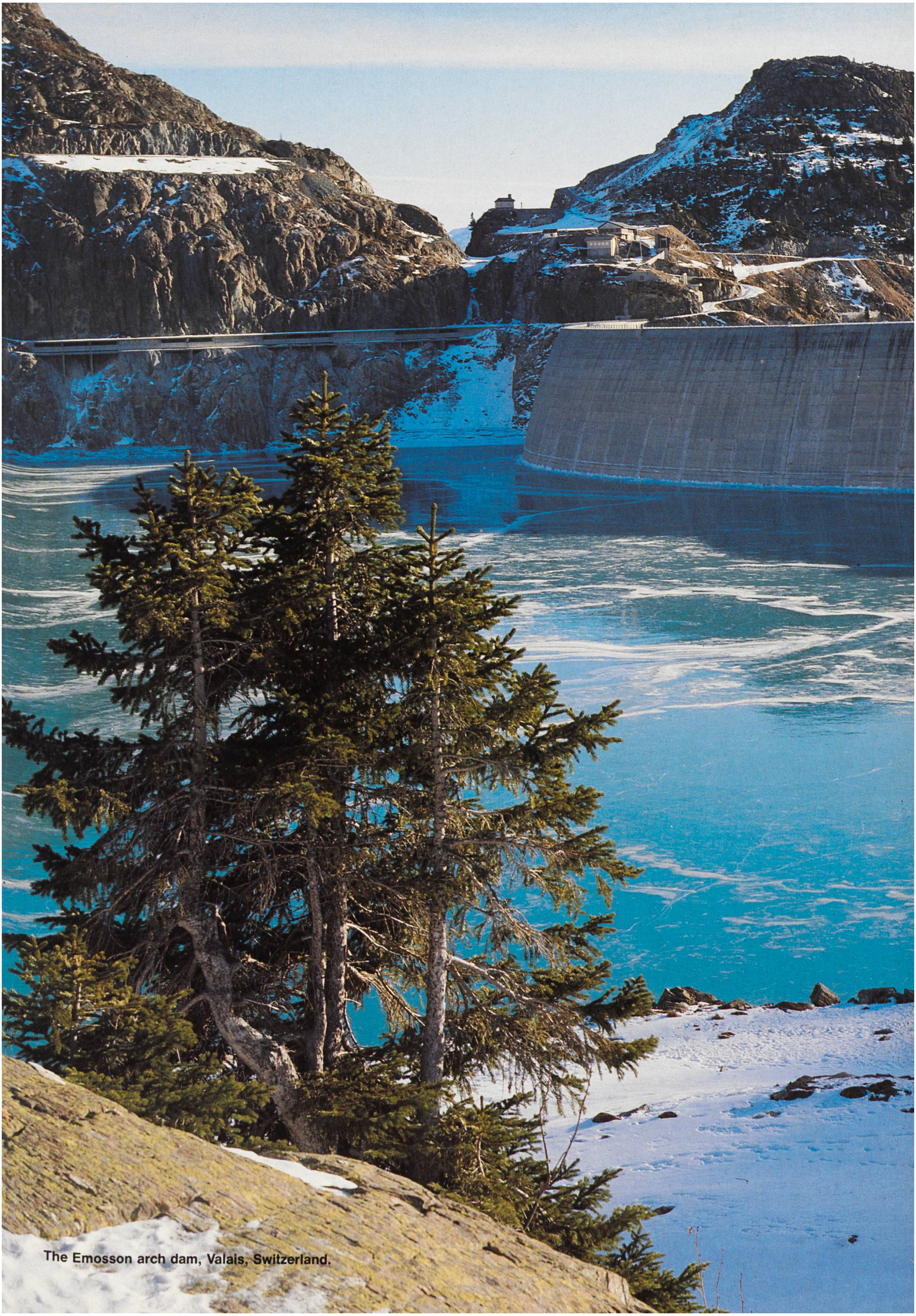
The inverted plumb line, fixed at its lower end, is provided with a float which can move freely in a purpose-built tank. The tensile force in the line is somewhere between 20 and 200 kg, for both instruments. The deflection of a section of



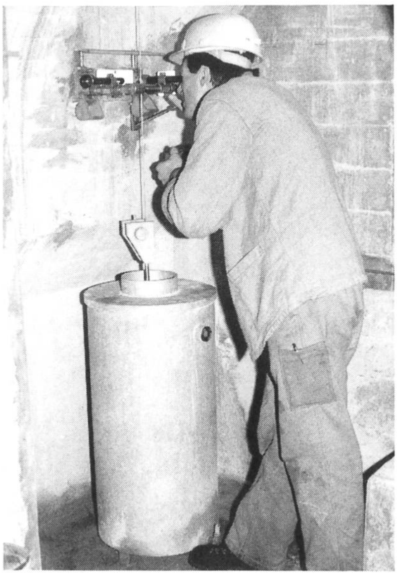
Reference number 2.1000(1), above. Typical example of a modern arrangement of plump lines. 1 Crest of dam, 2 Plumb line, 3 Point of suspension of plumb line, 4 Inverted plumb line, 5 Anchorage of inverted plumb line.



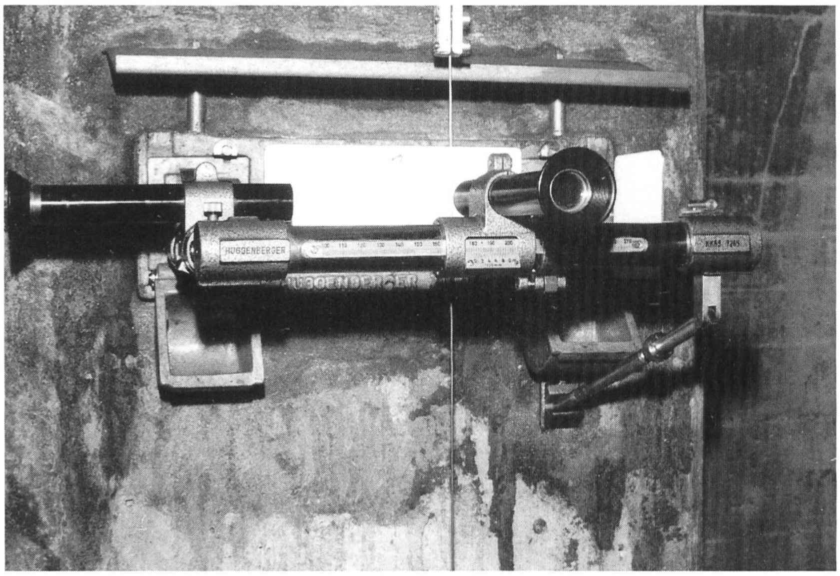
Reference number 2.100(2) at right. Schematic representation of plumb lines. 1 Crest of dam, 2 Plumb line, 3 Point of suspension of plumb line, 4 Inverted plumb line, 5 Anchorage of inverted plumb line, 6 Cement grout, 7 Measuring point, 8 Float/float tank, 9 Damping tank.



The Emosson arch dam, Valais, Switzerland.



Reference number 2.100(3). Measuring of dam deflection at the bottom of a plumb line. The weight is enclosed in a tank filled with oil or water.



Reference number 2.100(4). Optical instrument to read the position of the plumb line wire with the help of a vernier scale.

the dam can be determined at different levels by optic sighting of the wire with a specially devised instrument. Whereas, until now, the readings in the two orthogonal directions have been most often taken on a vernier scale, the most modern instruments have a digital reading.

2. Appraisal

Both types of plumb line have been well proven over many years; it is a simple and accurate measurement, which is practically irreplaceable for the periodic recording of the deflection of a dam.

Automisation of the recordings and long distance transmission of the data are possible and are very important for the remote monitoring of dams.

3. Possible problems and measurement errors

Careless placement of the reading instrument at the measuring point can lead to significant errors of measurement.

An insufficient quantity of water/oil:

- in the float tank of an inverted plumb line causes blockage of the float which leads to an incorrect position of the plumb line;
- in the damping tank of a plumb line causes an increase in the tension of the wire, by reducing the buoyancy, and results in an elongation of the wire, with the risk that the weight touches the bottom of the tank.

Reference number 2.100(5). Optical sighting of the plumb line position and digital data registration and identification of the measuring point.

In the presence of mechanical sensors for the remote transmission of measurements, the position of the wire can be incorrect as a result of too much friction.

A kink in the wire leads to significant inaccuracy of the measurements.

A plumb line can, occasionally, touch the neck of the damping tank; the weight can also touch either the bottom of the tank or mud deposited in it.

The freedom of movement of the wire in shafts and boreholes can be impeded by efflorescent deposits or by objects having fallen into them.

Careless centring of the wire can sometimes lead to a visible jump in the measured displacements.

The formation of ice around the point of suspension or in the float tank can not only lead to an incorrect position of the plumb line, but also to the breaking of the wire, which, in the case of the inverted plumb line, can also damage the float.

As a consequence of significant deformation in the rock foundation, on the first reservoir filling, the tube fixed in the borehole can sometimes rupture; if, in this case, water bursts into the tube, the inverted plumb line is set in motion which to all practical purposes, prevents the continuation of measurements without first repairing the tube.

A current of air in the shaft of the plumb line starts it oscillating which makes the readings difficult, inaccurate and sometimes impossible.

Simple reading errors are not uncommon.

4. Technical requirements

The points of suspension must be accessible to enable inspections.

The means of suspension must be provided with an accurate centring device for the wire.

The reading positions must be correctly lighted and protected as well as possible from water dripping down the plumb line shafts.

Currents of air in the shafts of the plumb line must be avoided, in order that the position of the plumb line is not disturbed. For this reason, all the measuring points must be separated from the system of control galleries and closed by doors.

In order to protect the personnel, the fall of possible counter weights (e.g. for intermediate centring by remote control) must be prevented by adequate means.

In order to prevent, for certain, the rupture of the tube installed in the borehole of an inverted plumb line, the installation must, if possible, be made in the downstream abutment of the dam (compression zone).

For the inverted plumb line it is imperative that the tension in the wire:

- can easily be verified by means of fixed reference points on the float, which indicate the corresponding tension, or
- can be measured directly by a suitable device.

For remote monitoring, the position of the wire should be relayed without contact, and if possible, by means of an instrument with no mechanical parts.

5. Checking of operation and maintenance

Check if the free space for horizontal movement is maintained along the whole length of the plumb line.

Verify that there is enough water in the damping tank and check by vertical movements that the distance between the weight and the bottom of the damping tank is sufficient.

Water/oil in the float tank must be verified at each measurement carried out manually. When necessary it is essential that liquid be added.

In the case of a sensor for a remote measuring instrument, verify that the wire resumes its original position after an imposed movement. If necessary, check the position of the wire after having dismantled or released the sensor.

Check in winter if there is a formation of ice around the point of suspension or in the float tank. If this is the case take measures to prevent it.

From time to time the plumb lines must be checked absolutely by geodetic measurements (at least once every five years) in order to verify the stability of their fixings.

6. Redundancy

Comparison with deflections observed in several sections of the dam.

Combination with geodetic measurements (or traverse).

Comparison of results obtained by plumb lines with those of other measurements of deformation (such as clinometer, tiltmeter).

7. Remarks

It is recommended to have a replacement reading instrument available.

Simple measurement of angles and distances

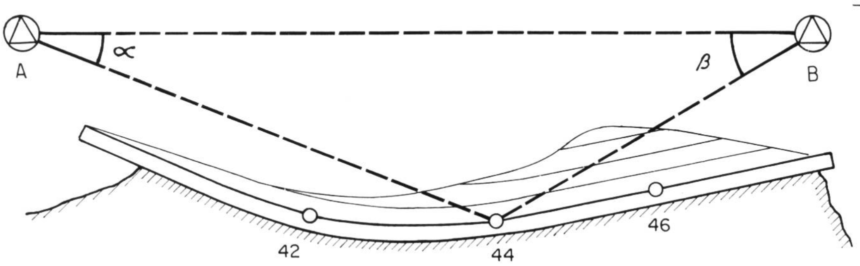
Reference number 2.101

1. Measuring method

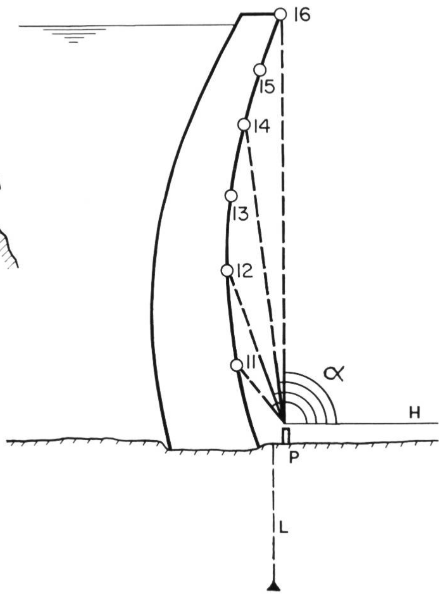
Simple angle measurements can be ranked in accuracy between optical alignment and triangulation, and as a rule are used for determining one-dimensional horizontal displacements. Instead of a vertical reference plane, on which the reference and control points lie for optical alignment, simple angle measurement makes use of elements of triangulation. The fixed points are one or two reference points on the valley sides downstream of the dam. Measurements are made of the angle α for suitable control points on the dam. The variations of this angle ($\Delta\alpha$) give information on the horizontal movement of the control point in the principal displacement direction (upstream – downstream). The points A and B are assumed not to move themselves but this must be checked from time to time. The distances between the control point and the reference points are also assumed not to change. The elevations of the reference points and control points can be freely chosen.

The angle measurements are made using a suitable theodolite, mounted on a pillar or tripod. Precise centring of the theodolite is essential. As a check the angle β can be measured from the opposite reference point (B). The displacement determined from this second measurement should be, within the acceptable limits of error, as determined from the point A.

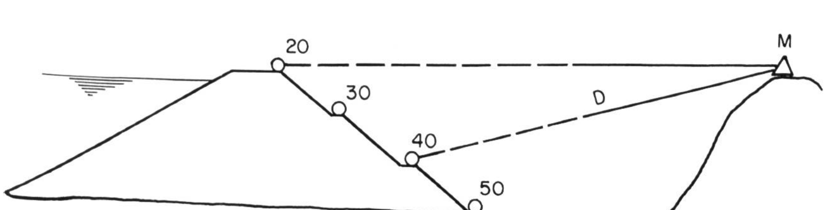
Simple measurement of vertical angles are used instead of plumb line measurements to determine deformations of vertically strongly curved or very thin arch dams. The verti-



Reference number 2.101(1). Simple measurement of angles used for determining horizontal displacements. The measurement system uses observations with a theodolite from a pillar (reference point A) to the control points on the dam (targets 42, 44, and 46) using reference point (B) as orientation. As a check analogical measurements can be made from the opposite reference point (B).



Reference number 2.101(2). Simple measurement of vertical angles used for determining the upstream/downstream deplacements of targets located on the downstream face of the dam. (P) Reference point, usually an observation pillar, (H) Horizon, (L) Inverted plumb line, 11 to 16 Control targets.



Reference number 2.101(3). Simple measurement of distances between control targets on the dam and fixed reference points downstream deplacements of the dam using an electro-optical distance meter. (M) Reference point, (D) Measured distance, 20 to 50 Control targets.

Stausee Valle di Lei der Kraftwerke Hinterrhein AG.

The Valle di Lei reservoir of the Kraftwerke Hinterrhein AG.

cal angles are measured from a reference point (usually an observation pillar) at the foot of the dam. The control targets are located on the downstream face of the dam in the same vertical plane as the reference point.
Displacement of the control targets in an upstream/downstream direction can be determined from the variations of the vertical angles ($\Delta\alpha$). The position and height of the reference pillar are assumed to be fixed and changes in the distances between this fixed point and control points are neglected. These assumptions have to be periodically checked by triangulation or possibly an inverted plumb line placed next to the measurement pillar.
It is theoretically possible by the measurement of horizontal angles also to determine displacements of the dam in a transverse direction. Measurement of vertical angles is difficult and requires the use of a high-precision theodolite with an elbow eyepiece to allow the very steeply-inclined observations to be made. Special targets on the dam may also be needed.
By *simple distance measurements* are understood the measurement of distances between control targets on a dam and fixed reference points downstream of the dam.
The change in the horizontal distance (ΔD) between consecutive measurements is equal to the one-dimensional displacement of the control target on the dam in the sighting direction.
The measurements are made using an electro-optical distance meter and access to the control points on the dam is necessary for setting up the reflectors. The accuracy of the measured displacement of the dam is a direct function on the precision of the distance meter.
These procedures make the calculation of the displacement of control targets very simple, but their use is only recommended as part of a full triangulation system.

2. Appraisal

The accuracy of deformation values obtained from the simple measurement of angles and distances is appropriate to this method, but redundancy can only be introduced if redundant measurements are made. Measurements of distances require the use of an electro-optical distance meter.
Specially qualified personnel must be used for the measurement of vertical angles. Because of the abnormal atmospheric stratification often encountered directly in front of a concrete dam, vertical angle measurements can be seriously affected by refraction. Other systematic errors, which can cause inaccuracies, are the height of the measuring instrument and its precise centring, deviations of the vertical as a result of changing reservoir level, etc. Use should be made of vertical angle measurements only when other methods cannot be justified.

3. Possible problems and measurement errors

The identification and correction of instrument errors, by the correct employment of survey principals (e.g. angle measurements with the telescope of the theodolite in face left/face right position) and the elimination of observation errors (e.g. index errors of the theodolite, scale errors of the distance meter) are of greater importance because of the lack of redundancy. Measurements are dependent on the weather (winter conditions at high altitude), and can be influenced to varying degrees by refraction.
The cleaning of control targets on the face of concrete dams is difficult when these are not accessible.

4. Technical requirements

The topographic features of the dam site must allow clear sight lines between the measurement and control points.
All reference points must be accessible and protected against rock fall, avalanches, and snow pressure.
Measurements by semi-skilled personnel are possible.

5. Checking of operation and maintenance

The control points and reference points have to be periodically checked for damage.
All survey instruments have to be regularly checked and if necessary adjusted.

6. Redundancy

Redundancy for simple angle and distance measurements can be provided by the establishment of a superior triangulation system. This is only possible to a limited extent for vertical angle measurements, which must be correlated with the readings of an inverted plumb line anchored deep in the foundation rock of the dam.

Deformations along horizontal lines

Wire alignment

Reference number 2.110

1. Measuring device

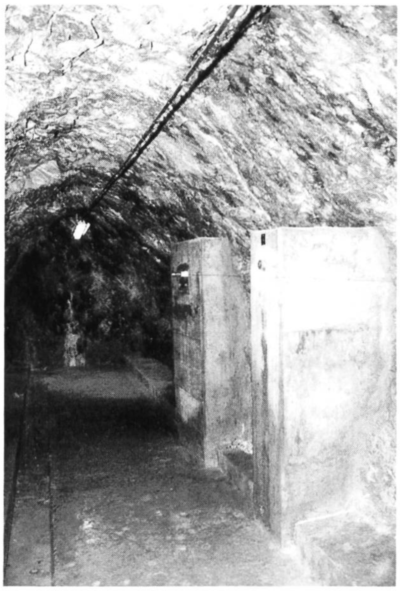
Essentially, the elements of the wire alignment are taken from those of the plumb line. As a general rule, a freely suspended wire is tensioned from one bank to the other along straight walls within galleries or along a parapet, at the level of the crest of the dam. This wire defines a vertical reference plane. The deformations with respect to this plane, that is to say the upstream-downstream components, which correspond to variations in the distance of the wire from the wall, are determined by means of a measurement scale. The measuring instrument is fixed to the wall. The position of the wire sighted vertically is read off the measurement scale (vernier or digital scale) as for a plumb line.
The wire is subjected to a constant tension such that the deflection does not vary, thus limiting the distance between the measuring instrument and the wire. The tension is maintained by a freely hanging weight at one end of the wire which is passed over low friction return pulley to bring it to the vertical position.
The span depends on the weight and quality of the wire. Spans of up to 200 m are possible with a maximum deflection of 20 cm. For longer spans, the level of the floor slab must be adapted to the deflection. This can be reduced by means of intermediate supports devised in the form of floats such that the wire oscillates in the vertical plane along the whole length of the span (floats similar to those of the inverted plumb line).
Wire alignment also enables the measurement of relative displacements at joints between two blocks (shearing).

2. Appraisal

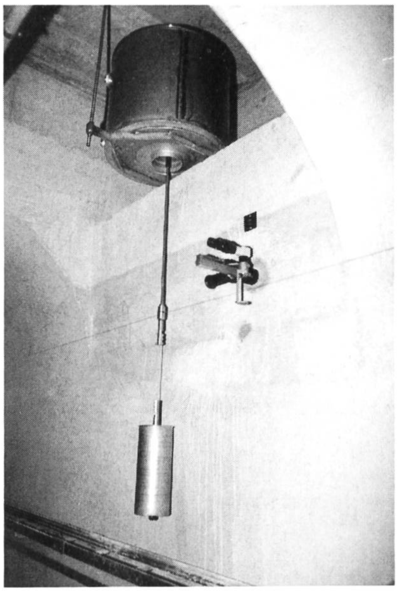
Measurement is simple and accurate, equal to that of a plumb line. Only applicable to rectilinear structures.
Replaces advantageously optical alignment; the accuracy is independent of the length of alignment and refractions; measurement is also possible in poor visibility.

3. Possible problems and measurement errors

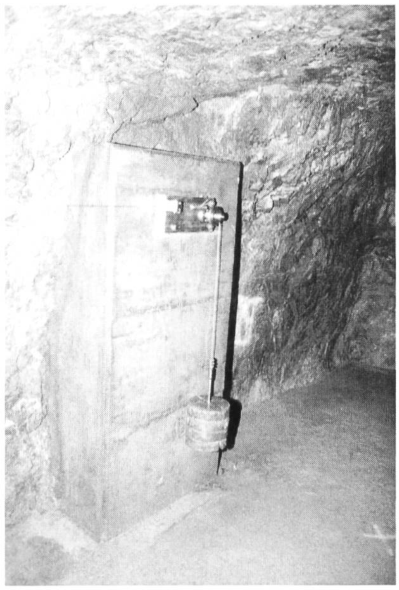
Bend in wire adjacent to fixed points or reading position.
Inaccurate centring of wire adjacent to fixed points. Bad installation of measuring instrument.
Current of air causing movement of the wire or false position. Alteration of the deflection of the wire due to the formation of condensation.



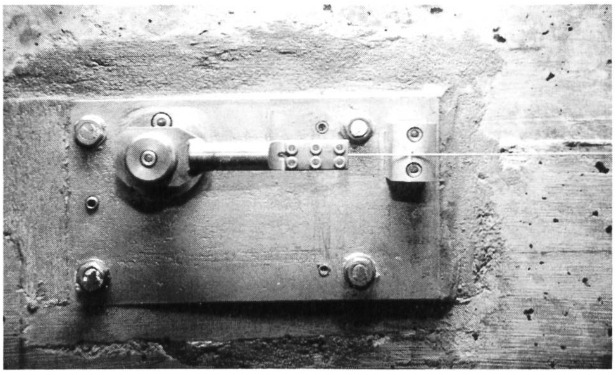
Reference number 2.110(1). Wire alignment. Measuring point in a gallery. The alignment is extended into the flanks of the valley by means of galleries to reach stable suspension points.



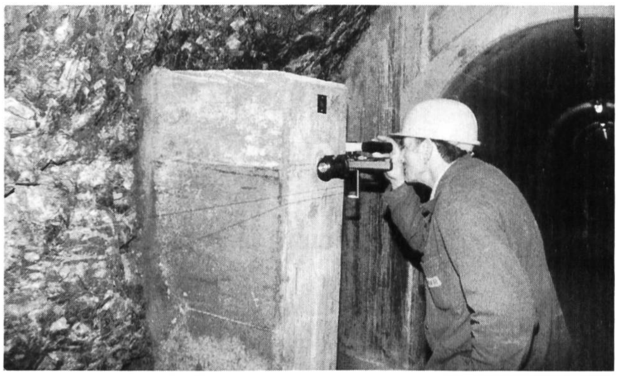
Reference number 2.110(2). Wire alignment. Intermediate support of the wire by means of a float to reduce the wire deflection.



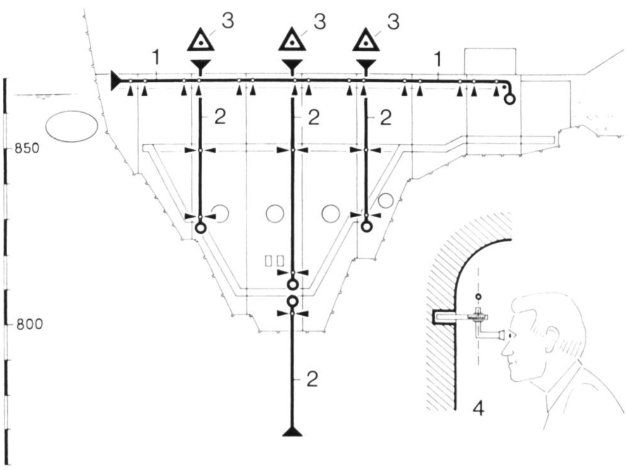
Reference number 2.110(3). Wire alignment. The weight spans the wire constantly at one end.



Reference number 2.110(4). Wire alignment. Fixed end of a wire.



Reference number 2.110(5). Optical measurement of the wire alignment, see reference number 2.110(6).



Reference number 2.110(6). Wire alignment combined with plumb lines and the triangulation network (Example of gravity dam of Mapragg). 1 Wire alignment along the crest of the dam, 2 Plumb lines, 3 Pillar of the triangulation network, 4 Detail of alignment measuring point.

4. Technical requirements

Long straight wall within a gallery or a parapet on the crest of the dam.

The installation for the measurement should be extended, if possible, into the flanks of the valley by means of galleries. If needs be, the profile of the floor of the gallery should be adapted to the deflection of the wire.

No mass-produced well-proven instrument is known. Long-term conclusive experiments have nevertheless been carried out in galleries or on the crest of the dams: Schräh (since 1973) and Rempen of Kraftwerke Wägital and Mapragg of Kraftwerke Sarganserland (Swiss Dams 1985, pages 62 and 214; ICOLD Congress 1985, Q56/R53, Vol. 1, pages 986 and 999).

Accurate guiding of the wire to the fixed points: co-axial wire clamps; mobile adjustable elements exactly in the same plane; additional support of the wire against the surface of a vertical cylinder, at both ends of the free span.

The wire must neither be bent nor otherwise deformed.

To maintain a constant tension, a device should compensate the variation in length of the wire due to temperature differences as well as variations in the distance between the fixed points, due to deformation of the structure (e.g.: low friction return pulley with freely hanging weight).

In the case of external use, it is advisable to protect the wire from currents of air (e.g.: groove in the parapet closed by a cover).

Careful centering and adjustment of the measuring instrument.

Make provision for measuring stations close to the fixed points to check the reading instrument. These stations will

guarantee, moreover, the reconstruction of the vertical plane of reference in the event of replacement of the wire or fixing.
Do not place the measuring stations too close to joints, angles, etc., in order to avoid the distortion of the measurements by local deformations not representative of those of the structure.

5. Checking of operation and maintenance

Before starting to take the measurements, tap the wire to remove condensation. Afterwards, let the wire stabilise.
Checks at the time of measurement: freedom of movement of the wire along the whole length of the span; freedom of movement of the tensioning device; check the measuring instrument at the stations set up for this purpose.
Periodical checks: the wire must neither be bent, nor deformed, nor nicked; freedom of movement of the return pulley.

6. Redundancy

Combination with plumb lines and triangulation or tying in of the latter.
Replacement reading instrument.

7. Remarks

The teletransmission of data from the wire alignment is carried out, in principle, in the same way as for the plumb lines.

Levelling

Reference number 2.111

1. Measuring method

Levelling is a simple procedure for measuring elevations. The difference in elevation between two adjacent points is determined by sighting horizontally through the levelling instrument onto vertical, graduated staves held at the two points. The difference in elevation is the difference between the readings on the two staves.
The instruments used for optical levelling are:
- Spirit-level instruments
- Compensator instruments

The accuracy of the measured elevation difference depends on the precision of the spirit-level or compensator of the levelling instrument, as well as of the staves. Level differences of a few hundredths of a millimeter can be determined between adjacent points. The staff consists of a wood or aluminium frame on which a precisely graduated invar scale is fixed.
Differences in elevation can also be measured by trigonometric levelling (measurement of vertical angles) or to a limited extent by hydrostatic levelling using a hydraulic settlement gauge (see reference number 3.102).

2. Appraisal

Levelling is a well-tried, simple and adaptable method for the determination of differences in elevation.
If great accuracy is required (better than ±1 mm between adjacent points) the systematic errors of the levelling instruments (in particular of compensator levels) as well as of the staves have to be eliminated.
The evaluation of level readings is simple and easily understandable.

3. Possible problems and measurement errors

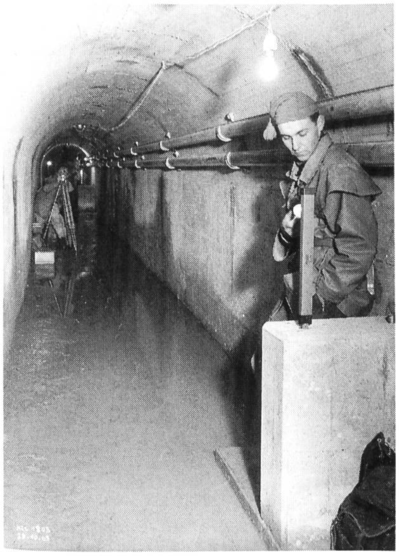
High-precision levelling is very sensitive to the systematic errors of instruments and staves.
Instruments:
- Inclination errors (see paragraph 5)
- Settlement (the instrument should always be set up on firm ground)
- Focussing errors (inclination of the sighting line due to movement of the focusing lens)
- Electric fields (magnetism) when compensator levels are used

Levelling staves:
- Graduation errors, errors of the zero point
- Inclination of the base of the staff
- The staff not held vertically
- The base of the staff must be clean as must be the bench mark or shoe on which it is placed
- Settlement of the staff into the ground

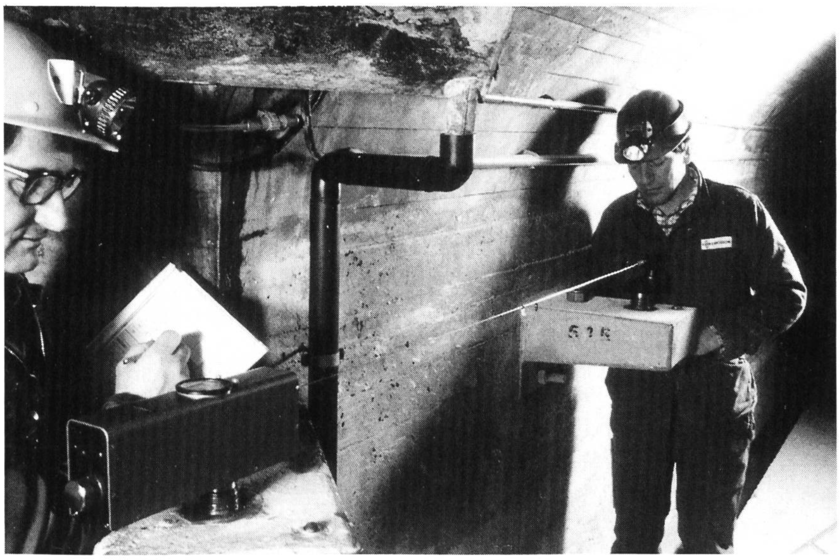
It is recommended that the level should always be set up at equal distance from the adjacent points (equal sighting distances).

4. Technical requirements

Uninterrupted sight lines between the level and the staff.
Establishment of permanent levelling points and possibly



Reference number 2.111. Levelling inside a concrete dam. In the rear the levelling instrument on a tripode; in front the target scale is illuminated by an electric torch.



Reference number 2.113. Distance measurement for a traverse using invar wires.

also permanent intermediate points. Suitable and permanent establishment of reference points and bench marks. High-precision instruments.

5. Checking of operation and maintenance

The levelling points have to be checked for integrity and damage.
The instruments and staves should be checked for:
- Inclination errors, possibly requiring adjustment
- Graduation errors of the staff (errors of the zero point can be allowed for in calculations)
- Inclination of the staff (adjustment if necessary of the attached circular bubble)
- Inclination of the base of the staff

6. Redundancy

Independent forward and backward levelling.
Incorporation in a triangulation network (trigonometric determination of elevations).

Optical alignment

Reference number 2.112

1. Measuring method

The field of vision from a theodolite to a known reference point forms a vertical reference plane on which the control points are located. Deformations are determined as variations of the distance (offset) of these points from this reference plane. The offset measurements can be made in several ways:
- A one-dimensional slide with movable target is set up at the control point, and the target is adjusted until it is aligned with the field of vision (cross-hairs) of the theodolite. The deformation at the control point (i.e. its distance from the reference plane) can be read directly on the scale of the compound slide.
- Fixed targets are anchored to the structure at the control points, but the sighting theodolite is mounted on a one-dimensional slide. After sighting on a reference point the theodolite is displaced sideways until its field of vision passes through the fixed target, and the deformation is read directly off the scale of the slide.
- The angle between sightings on a reference point and on a fixed target on the structure is measured, so that the corresponding displacement can be calculated on the assumption that the distance between theodolite and control point remains constant (see simple angle measurements in reference number 2.101).

The reference field of vision can be reestablished by sighting on a number of known reference points set up around the position of the theodolite. As a rule, the reference points for optical alignment are included in a triangulation network, in order to allow their stability to be periodically confirmed.

2. Appraisal

This is a simple and proven measurement procedure. Accuracy is dependent on the sighting distances and refraction conditions. Calculation of offset from measured horizontal angles is usually more appropriate than their direct measurement using a one-dimensional slide.

3. Possible problems and measurement errors

Refraction, above all for sightings close to the surfaces of structures, water, snow or the ground.
Restricted sight-lines due to snow, vegetation, fog or rain, etc.
Damage or destruction of the measurement points by avalanches, snow slides or rock falls, etc.
Instrument errors.
Centring errors.

4. Technical requirements

Perfect surveying procedures for the elimination of observation, instrument and centring errors.
The survey network (reference points) should be selected taking into account refraction effects and other restrictions.
As stable areas as possible should be selected for instrument and reference points.
These requirements can only be partly met when using one-dimensional slides, above all because of the need to set up very accurately the vertical reference plane. Angle measurements offer much greater latitude for adaption to local conditions, but require qualified personnel.

5. Checking of operation and maintenance

The measuring station, reference target points and control points must be periodically checked for damage.
Vegetation should be cleared along sight lines.
Periodic control of the functioning and centring of the instruments, and if necessary adjustment or repair.

6. Redundancy

By measurements of the superior triangulation network or correlation with an inverted plumb line anchored deep in the foundation rock.

Traverse

Reference number 2.113

1. Measuring method

A traverse is a series of contiguous vectors. It can also be considered as a simplified triangulation network (see 2.130). The same survey equipment and instruments are used for the measurement of these vectors:
- Precision theodolite (mean observation error $\pm 2^{cc}$)
- Precision distance meter (mean observation error depending on requirements, from ±2 mm for embankment dams to ±0.02 mm for concrete dams).

Because of the propagation of errors, traverse surveys are generally used in combination with plumb lines and/or triangulation networks.
Given the short vectors and the high relative accuracy required the centring of the instruments is of great importance. Depending on conditions (e.g. the extent of the deformations to be measured, or the required accuracy) centring should be possible with a precision of between ±1 mm and ±0.01 mm.
The survey instruments have to fulfil these requirements both for ground surface control points (measurements from tripods) and pillars or brackets with centring plates in control galleries.

2. Appraisal

This is a well-tried method for the determination of coordinates. The complexity of the survey equipment depends on the degree of accuracy required. Differences in elevation can be generally determined by levelling (see 2.111), but possibly also by the measurement of vertical angles.

3. Possible problems and measurement errors

Traverse surveys are sensitive to systematic errors. The instruments and their setting up must be regularly checked.
Traverse surveys in control galleries are not affected by atmospheric conditions, but strong air currents in galleries can result in erroneous readings.

Reference number 2.120-1(1). Rod extensometer for concrete dams. Measuring head with mechanical and electrical reading.

Reference number 2.120-1(2). Rod extensometer for concrete dams. Measuring head for measurements by hand (using a digital dial gauge) and with digital data registration and identification of the measuring points.

4. Technical requirements

Clear sight lines between adjacent traverse points.
Comprehensive instruments.
Depending on the accuracy required, the traverse points should be established as ground bolts or as brackets.
Traverse surveys should wherever possible be extended into the rock of the valley flanks.
When distances are to be measured using Invar wires or bands, equal distances between points should be selected and allowance made for sag in the band. (Measurement of the traverse vectors should be repeated using several wires or bands.)
Air currents in control galleries must be avoided.

5. Checking of operation and maintenance

All fixed points should be checked for damage.
The instruments should be checked.

6. Redundancy

Independent forward and return reading of traverse angles and traverse distances.
Correlation with plumb lines and/or triangulation networks.

Variation in length and deflections

Rod or wire extensometer (for concrete dams)

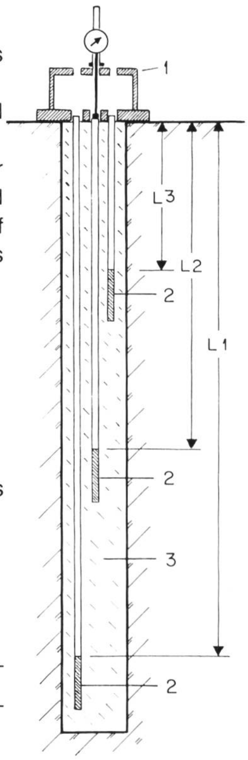
Reference number 2.120–1

1. Measuring device

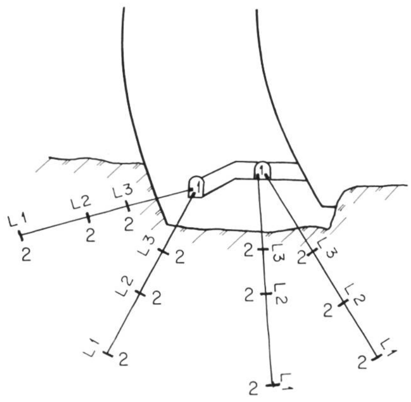
The numerous extensometers, with one or several rods or wires, available commercially are all capable of measuring the variations in length in a borehole, between a fixed point (of a rod or wire) and the measuring head fixed at the entry of the borehole. As a rule, the extensometers differ from each other in 3 domains:
- Type of fixing
- Construction of longitudinal elements: rods or wires
- Manner in which the variation in length is obtained: mechanically or electrically (by the principle of variation of electrical resistance or that of the vibrating wire).

2. Appraisal

The instruments do not have a very high level of accuracy (approximately ±0.5 mm). However, provided that the presumed movements are at least some millimeters, the instruments provide reliable information on the deformations occurring in a rock foundation. If, on the other hand, the deformations are too small, these instruments cannot provide satisfactory results.



Reference number 2.120-1(3), left. Rod extensometer for concrete dams. Typical layout of the measuring system. 1 Measuring head with dial depth gauge, 2 Anchorages of different rods, 3 Cement grout, (L1, L2, L3) Measurement lengths.



Reference number 2.120-1(4), above. Possible arrangement of extensometers in the foundation of an arch dam showing four borings equiped with three extensometers anchored at different depths.

By means of a careful arrangement of the fixed points of a multiple rod (wire) extensometer, one can also localise the approximate position of cracks or joints in the rock, which open or close, as well as being able to determine their approximate movements.

3. Possible problems and measurement errors

The anchorage does not hold; most often this problem can be resolved, given that this fact is normally already recognised when the checks are carried out at the time of installation of the instrument or at the time of taking the initial measurements.
The rods or wires can become blocked at the time of grouting the boreholes. In this case, the equipment must be replaced by supplier under guarantee.
The measurements are affected to a smaller or greater extent by friction.
In the case where the quality of the steel is insufficient rust will appear which, in the long term, will lead to the ruin of the instrument.
In the case of wire extensometers there is a risk of sudden

changes in the quality of the steel caused by ageing and leading to inaccurate measurements.
The range of the instrument is exceeded.

4. Technical requirements

As a general rule, use only well-proven instruments.
It is imperative that the installation is carried out by a specialist, who must also take the first measurements.
The correct functioning of the instrument as well as the significance of the influence of friction between the rod/wire and the protecting hull must be able to be verified after installation, thereafter at intervals of several years, by means of judiciously planned tensile tests.
When choosing the equipment it is necessary to specify that the supplier provides a suitable instrument for carrying out these tests. Such an instrument should also be specified for checking extensometers intalled a long time ago.
Where possible, the measurement heads should also be made accessible in the case of measurements being taken at long distance.
The band of measurements should, if necessary, be able to be readjusted, without the whole series of measurements being interrupted by a jump of unknown value.

5. Checking of operation and maintenance

The operation of the extensometers must be checked, at intervals of several years, by a suitable tensile test (see technical requirements).
In the case of remote monitoring, the results obtained must be verified periodically by means of a mechanical measurement (carried out manually).

6. Redundancy

A fair amount of redundancy can be obtained by the installation of multiple rod/wire extensometers, comparison of the variations in length of the different segments to show if the results obtained are plausible or not.
Combination with inverted plumb lines or geodetic measurements.
Redundancy can also be obtained by a spatial arrangement of several extensometers in the zone of the foundation.
The installation of several extensometers under a dam increases the reliability of the measurements, the results obtained can be compared with each other, and also with the deformations of the dam.

7. Remarks

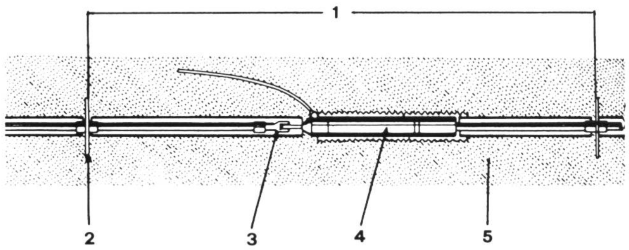
An instrument for testing the correct operation of the extensometers has already been used for many years by Vorderrheinkraftwerke.

Rod extensometer (for embankment dams)

Reference number 2.120–2

1. Measuring device

This is an instrument consisting of a measuring element and an extension bar (3 to 6 m long) between two anchor plates, which is buried in the fill of the dam. In the measuring element, the deformation (of up to 30 cm) is transmitted through a hinged linkage from a long measurement cone to a membrane. This acts on a taut, thin wire, so that the measured deformation can be transmitted as an electrical current proportional to the resulting change in the resistance or vibration frequency of the wire. Usually, a number of extensometers are placed, either slightly overlapping or one after another, to form a horizontal, vertical or occasionally inclined chain.



Reference number 2.120-2. Rod extensometer for embankment dams. 1 Measurement lenght, 2 Anchor plate, 3 Flexible joint, 4 Measuring element (extensometer unit), 5 Fill material [Hanna 1985].

2. Appraisal

This is a well-tried system for the monitoring of deformations in critical zones of fill dams. It serves in particular for the determination of differential deformations of fill on difficult foundation or contact conditions.

3. Possible problems and measurement errors

Total failure of the extensometer if the measurement range is exceeded. (As it is extremely difficult to forecast the deformation of fill in critical areas this is a very common cause of failure; where in doubt select short extensometer(s) with large measurement scale range.)
Breakage of cables due to excess tension.
Breakage of cables due to careless construction work; effective protection is essential: e.g. the laying of cables in trenches excavated in the placed fill.
The influence of extraneous electrical flow (lightning or natural ground currents).
Failure of the reading equipment.

4. Technical requirements

In view of the relatively large deformation of the fill body the measurement range must be sufficiently large: at least 5% of the measurement length (e.g. 30 cm for 6 m).
The expected deformation (extension or shortening) must be taken into account when fixing the zero point so that the full measurement range can be used.
The connection of the measurement cable to the measuring element must be hermetically sealed and water tight. The cable must be protected against overvoltage (lightning) and must not be spliced between the instrument and the measurement chamber. The cables must be of high tensile strength and should be laid in zig-zag fashion in the cable trenches (to allow for later settlement of the trench).
In very high dams it is advantageous to lead the measurement cables vertically to the dam crest so that the delicate crossing of boundaries between zones of different materials is avoided.

5. Checking of operation and maintenance

Maintenance of the electrical reading equipment, in particular electrical contacts.

6. Redundancy

When the extensometer is placed horizontally:
– Geodetic measurement of the dam crest
– Distance measurements using invar tapes
For (exceptional) vertical placing of the extensometer:
– Settlement gauges (see also 3.101 and 3.102)
The redundancy indicated above is, however, not wholly sufficient. True redundancy can only be achieved by the placing of several extensometer sets adjacent to each other.

7. Remarks

Particular care is called for when crossing zones of impermeable material.

The placing of measurement cables in shafts or galleries can cause serious difficulties and the subsequent failure of the measurement equipment.
The zero point should only be defined after completing installation of all equipment components.

Sliding micrometer

Reference number 2.121–1

1. Measuring device

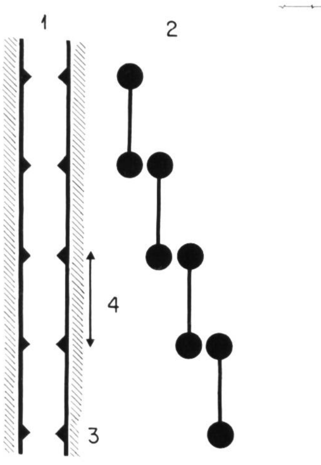
A mobile measuring instrument which enables the differential variations of length along the borehole to be determined, in successive segments, for example.
The borehole is fitted out with a grooved plastic tube with reference points which is fixed to the surrounding material (rock, concrete, earth) by grout.
It can be employed in boreholes of up to 150 m in length.

2. Appraisal

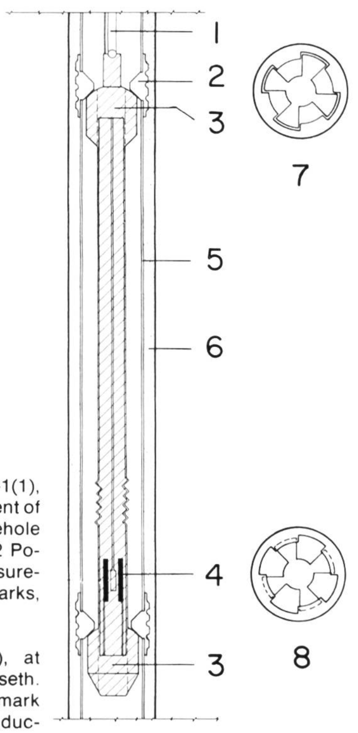
This instrument enables highly accurate measurement (greater than 1/100 mm/m) of the variations in length in rock and concrete. Principally, the measurements enable the localisation of possible cracks and joints in the dam or the foundation as well as the measurement of their movement (for example as a function of the level of the reservoir). Under certain conditions, it is possible to determine deformations perpendicular to the borehole by means of two parallel measurement lines (two boreholes).
The measurements can easily be carried out by one person.
The recording and study of the data is best done by means of a computer.

3. Possible problems and measurement errors

Dirt on the measuring probe and in the tubing can affect the accuracy of the measurements.
(The probe and cable must be kept clean. No dirt must enter the tubing; in the event of major clogging up, cleaning is necessary.)



Reference number 2.121-1(1), above. Principles of measurement of the sliding micrometer. 1 Borehole casing with reference points, 2 Positions of instrument for measurements, 3 Measuring marks, 4 Measurement segment.



Reference number 2.121-1(2), at right. Sliding micrometer Iseth. 1 Guide rods, 2 Measuring mark (cone), 3 Spherical head, 4 Induction measurement sensor, 5 Casing, 6 Grout, 7 Sliding position of the instrument in the borehole, 8 Measuring position (heads rotated by 45°).

Insufficient fixing of the reference points.
(The grouting between the tubing and the wall of the borehole must be carried out very carefully.)
Too ridig or too supple grouting of the tubing in the borehole ("pile effect").
Jamming of the probe as a result of significant movement perpendicular to the axis of the borehole.

4. Technical requirements

All elements of the equipment must be robust and wear resistant.
Probe and cable must be waterproof (for a water pressure of at least 1.5 MPa).
The cable must be armed, in order to withstand the tensile forces.
The probe and cable must be resistant to corrosion.
The installation and grouting of the measuring tube must be carried out by a qualified person.
The reading and analysis of the data by the personnel of the owner is possible after suitable training.

5. Checking of operation and maintenance

High levels of accuracy require a measurement of calibration before and after each series of measurements.
(The calibrating device must form part of the measuring instrument.)
It is recommended, but not essential, to carry out a periodic service of the equipment.

6. Redundancy

Redundancy is not always necessary, but can be achieved by the installation of two or more lines of measurement (boreholes) in the zone observed.

Sliding micrometer with inclinometer

Reference number 2.121–2

1. Measuring device

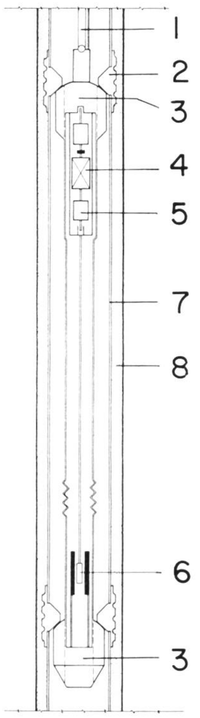
A mobile measuring instrument which enables the determination of displacements in 3 orthogonal directions along a vertical borehole by continuous segments of 1 m.
The borehole is fitted out with a grooved plastic tube with reference points which is fixed to the surrounding material (rock, concrete, earth) by grout.
It can be employed in boreholes of up to 150 m in length.

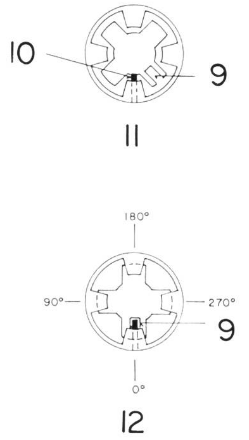
2. Appraisal

This instrument provides the possibility to determine with great accuracy the horizontal and vertical displacements along a vertical borehole. Principally, the measurements enable the localisation of possible cracks and joints in the dam or in the foundation as well as the measurement of their movement (for example as a function of the level of the reservoir) and the horizontal deformations. In addition, it is possible to determine the position of sliding planes.
The measurements can easily be carried out by one person.
The recording and study of the data is best done by means of a computer.
The sensitivity and accuracy of measurements in the horizontal direction (inclinometer) is smaller than in the vertical direction (micrometer).

3. Possible problems and measurement errors

Dirt on the measuring probe and in the tubing can influence the accuracy of the measurements.
(The probe and cable must be kept clean. No dirt must enter the tubing; in the event of major clogging up, cleaning is necessary.)
Insufficient fixing of the reference points.





Reference number 2.121-2. Trivec Iseth-sliding micrometer with inclinometer. 1 Guide rods, 2 Measuring mark (cone), 3 Spherical head, 4 Inclinometer, 5 Positioning motor, 6 Induction measurement sensor, 7 Casing, 8 Grout, 9 Groove, 10 Bolt, 11 Sliding position of the instrument in the borehole, 12 Measuring position (heads rotated by 45°).

(The grouting between the tubing and the wall of the borehole must be carried out very carefully.)
Too rigid or too supple grouting of the tubing ("pile effect").
Jamming of the probe as a result of significant movement perpendicular to the axis of the borehole.
The modification of the orientation of the plane of measurements of the inclinometer due to twisting of the tube at the time of installation renders the measurements incorrect.

4. Technical requirements

All elements of the equipment must be robust and wear resistant.
Probe and cable must be waterproof (for a water pressure of at least 1.5 MPa).
The cable must be armed, in order to withstand the tensile forces.
The probe and cable must be resistant to corrosion.
The installation and grouting of the tubing must be carried out by a qualified person.
Verify the plane of measurement of the inclinometer with respect to twisting.
The reading and analysis of the data by the personnel of the owner is possible after suitable training.

5. Checking of operation and maintenance

High levels of accuracy require a measurement of calibration before and after each series of measurements.
(The calibrating device must form part of the measuring instrument.)
It is recommended, but not essential, to carry out a periodic service of the equipment.
(The calibration measurement will indicate immediately the state of the measuring instrument and its reliability.)

6. Redundancy

Redundancy is not always necessary, but can be achieved by the installation of two or more lines of measurement (boreholes) in the zone observed.

Pipe inclinometer

Reference number 2.121–3

1. Measuring device

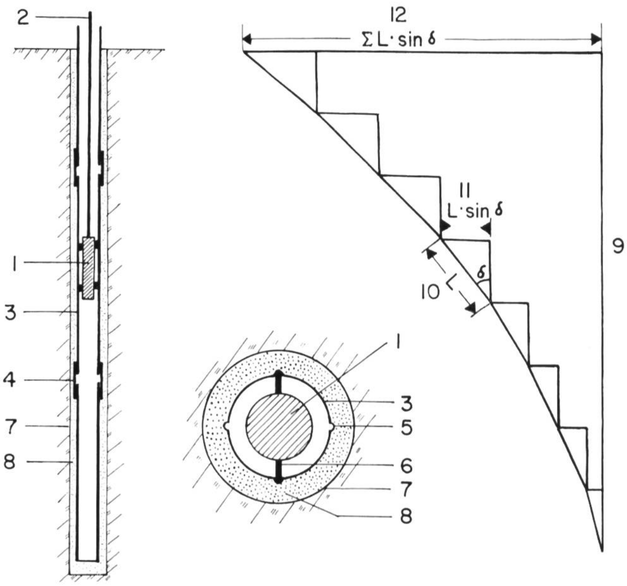
Portable instrument for determining principally the horizontal deformations along a line in a fill dam or a foundation.
The installation consists of a vertical grooved PVC or aluminium tube which is installed during the placing of the fill, and which extends to the crest of the dam. The individual sections of tube must not be more than 6 m long. The tube can also be placed in a borehole.
During and after construction, a sensor (equipped with a plumb bob connected to a potentiometer) is introduced into the tube and inclination readings are taken. The sensor measures the inclination in perpendicular vertical planes. From the inclination difference between consecutive measurements, the horizontal deformation can be determined.
The position of the head of the tube should be surveyed into a triangulation network.

2. Appraisal

This is a precise and flexible instrument for the monitoring of deformations of embankments or foundations. If such instruments are systematically placed in different sections of an embankment, a complete network of deformation lines can be established. The combination in the same tube of an inclinometer and a settlement gauge makes possible the integral monitoring of the spatial deformations.
The placing of inclined tubes during the placing of embankment fill is not recommended but such tubes can be installed subsequently in a borehole.
This instrument is neither as precise nor as sensitive as the sliding micrometer with inclinometer used for concrete structures and rock. Furthermore, its precision depends on the quality of the guidance grooves.

3. Possible problems and measurement errors

Damage or loss of the tube during the course of construction. Effective protection measures are indispensable.



Reference number 2.121-3. Measurement principle of the pipe-inclinometer [*Hanna* 1985]. 1 Sensor, 2 Cable, 3 Guide tube, 4 Sleeve, 5 Guide groove, 6 Guide wheels on the sensor. For installation in a borehole: 7 Borehole, 8 Grout. Measurements: 9 Reference measurement, 10 Partial measurement section, i.e. distance between successive readings, 11 Horizontal displacement of the partial measurement section, 12 Total horizontal displacement.

Jamming of the sensor if the grooves are dirty or if displacement occurs at the connection of two adjacent sections of pipe.
The measurement range can be exceeded in the case of pronounced horizontal deformations, principally of high embankments of plastic fill material.
Measurement can be influenced by a magnetic or gravitational field occurring at the dam site or within the body of the dam.
Rotation of the tube about its axis during placing.

4. Technical requirements

The equipment must be of robust construction and resistant to wear. All elements must be watertight.
Careful construction of the guide mechanism with well-sprung rollers.
The sensor must be of sufficient length: at least 50 cm between the upper and lower guide rollers. The longer the measurement length, the greater the precision of the measurements but also the greater the risk of blockage of the sensor in the tube.
The cable of the sensor should be reinforced to prevent tearing or breakage. A guidance system should be used at the top of the tube.
The joints between sections of tube should be provided with sleeves and covered with adhesive tape.
The orientation of the measuring plane must be carefully defined.
Measurements must be taken when lowering and raising the sensor in both positions and for each measuring plane.
A complete set of spare equipment should be available at all times and should include a cable and the reading apparatus.

5. Checking of operation and maintenance

The equipment must be calibrated before and after every use.
The sensor and reading equipment should be periodically checked by the manufacturer.

6. Redundancy

Redundancy is not necessary, but can be provided by the setting up of several measurement lines.

Spatial displacements of individual points

Triangulation and trilateration

Reference number 2.130

1. Measuring method

The principal of triangulation is the determination of the position of a point by geodetic techniques; in general defined by spatial coordinates (in three dimensions; horizontal position and elevation) by:
- The intersection of two bearings (angle measurements)
- The intersection of two distances (distance measurements)
- In general, a combination of these two methods of measurement.

The determination of the "absolute" displacement of the control points on a dam and in its immediate vicinity, with respect to reference points situated outside the zone of influence of the dam, is possible by the measurement of bearings (horizontal angles), vertical angles and distances.
The instruments employed for this work are:
- The precision theodolite, mean observation error of a direction: ± 2 cc
- The precision distance meter, mean observation error: ± (0.2 mm + 1.0 mm per km measured)

The centring error of the instruments is less than or equal to ± 0.1 mm.
Traverses, simple measurements of angle and optical alignment (see reference numbers 2.101, 2.112, 2.113) are simplified applications of triangulation. Very often, a levelling survey is combined with triangulation (see reference number 2.111).

2. Appraisal

Triangulation has for a long time been the proven method for the determination of "absolute" displacements. It is time-consuming and expensive, requiring special personnel, instruments and experience, but is very reliable due to the very many redundant observations which have to be made. In general the evaluation of the survey readings is carried out using a computer. Triangulation can be combined with advantage with plumb line measurements and with traverses and levelling surveys.

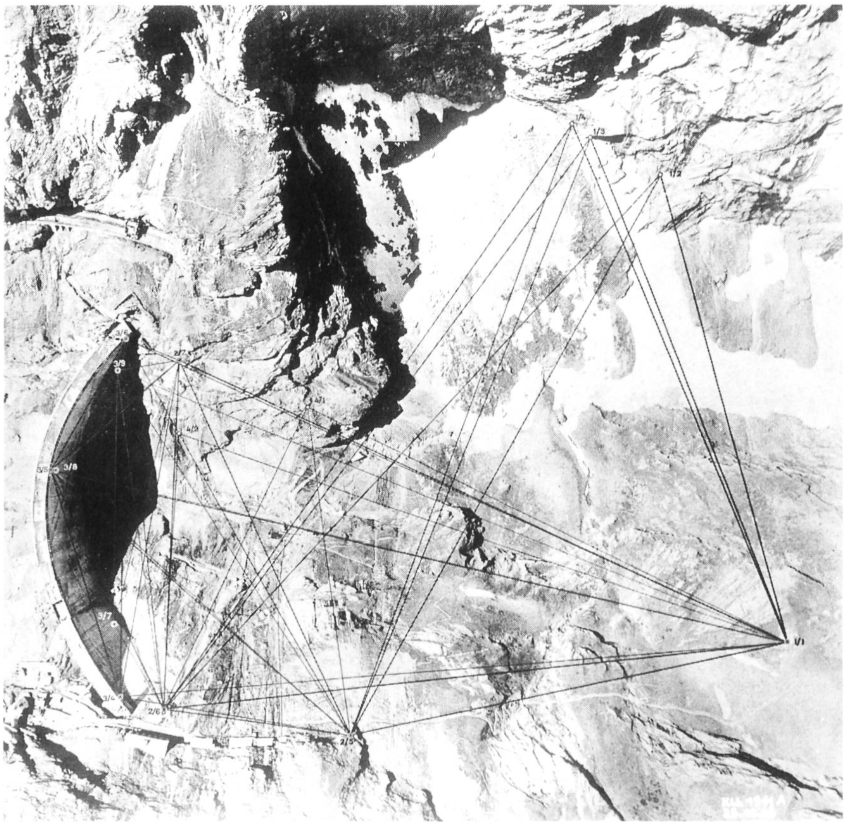
3. Possible problems and measurement errors

Triangulation measurements are dependent on weather conditions.
Atmospheric effects (refraction, shimmer, etc.) can result in measurement errors.

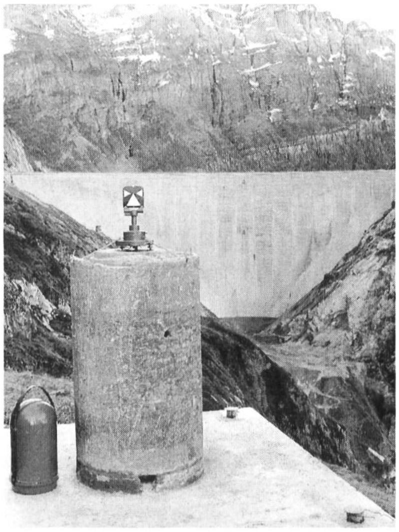
4. Technical requirements

Comprehensive instrumentation.
The network must be set up with the close collaboration of the civil engineer, an experienced surveyor and the geologist.
Clear sight-lines between triangulation points are essential (pay attention to vegetation and snow) and refraction effects must be taken into account (when sighting close to the ground or near to structures).
Access must be assured to reference points and sometimes also to the control points (this may not always be the case in winter at high altitude).
All reference points must be established in stable terrain (check geological conditions).
In general pillars are set up at the instrument stations (financial consideration: single payment/recurrent costs).
Thermal and mechanical influences on the pillars must be allowed for.
Redundant measurements are analysed by means of a mathematical and stochastic model by computer.
Concept and analysis of a triangulation network call for sound theoretical knowledge and extensive practical experience on the part of the responsible surveyor.

Reference number 2.130(3). Reference point with theodolite. The concrete pillar is protected to avoid thermal influences.



Reference number 2.130(1), left. Triangulation network to determine displacements of the control points on the dam. The network is traced in a vertical aerial photograph.



Reference number 2.130(2), above. Reference point on a concrete pillar with optical target.

5. Checking of operation and maintenance

All triangulation points must be checked for possible damage.
Sights must be checked (need for celarance of vegetation, obstruction by structures, etc.).
The instruments and their centring plates must be checked during periodic examinations, and by means of the critical analysis of the observed readings.

6. Redundancy

Redundant reference points.
Redundant observations.
Correlation with the readings of the monitoring equipment of the dam.

Movements at the accessible cracks and joints

Micrometer, deformeter, dilatometer and deflectometer

Reference number 2.140

1. Measuring device

All the instruments mentioned are based on the same principle and enable the accurate measurement of the length between two reference points fixed to the concrete surface, e.g. across to a crack or joint. According to the make or model of the instrument, the base length ranges from a few centimetres to around 120 cm.
In principle the following three measurements are possible:
Type 1: Movements across a joint or crack.
Type 2: Movements across and parallel to a joint (crack). The procedure consists of measuring 3 sides of an equilateral triangle having one side parallel to the joint (see figure).
Type 3: Movements in 3 orthogonal directions. By means of a special instrument one can measure the movements parallel to a concrete wall (perpendicular and parallel to a joint) and normal to this face.

2. Appraisal

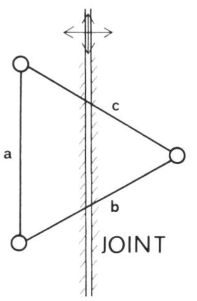
An accurate measurement which, in certain cases, is very significant and interesting. The results depend heavily on the way the instrument is handled. The significance of the measurement is often limited, given that the results are influenced by the local disturbances of forces in the vicinity of a gallery and that the results are not absolutely representative of the global behaviour of a part of the structure. The mensuration of long series of measurements, for example in galleries in rock or in a dam, requires a considerable amount of work, compared to the value of the results obtained.

3. Possible problems and measurement errors

A reference point can be displaced as a result of a knock.
The fixing of the reference point does not hold due to an inferior quality of the concrete (e.g. honeycombing) or due to the reference point being too close to the joint/crack (edge of concrete breaks off).
False reading due to careless handling of instrument.
Inaccurate positioning of the instrument on the reference points leads to a jump in the measurements.
Irregular use of the regulating instrument leads to irregular results.
The range of measurement is exceeded.

4. Technical requirements

It is imperative that the reference points, with respect to the fixings of the special measuring devices, are placed sufficiently far away from a joint (crack) and are securely anchored.
For their own protection, the reference points should be recessed in the concrete and always be protected by a cover.



Reference number 2.140(1), left. Measurement of the movements of a joint or crack. The procedure (type 2) consists of measuring 3 sides of an equilateral triangle having one side parallel to the joint.

Reference number 2.140(2), beyond. Vertical joint between two concrete blocks controlled by a dilatometer (type 3). The movements are measured in three orthogonal directions.

The reference points must be cleaned and greased periodically.
Each measuring instrument must be complemented by a control instrument (e.g. an invar control base-plate with two reference points).
In the event of some doubt relating to the order of magnitude of the presumed movements, it is necessary to use, if possible, special reference points which enable the normal range of measurements to be extended by a few millimeters, if necessary.

5. Checking of operation and maintenance

Verify the correct operation of the measuring instrument by means of the control instrument before each measurement.
Have the measuring instrument serviced by the manufacturer from time to time. However, such a service often leads to a jump in the results.

6. Redundancy

Generally, not necessary.

7. Remarks

As a general rule give preference to less accurate instruments with a larger range of measurement than to very accurate instruments with a small range. In general, an accuracy in the order of ¹⁄₁₀ mm is sufficient.
In certain cases, such a measurement can also be replaced by check-marks carefully placed.
Movements of cracks and joints can also, when necessary, be monitored by means of electric dilatometers (see reference number 2.160).

Local rotations in the vertical plane

Clinometer

Reference number 2.150

1. Measuring device

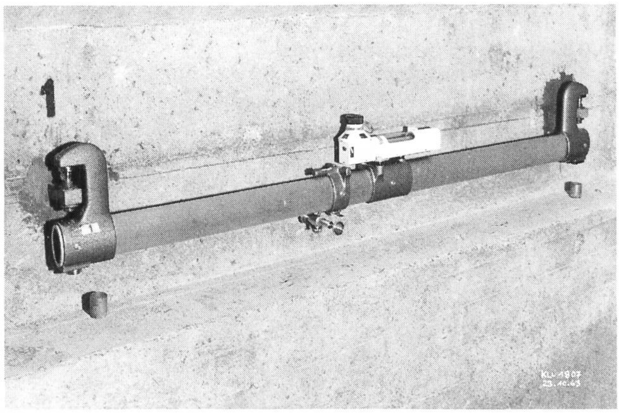
The clinometers are either based on the principle of water level, or on that of the plumb line and enable variations in inclination to be measured in certain points. There are portable and permanently installed instruments.
The portable instruments are placed horizontally on reference points. In order to improve the accuracy, the measurement is carried out in both positions of the instrument.
Among the permanently installed instruments it is appropriate to mention the tiltmeter whose measuring element consists of an electrolytic plumb line.
The base length of these instruments varies between approximately 10 and 120 cm.

2. Appraisal

When measurements are carefully taken, these instruments provide accurate and reliable results, one must not, however, forget that variations in inclinations in the vicinity of galleries and measuring recesses are influenced by local forces. Where local conditions permit, the reliability of the results can be improved by installing a series of measurement points comprising 4 to 6 reference points. The clinometer should not, as a general rule, be used as the only instrument for dam monitoring.

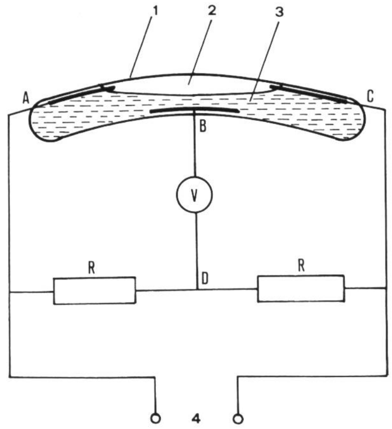
3. Possible problems and measurement errors

The measuring instrument is very sensitive to sources of heat (body heat, light sources, etc.).
The instrument can give incorrect readings as a result of being knocked.
A reference point can be displaced following a knock.
Dirty reference points can lead to deviations in the measurements.
In the case of electrical instruments, erroneous results can appear under the effect of electric currents. Loss of instruments as a result of overvoltage (lightning) are not uncommon.



Reference number 2.150(1). Clinometer placed on the two reference points.

Reference number 2.150(2), right. Tiltmeter with electrolytic level transducer. 1 Spirit level vial, 2 Bubble, 3 Electrolyte, 4 DC supply; (A), (B), (C) Electrodes, (R) Resistors, (V) Voltmeter. The bubble within the vial changes position with tilt and causes a change in the ratio of electrical resistance across AB and BC which can be detected by a Wheatstone bridge unit [*Hanna* 1985].



4. Technical requirements

The reference points must be cleaned and greased regularly, and constantly be protected by a cover.
With portable instruments one must always take measurements in both positions of the instruments.
In the case of electric instruments, particular attention must be paid to protection against overvoltage.

5. Checking of operation and maintenance
Portable instruments

As an overall check, verify that the sum of the readings taken in both positions of the instrument remains constant over long periods.
If it is possible, make allowance for a control measuring station, which is not subject to rotation or only minimal rotation. However, this condition can often only be satisfied to an insufficient degree.
Have the instrument checked and serviced by the maker from time to time. It should be noted that the sum of the readings taken in the two positions of the instrument often changes after such a service, and this leads to a jump in the results of the measurements.

Fixed instruments

As an overall check verify periodically the inclination of the base plate of the instrument by means of a portable clinometer.

6. Redundancy

As a general rule redundancy is essential, it is normally obtained by comparing the results of measurement with the tangents to the deformations along the vertical sections of the dam (plumb lines).
In particular cases redundancy can also be obtained by levelling two points carefully chosen.

7. Remarks

With respect to the tiltmeter, see article by *P. J. Deinum:* The Use of Tiltmeters for Measuring Arch Dam Displacements, "Int. Water Power and Dam Construction" June 1987, p. 38–40.
Given that this instrument did not exist until a few years ago, its long-term behaviour is not yet known at this time.

Local specific deformations

Electric deformeters embedded in the concrete

Reference number 2.160

1. Measuring device

These instruments, generally embedded in the concrete at the time of construction, make possible the local measurement of the specific extension in a given direction, at the same time as the variations in temperature undergone by the concrete. Each measurement sensor, of 20 to 30 cm length, is linked by an electric cable to the junction box to which the instrument is connected. The sensors are either based on the principle of resistance or on the principle of the natural frequency of a vibrating cord, both varying as a function of the specific extension undergone by the concrete.

2. Appraisal

The calculations of specific deformations and corresponding stresses in the concrete are lengthy, complicated and delicate; they require a thermal compensation for the measured values as well as the knowledge of the evolution of the modulus of elasticity and creep of the concrete during this period. The principal drawback of these measurements lies in the fact that the compensations applied to the raw results are often appreciably greater than the order of magnitude of the final result, to the extent that the results obtained are rather uncertain. In addition, the sources of errors are numerous and difficult to detect.
With the objective of being able to compensate for the specific deformations, independent of mechanical actions, such as shrinkage and swelling of the concrete and to observe the possible stray currents of ohmic resistance, sensors are placed, embedded in the mass, but at the same time, isolated from mechanical stresses. These elements, known as "no stress meters" make it possible to observe the regularity of the results in the long term.
The reliability, above all in the long term, is not satisfactory, to such a degree that the measurements do not, under any circumstances, permit an efficient surveillance of the dam; they can, however, provide some interesting supplementary information in the first few years of operation of the structure. The detecting of sources of error requires the knowledge of a specialist in electrical measurements. These instruments are thus better suited to laboratory tests than to surveillance of dams.

3. Possible problems and measurement errors

These instruments are sensitive to both lightning, overvoltage and other vagabond currents.
Insufficient conductivity at the connections due to corrosion is frequent.
At the time of placement the risk of damage and confounding of cables is high.
The range of measurement being small and the conditions of installation being very difficult, the limits of the domain of measurement are sometimes unexpectedly exceeded and often without one being aware of it.
The "zero" point of the electrical instruments drifts with time and inexplicable jumps in measurement are frequent.
Incorrect connection of the wires to the measuring bridge is all too easy.

4. Technical requirements

The installation of the instruments must be carried out extremely carefully, the correct orientation and embedding being essential. The aggregate grading of the surrounding concrete must be adjusted to suit.
The cables (conducting wires and their isolation) as well as the cabling must be of the highest quality. Spliced joints between the sensors and the connection box must be avoided at all costs. The cables must also resist the shocks and tensile forces inevitably occurring during construction.
The routing of the cables must be studied in order to limit the infiltration of water along the cables and to facilitate their placement.
The connection boxes must be protected from dust, humidity, oxidation, and overvoltage. Their regular maintenance is essential.
Sensors must be placed in excess numbers in order to insure redundancy and continuity of measurements in the event of failure of a sensor.

5. Checking of operation and maintenance

The measuring instrument (Wheatstone bridge) as well as its linking wire or wires to the connection box must be subject to a yearly or twice yearly check by a specialist for the whole range of measurement.
The verification of the agreement of measurements between sensors placed in parallel and the consistency of the measurements on the "no stress meters" must be made after every measurement.

6. Redundancy

This is essentially obtained by the comparison of the results of measurement amongst themselves and because of the instruments placed in excess numbers.

The installation at an accessible spot of an electrical sensor in parallel and of reference point for a mechanical deformeter is desirable (generally only possible in exceptional circumstances).

7. Remarks

Constructed on the same basic principles, there exist commercial dilatometers for embedding in the concrete across contraction joints, for example. They measure the variations of the joint in millimeters as well as the temperature of the concrete. The calculations are more simple but the sources of error are similar, and they are equally as unreliable as with the electric deformeters.

Quantity of seepage and drained water

Volumetric measurements

Reference number 2.200

1. Measuring devices

The water flowing in the drainage channel of a tunnel or gallery or from a borehole, joint or fissure is collected in a calibrated container and the time necessary to fill this container is measured.

2. Appraisal

A simple, reliable method of measurement, which is well-proven.

3. Possible problems and measurement errors

Stop watch defective or unavailable.

The container is too small to allow correct measurement of the filling time.

Inadequate or incomplete collection of the water.

Unsuitable arrangement for conducting the water into the measurement container.

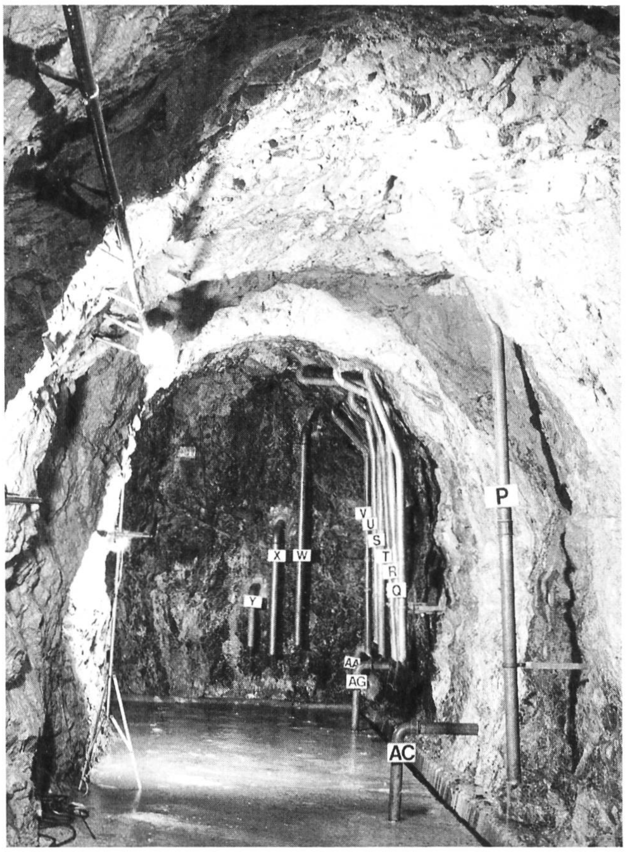
4. Technical requirements

The measuring point must be adapted to the local conditions, to ensure that the water can flow into the container without loss.

The capacity of the container must be selected taking account of the flow discharge, to ensure that the time of filling is at least 10 but if possible more than 20 seconds.

When large discharges have to be measured a fixed

Reference number 2.200(2). Seepage measurement at the downstream toe of an embankment dam. The seepage water is measured by calibrated container at the outlets which drain a different sector of the dam each.



Reference number 2.200(1). Drainage gallery with pipes collecting seepage water. The seepage can be measured with a calibrated container and a watch for each pipe separately. (Photo Feuerstein)

container must be installed which can be emptied, and this must be provided with suitable equipment for the collection and diversion of the flow.

The different zones (or sectors) of the dam or the tunnel from which the water is flowing must be clearly delimited one from another.

If possible infiltration and drainage flows should be collected and measured separately.

Rain and snow melt should be prevented as far as possible from entering into the infiltration and drainage water collection system.

5. Checking of operation and maintenance

The measurement container, measurement point and drainage channels must be regularly cleaned.

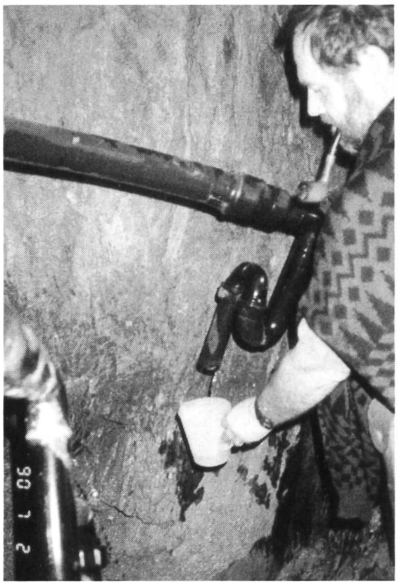
A periodic check must be made that all water is being collected by the measurement equipment.

6. Redundancy

Redundancy is not required. Nevertheless, one possible way of checking the equipment is to compare the sum of the sectorial discharges with the total discharge at the dam site.

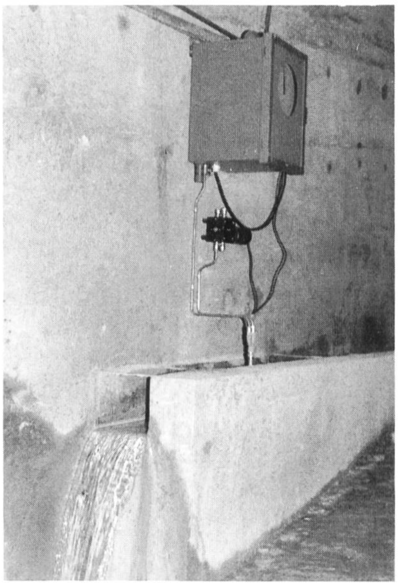
7. Remarks

When interpreting the measurement results the meteorological conditions must also be taken into account (rainfall and snow melt), as these can seriously influence the measured flows.



Reference number 2.200(3). Drainwater measurement by means of a calibrated container.

Reference number 2.201(1). Triangular weir in a seepage channel. To measure the discharge, the water level is determined by means of a measuring pointer.



Reference number 2.201(2). Drainage flow measuring flume with rectangular weir and bubbler-meter for the determination of the water level.

Weir and measuring flume

Reference number 2.201–1

1. Measuring devices

The discharge flowing in a channel is measured either by means of a calibrated triangular or trapezoidal weir, or with the aid of a calibrated Venturi flume. The water level is measured upstream of the zone of direct influence of the weir or flume by means of a graduated scale, a measuring pointer, an echo-sounder or with a pressure balance.

2. Appraisal

This is a simple and precise way of measuring discharges of more than 0.05 l/s. It is not recommended for smaller discharges, for which it is not sufficiently accurate.
Remote control and teletransmission are possible and desirable.

3. Possible problems and measurement errors

If the water collection system leaks, a part of the discharge may possibly flow around the measurement point.
The deposition of carbonates in the canal or on the crest of the weir can lead to inaccurate readings.
When the water level is measured with the aid of a pressure balance the measurement tube can become blocked.
Flow constriction just downstream of the measurement weir can cause in inaccurate readings.

4. Technical requirements

The dimensions of the weir and of the canal must be selected taking account of the discharge, and with allowance made for sufficient reserve.
It is essential that constricted discharge conditions just downstream of the measuring section are avoided.
Both canal and weir must be periodically cleaned.
With remote monitoring, it is important to ensure that the measurements can be checked by making volumetric discharge measurements at the measuring station, or by measuring the water level with the aid of a graduated scale or measuring pointer.
The tubes of the pressure balance must be accessible and removable for easy cleaning.
The various zones or sectors of the dam or tunnel from which the water flows must be clearly delineated one from another.
If possible infiltration and drainage water must be collected and measured separately.
Rainwater and snow melt must if possible be prevented from flowing into the infiltration and drainage water system.

5. Checking of operation and maintenance

The discharge must be checked periodically by volumetric measurement.
The water level must be checked periodically using a graduated scale or a measurement pointer.
The canal and pipes of the pressure balance must be regularly inspected for cleanliness.
Periodically checks are needed that all of the discharge is being conducted to the measurement weir (i.e. that no part of the flow is leaking around the weir).

6. Redundancy

Redundancy is not required, but verification is possible by comparing the total of the sectorial discharges with the total discharge flowing from the dam.

7. Remarks

When interpreting the measurement results, allowance must be made for meteorological conditions (rainfall and snow melt), as these can have a considerable influence on the measured discharges.

Sonar gauge

Reference number 2.201–2

1. Measuring device

The equipment determines the water level at a measurement section by measuring the time of reflection of a sound wave from the water surface.

2. Appraisal

Once calibrated, this apparatus allows direct reading of the discharge as a function of the water level for canals of different cross-sections.

It is easily installed and very accurate.

3. Possible problems and measurement errors

Displacement of the zero point due to the deposition of sediments in the canal.
The apparatus is sensitive to voltage surge.

4. Technical requirements

All equipment must be designed to function satisfactorily in humid conditions.
Protection is necessary against voltages surge.

5. Checking of operation and maintenance

The measurement canal must be regularly cleaned.
Periodic recalibration is necessary using a graduated scale to measure the water level whilst the discharge is determined by volumetric measurement.

6. Redundancy

Any of the other systems of discharge measurement.

7. Remarks

This equipment is well suited for remote monitoring using data transmission, combined possibly with a warning signal to indicate when maximum permissible values are exceeded.

Measurement of flow in pipes

Reference number 2.202

1. Measuring devices

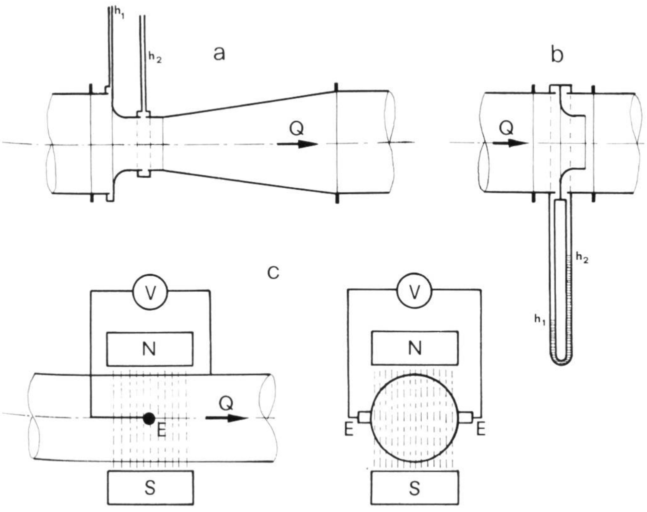
There are two different systems:
a) Venturi meters
b) Electromagnetic or ultrasonic systems of which no parts come into direct contact with the water.

2. Appraisal

Neither of these systems have moving parts, and they therefore require very little maintenance once they have been calibrated.

3. Possible problems and measurement errors

Sediments and deposited carbonates can affect operation and lead to incorrect readings.
The electromagnetic and ultrasonic systems are sensitive to voltage surge.



Reference number 2.202. Measurement of flow in pipes. (a) Venturi meter, (b) Flow nozzle, (c) Electromagnetic flowmeter; (N, S) Poles of the magnetic field, (E) Electrodes, (V) Voltmeter for measuring the induced voltage which is proportional to the average velocity of the fluid, (Q) Discharge.

4. Technical requirements

All equipment must be designed to function in a humid environment. All metal parts must be manufactured in stainless steel.
If necessary, the equipment must be protected against the formation of ice.
Electromagnetic and ultrasonic systems must be protected against voltage surge.

5. Checking of operation and maintenance

The calibration of the apparatus must be checked periodically, for example using a volumetric measurement system, provision of which must be allowed for when designing the measurement equipment.

6. Redundancy

Discharge verification using another system of flow measurement.
Comparison of the total flow from the dam with the measured sectorial discharges.

7. Remarks

These systems allow remote transmission and registration of readings, and can be combined with equipment to indicate when maximum permissible values are exceeded.
When interpreting the measurement results account must be taken of hydrological conditions (rainfall and snow melt) as these can seriously influence the measured discharges.

Uplift and pore water pressure

Open borehole / standpipe (for concrete dams)

Reference number 2.300–1

1. Measuring device

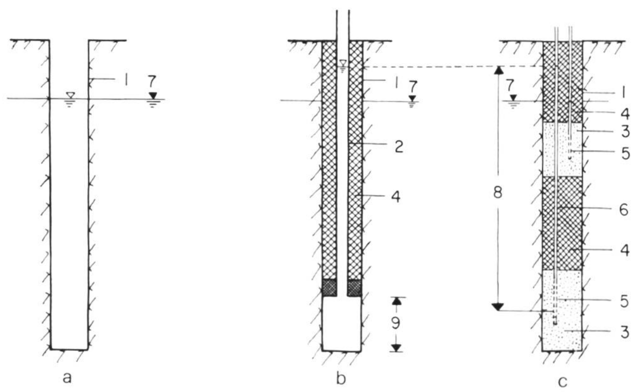
The water level within the dam foundation is determined with the aid of a light or acoustic gauge. The boreholes for the installation of the measuring equipment can be sunk from a gallery or from the ground surface. They can be vertical or, rarely, inclined.
Three different systems exist (see Figure): (a) Open borehole, (b) Standpipe, (c) Standpipe with filters.
Whereas the measuring system (a) only measures the level of water in the rock mass, the systems (b) and (c) allow the determination of the uplift in a given section. As a general rule system (a) should be avoided.

2. Appraisal

The measuring system is only advisable for measurement where the water level lies below the head of the borehole. Where the level of water is above the head, a manometer is used (see reference number 2.301–1).
The measuring systems (a) and (b) are only suitable for the measurement of uplift in permeable rock. In less permeable rock these two systems should only be applied under structures where the water level upstream and downstream remains practically constant. In the measuring system (c) the diameters of the measuring pipes are small, so that this system can also be used in a less permeable rock (shorter reaction time).
The measurement is simple, precise and well proven.

3. Possible problems and measurement errors

The rock, pipes, and for system (c) equally the filters, can be obstructed in the course of time by efflorescence or mud. In the case of non-watertight pipes for systems (b) and (c) or of an insufficient surrounding of the pipes by the grout, the results of measurements can be erroneous due to water circulation along the pipes.



Reference number 2.300-1(1). Open borehole of standpipe measuring equipment for concrete dams. (a) Open borehole, (b) Standpipe, (c) Standpipe with filters; 1 Borehole, 2 Pipe (diameter 2" to 2,5"), 3 Sand, 4 Grout, 5 Porous filter, 6 Flexible tube (internal diameter 8 to 12 mm), 7 Phreatic water level, 8 Height of uplift, 9 Measuring section < 5 m.

In the event of water penetration from the surface the measurement will be incorrect.
After a penetration of mud, stones or other objects into the measuring system, taking the measurements can become impossible (at least for certain water levels).

4. Technical requirements

The head of the boreholes or the pipes must be protected against penetration of water from the surface, from mud, stones and other objects. If possible, the boreholes or pipes should be closed with a cap. This closure must not disturb either the aeration or the ventilation of the measuring system.
The exact geometry of the measuring instruments must be recorded (levels of measuring sections, head of borehole, inclination of borehole, etc.).
The borehole for system (b) must have waterproof piping until the level of the measuring section. Moreover, the surrounding of the pipe must be sufficiently watertight to prevent the circulation of water along the pipe, which will make the measurements incorrect.
The installation of system (c) must only be carried out by experienced persons. Every attention must be paid towards a good water proofing between the different levels of measurement.
The boreholes planned for the measurement of uplift must only be executed after all the grouting works have been carried out in the neighbourhood.

5. Checking of operation and maintenance

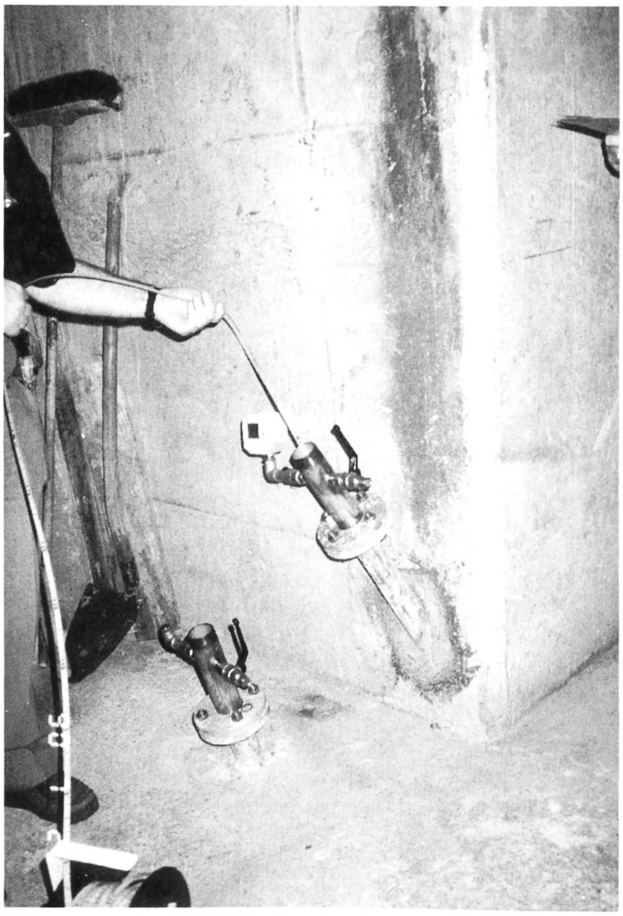
All the tubes (boreholes) must be checked periodically along their whole length with respect to efflorescent deposits or mud, and, if needs be, they must be cleaned.
The correct functioning of the light (acoustic) signal must be checked periodically.

6. Redundancy

A fair amount of redundancy is obtained from the comparison of results at several points of measurement spread out over the whole surface of the foundation.
It is recommended to install groups of measuring points in several transversal sections of the dam.

7. Remarks

For the installation of such instruments during operation of a dam it is necessary to take into account the limited space available for carrying out the boreholes, as well as the exact position of the surface of the foundation (topographic recording of the excavations carried out during construction).
When choosing the sections for measurement it is necessary to take into account the geotechnical properties of the rock foundation.
The boreholes must be of the rotary type with withdrawal of cores. It is recommended to measure the permeability of the concrete and rock before installation of the measuring equipment.
In cases where the pressures diminish progressively during the course of time, in spite of periodic maintenance of the systems, or where the pressure remains constant with a variable level of the lake, new measuring equipment should be installed in the vicinity of the old one. This will show if the whole rock foundation is being silted up or only a zone in the immediate vicinity of the measuring sections.



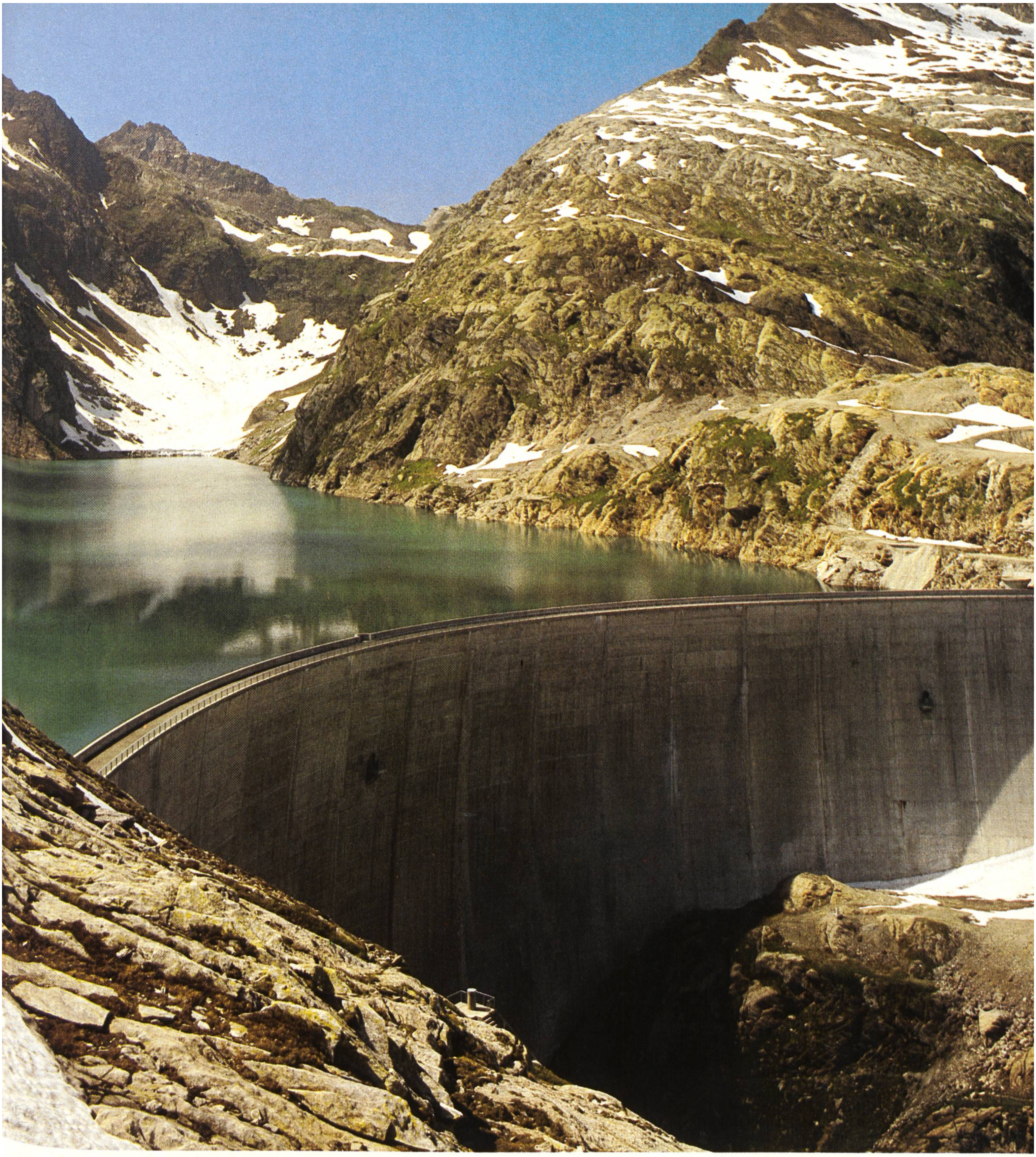
Reference number 2.300-1(2). Open borehole/standpipe. Measurement of the water level by means of a light or acoustic gauge fixed to a tape-measure. For water levels above the head of the borehole the pipe is closed and the uplift measured by means of the manometer.

Open borehole / standpipe (for embankment dams)

Reference number 2.300–2

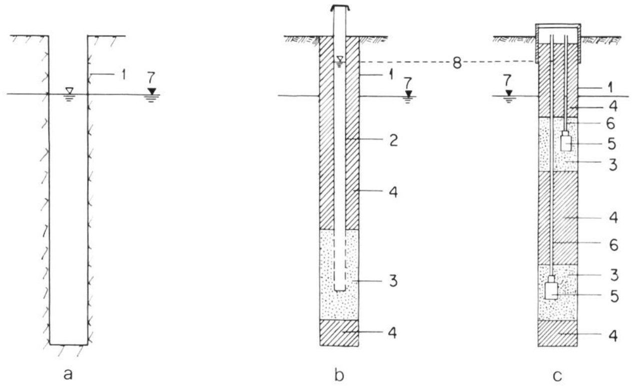
1. Measuring device

The water level within an embankment dam or a foundation is determined with the aid of a light or acoustic gauge. The boreholes for the installation of the measuring equipment can be sunk from the ground surface or from a gallery. They can be vertical or, rarely, inclined.
Three different systems exist (see Figure): (a) Open borehole, (b) Standpipe, (c) Casagrande-type piezometer.
The open borehole (type a) can only be located in rock and only allows the measurement of the phreatic water level in the bed rock. To measure the uplift or pore water pressures



Bogenstaumauer und Stausee Cavagnoli der Maggia Kraftwerke AG.

Reservoir and arch dam Cavagnoli of the Maggia Kraftwerke AG.



Reference number 2.300-2. Open borehole or standpipe measuring equipment for embankment dams. (a) Open borehole, (b) Standpipe, (c) Casagrande-type piezometer; 1 Borehole, 2 Perforated pipe (diameter 2" to 2,5"), 3 Sand, 4 Impervious fill, 5 Porous filter, 6 Flexible tube (internal diameter 8 to 12 mm), 7 Phreatic water level, 8 Piezometric level.

at given points in a fill dam or in a foundation piezometers of types b and c have to be used.
In the case of the standpipe (type b), a tube of 2 to 2.5" diameter, perforated at the selected measurement level, is introduced into a borehole. The space between the tube and the sides of the borehole is filled with filter material at the measurement level and elsewhere with impervious material.
The Casagrande piezometer (type c) is used in relatively impermeable material. In order to reduce the reaction time small plastic measurement tubes are used (internal diameter 8 to 12 mm). The end of each tube is connected to a measurement cell with a porous filter. Up to three measurement cells at different depths can be located in the same borehole.

2. Appraisal

The open borehole is suitable for use only in permeable rock or, in less permeable rock, providing the upstream and downstream water levels remain practically constant.
The standpipe (type b) is suitable for both permeable and less permeable material, but in the latter case only if the variations of pressure are neither too pronounced nor too rapid. This equipment is robust and very reliable.
The Casagrande piezometer (type c) is also used in material of low permeability because the small diameter of the measurement tubes means that small flows are sufficient to register a change in pressure.
Measurement is simple, accurate and well-proven in the field.
This equipment is only suitable for the measurement of water levels within the borehole. Should the water level rise so that water flows out of the piezometer tube, then a manometer must be connected to this tube (see reference number 2.301–2).

3. Possible problems and measurement errors

The tubes and filters of the Casagrande piezometer as well as the pervious material at the measurement level can become obstructed after a time by efflorescence or mud.
If the tube is not perfectly watertight, or if the packing material around the tube is not well placed, measurements can be influenced by the circulation of water.
If surface water can penetrate the borehole, incorrect measurements will result.
Incorrect readings will result if the perforated section of the piezometer pipe crosses the boundary between adjacent fill zones in which the pore water pressure is different.
The penetration of mud, stones or other matter into the measurement system can at certain water levels make measurements impossible.

4. Technical requirements

Care must be taken that surface water or dirt cannot enter the measurement system. This should therefore be closed with a cover which, however, must not affect either the ventilation or deaeration of the measurement system.
Precise dimensioning of the installation must be measured and recorded (level of the measuring point, level of the head of the borehole, inclination of the borehole, etc.).
For the piezometer of types b and c, the borehole must be sealed down to the measurement level, in order to avoid the circulation of water along the piezometer pipe/tube which could influence the measurements.
When placing the equipment account has be taken of the various zones of fill material in the dam, or of the strata of the foundation.
When installing a piezometer pipe/tube during the placing of dam fill great care must be taken to avoid any damage by the earth-moving machines (erect barriers and warning signs, and post guards). In certain cases, it may well be more convenient to install the piezometer in boreholes after completion of dam construction.

5. Checking of operation and maintenance

All tubes and boreholes must be periodically checked over their entire length for efflorescence or deposits of mud. If necessary, they must be cleaned.
The satisfactory operation of the light or acoustic gauge must be periodically confirmed. The reliability of the measuring system has to be checked by tests in which the water level in the tube is raised or lowered. If necessary flushing under pressure must be undertaken.

6. Redundancy

Certain redundancy can be obtained by comparison of the results measured at a number of points distributed within the fill or foundation. It is recommended that the piezometer measuring points for a dam be located along a number of cross-sections.

7. Remarks

The boreholes must be sunk by rotation drilling with the extraction of cores. Appropriate tests should be carried out before placing the measuring equipment to determine the permeability of the rock at the measurement levels.
Should the measured pressure diminish progressively with time, despite periodic maintenance of the measuring systems, or should this pressure remain constant for varying levels in the lake, new equipment should be installed near to the original equipment in order to assess whether the entire zone has been affected by aggregation or whether this has occurred only in the immediate proximity of the piezometer measuring point.
In suitable fill material, the standpipe (type b) can be driven directly, without the need of boring, providing that it is sufficiently robust.

Closed borehole (for concrete dams)

Reference number 2.301–1

1. Measuring device

In the measuring equipment devised for the closed borehole, the measurement of uplift is carried out by means of a manometer connected by a pipe to the measuring point located in the rock foundation. The boreholes necessary for the installation of the measuring equipment can be vertical or inclined.

The principle of measurement described is applicable to those cases where the presumed uplift exceeds the level of the top of the borehole.

Normally one of the following four systems is used for measuring uplift (see Figure): (a) Simple pipe, (b) Pipe with uplift bell, (c) Pipe with filters, (d) Tubes with rinsable measuring cells.

2. Appraisal

The measuring equipment (a) is the most often applied for the measurement of uplift, whilst the equipment (b) is rarely used anymore. In practice, the measurement of uplift using the closed tube principle is well proven. The accuracy of the manometer measurement should normally reach 1 % of the range of measurement.

3. Possible problems and measurement errors

At the time of installation of the measurement equipment type (c) and (d) a measuring point is sometimes lost from the beginning, as a result of the grouting necessary in the borehole.

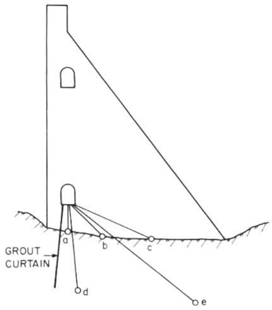
The rock or the pipe, in the case of the measuring equipment (c) as well as the filter material, can become blocked up by efflorescence or mud; this is also applicable for the system (d) in the case where the measuring points are not rinsed out sufficiently often.

In the case of piping not sufficiently waterproof or of a poor surrounding of the pipes with the grout, false measurements can arise from water circulation along the pipes.

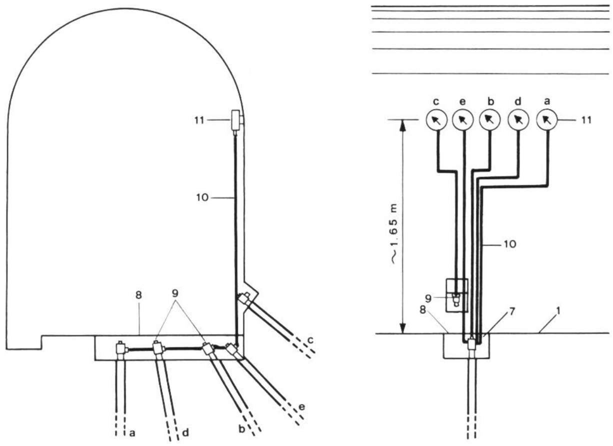
Entry of air into the system can induce false readings.

Inaccuracy of measurements can arise as a result of deposits of carbonates or fatigue of the measuring instrument.

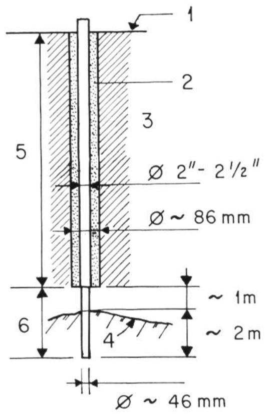
After a possible discharge of the system (e.g. for cleaning) the pressure sometimes resettles very slowly; the results of measurements after such a discharge can thus be false.

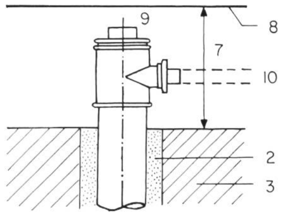


Reference number 2.301-1(2). Typical layout of uplift measurements of type (a).



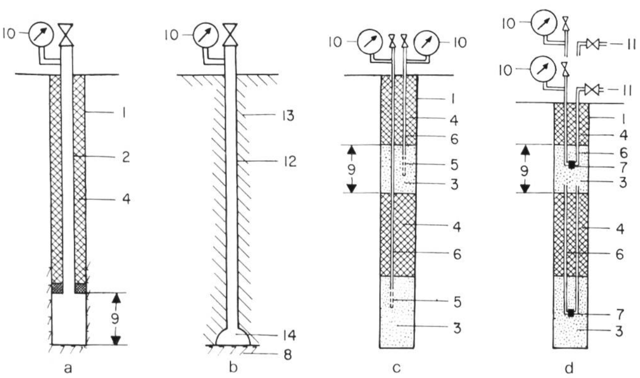
Reference number 2.301-1(3). Connections of pipes to manometers. Floor wall, 2 Grout, 3 Concrete, 4 Rock-concrete interface, 5 Tubed length of borehole, 6 Non-tubed borehole, 7 Ditch, 8 Metal cover, 9 T-piece (e.g. 2″ to 2,5″) acting as pipe closure and connection to pressure tube, 10 Flexible pressure tube, 11 Manometer.



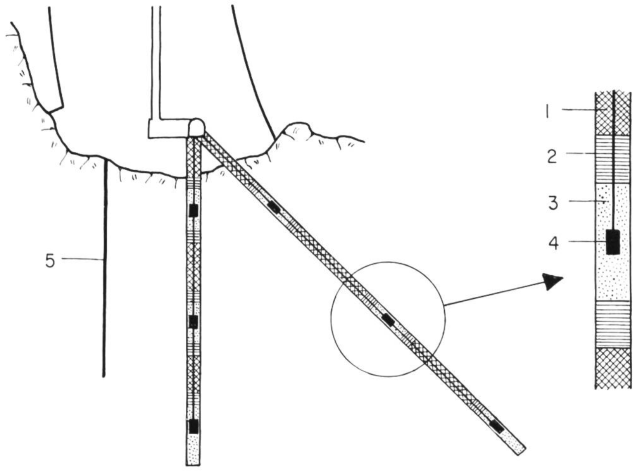


Reference number 2.301-1(5) Head of pipe detail (legend see Ref. no. 2.301-1(3).

Reference number 2.301-1(4), left. Borehole detail (legend see Ref. no. 2.301-1(3).



Reference number 2.301-1(1). Closed borehole measuring equipment for concrete dams. (a) Simple pipe, (b) Pipe with uplift bell, (c) Pipe with filters, (d) Tubes with rinsable measuring cells; 1 Borehole, 2 Pipe (diameter 2″ to 2,5″), 3 Sand, 4 Grout, 5 Porous filter, 6 Flexible tube (internal diameter 8 to 12 mm), 7 Measuring cell, 8 Foundation rock, 9 Measuring section, 10 Manometer, 11 Flushing stop-cock, 12 Embedded pipe (diameter 2″ to 2,5″), 13 Concrete, 14 Bell.



Reference number 2.301-1(6). Possible layout of uplift measurements of types (c) and (d) in the foundation of a dam. 1 Grout, 2 Clay pellets, 3 Quartz sand (grain size 1,5 to 2 mm), 4 Piezometer, 5 Grout curtain.

4. Technical requirements

Only the most robust products made from material resistant to oxidation should be used as manometers.
The range of measurement of the manometer must adequately exceed the maximum presumed pressure.
To avoid an erroneous interpretation of the uplift conditions, the measuring pipes and the manometers must only be discharged in exceptional circumstances for example for cleaning work. On the other hand, the manometers can be discharged, after taking a measurement, by a special flushing valve, provided the system is devised in such a way as to avoid all loss of water (no false measurements).
The measuring pipes must be used exclusively for the taking of uplift pressures. To relieve the rock foundation, separate drainage boreholes should be provided.
The exact geometry of the measuring equipment must be recorded (levels of measuring sections, top of borehole, inclination of borehole, etc.).
Boreholes containing measuring equipment types (a) and (b) must be fitted out with waterproof pipes down to the level of the measuring point. Equally, the surrounding of the pipe must be sufficiently waterproof to prevent water circulation along the pipe.
The installation of measuring equipment (c) and (d) must only be carried out by qualified persons. Every attention must be paid towards a good water proofing between the different levels of measurement.
The boreholes planned for the measurement of uplift must only be executed after all the grouting works have been carried out in the neighbourhood.

5. Checking of operation and maintenance

The measuring pipes must be checked from time to time along their whole length, and, if needs be, cleaned.
The correct functioning of the manometers must be verified periodically. This check is carried out preferably at different levels of pressure, by means of a pump and an accurate manometer. Provisionally, the manometer to check can also be connected to a water pipe whose pressure is known (e.g. pressure in the reservoir). Faulty manometers must be quickly serviced or, if needs be, replaced. Some replacement manometers must be kept in reserve.
The connecting pipes between the measuring tubes and the manometer, and the connections themselves must be checked periodically, as well as when there is an unusual fall in pressure, with respect to their waterproofing or possible obstructions.

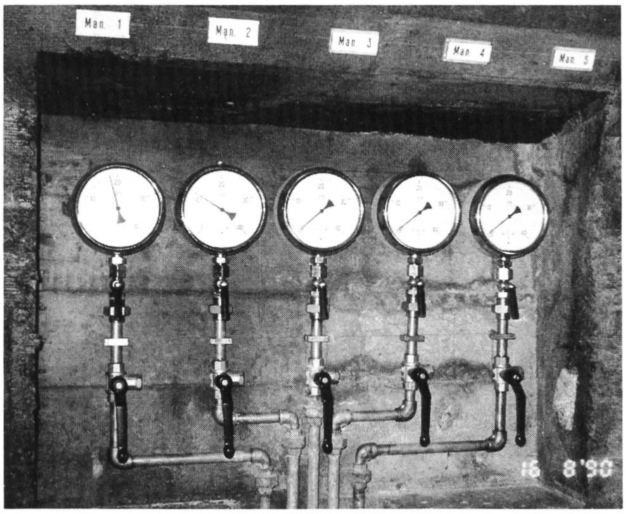
6. Redundancy

A fair amount of redundancy results from the comparison of the results obtained at several points of measurement spread out over the whole surface of the foundation. It is recommended to install groups of measuring points in several transversal sections of the dam.

7. Remarks

For the installation of such instruments during operation of a dam it is necessary to take into account the limited space available for carrying out the boreholes, as well as the exact position of the surface of the foundation (topographic recording of the excavations carried out during construction). When choosing the sections for measurement it is necessary to take into account the geotechnical properties of the rock foundation.

Opposite page: Grande Dixence gravity dam with a height of 285 m is the highest dam in the world.



Reference number 2.301-1. Uplift measurement by means of closed boreholes. The manometers are connected to boreholes spread out over the foundation in an upstream-downstream section.

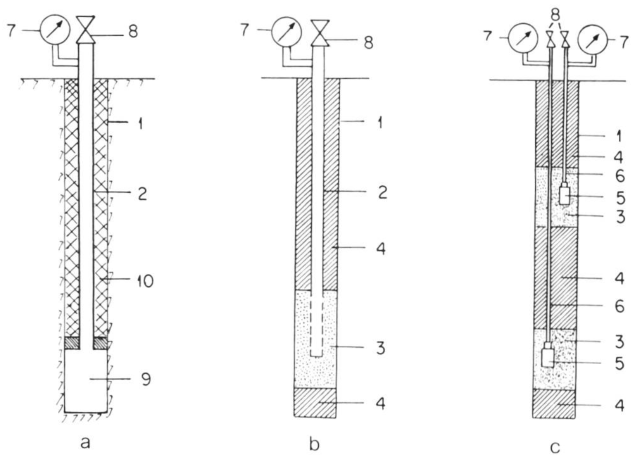
The boreholes must be of the rotary type with withdrawal of cores. It is recommended to measure the permeability of the concrete and rock before installation of the measuring equipment.
In cases where the pressures diminish progressively during the course of time, in spite of periodic maintenance of the systems, or where the pressure remains constant with a variable level of the lake, new measuring equipment should be installed in the vicinity of the old ones. This will show if the whole rock foundation is being subjected to a silting up or only a zone in the immediate vicinity of the measuring sections.

Closed borehole (for embankment dams)

Reference number 2.301–2

1. Measuring device

So-called closed borehole measurement of the water pressure is made with the aid of a manometer connected by a pipe with the measuring head situated within the fill dam or in the foundation. This method of measurement is applied when the hydrostatic pressure is expected to exceed the elevation of the head of the borehole.
Three different systems are described (see Figure): (a) Simple pipe, (b) Standpipe, (c) Casagrande-type piezometer.
The boreholes for placing of the measuring equipment are drilled from the ground surface or a gallery. They are normally vertical but can be, in rare cases, inclined.
System (a) can only be installed in rock. The measuring section, the length of which should be less than 5 m, is connected to the manometer by means of a pipe of 2 to 2.5″ diameter. The space between the pipe and the side to the borehole is grouted, and for this purpose a packer is provided at the lower end of the pipe.
The measuring systems of types (b) and (c) can be used both in rock as well as in earth fill.
For the standpipe (type b), a pipe of 2 to 2.5″ diameter is introduced into the borehole. This pipe is perforated at the measurement level. The Casagrande piezometer (type c) is equipped at the measurement level with a porous filter body connected to the manometer by a small diameter flexible tube (internal diameter 8 to 12 mm). In both cases the area around the measuring point is filled with sand and the



Reference number 2.301-2. Closed borehole measuring equipment for embankment dams. (a) Simple pipe, (b) Standpipe, (c) Casagrande-type piezometer; 1 Borehole, 2 Pipe (diameter 2″ to 2,5″), 3 Sand, 4 Impervious fill, 5 Porous filter, 6 Flexible tube (internal diameter 8 to 12 mm), 7 Manometer, 8 Pressure relief and flushing valve, 9 Measuring section in the rock, 10 Grout.

remaining space between the pipe/tube and the borehole sides is filled with impermeable material (clay or grout, etc.). Up to three measuring points can be installed at different levels in the same borehole.

2. Appraisal

With these closed systems, variations of pressure are recorded after a short reaction time (reference time). Measurement is simple, precise and well-proven.

The pipes of type (a) and (b) are robust and ensure high operational security although their accuracy is not equal to that of the Casagrande-type piezometer (type c). The measurement precision of the manometer is ± 1% of the measurement range and is normally adequate.

3. Possible problems and measurement errors

The pipes and tubes as well as the filters of system (c), and the material situated around the measuring head can become obstructed with time by efflorescence or mud.

Consolidation grouting in boreholes has resulted in measuring points being unusable from the time of their installation.

If the piezometer pipe/tube leaks or if the packing material around it is not satisfactorily placed, measurements can be influenced by the circulation of water.

If adjacent soil strata, in which the hydrostatic pressure is different, are connected by the perforated section of the pipe, erroneous readings can result.

Entry of air into the measurement systems can lead to incorrect readings.

Errors can result from the deposition of carbonates or from metal fatigue of manometer parts.

After releasing the pressure in the measurement system (e.g. for cleaning), under certain circumstances it can take time for a stable pressure to reestablish itself, and measurements made during this period can as a result be incorrect.

4. Technical requirements

The manometers must be of robust construction in stainless steel.

The range of the manometer must exceed the maximum presumed pressure to be measured.

To avoid false interpretation of the pressure distribution, the pressure in the measuring pipes and manometers may only be released in exceptional cases, for instance for cleaning. On the other hand, after having taken a measurement, it is possible to relieve the manometers by means of a special closure and emptying valve, providing that the system is such that no loss of water can occur, which could result in incorrect readings.

The measurement system must only be used for measurement of the hydrostatic pressure. If pressure relief within a foundation is necessary separate drainage holes should be provided.

The exact geometry of the measuring equipment must be recorded (level of the measuring sections, top of borehole, inclination of borehole, etc.).

Boreholes containing measuring equipment types (a) and (b) must be fitted out with waterproof pipes down to the level of the measuring point. Equally the surrounding of the pipe must be sufficiently waterproof to prevent water circulation along the pipe.

Experienced personnel are necessary for the installation for piezometers of type (c). Particular attention must be given to ensuring good insulation of the different measurement levels from each other.

When placing the equipment, allowance must be made for the different fill zones in the dam or different strata of the foundation.

When installing the pipes and tubes during the placing of fill material great care must be taken to avoid damage by earth moving machines (erection of barriers and warning signs, posting of guards).

In certain cases it is more convenient to install the piezometers in the borehole after completion of the placing of fill.

5. Checking of operation and maintenance

All pipes, tubes and boreholes must be periodically checked over their full length for possible deposits of mud or for efflorescence. If needed they must be cleaned.

The operation of the manometers must be periodically checked. This check can be carried out by establishing different pressure levels using a pump and precision manometer. Temporarily, a manometer needing to be checked can also be connected to a pipeline in which a known pressure exists (e.g. that corresponding to the level of the reservoir). Any manometers which give false readings must be immediately repaired or if necessary replaced. Reserve manometers must be available at all times.

The connecting between the manometer and the piezometer pipe, as well as their corresponding connections, must be periodically checked for water tightness and blockage. These checks should also be made in event of any unusual pressure drop.

6. Redundancy

Certain redundancy can be obtained by the comparison of the results measured for several distinct points in the fill or foundation. It is recommended that the measuring points for a dam be grouped along a number of cross-sections.

7. Remarks

The boreholes must be drilled by rotation, and cores must be taken. Appropriate permeability tests should be made prior to the installation of the measuring equipment.

Should the measured pressure diminish progressively with time, despite periodic maintenance of the measuring systems, or should this pressure remain constant for varying levels in the reservoir, new equipment should be installed near to the original equipment in order to determine whether the entire foundation has been affected by colmatation or whether this has occurred only in the immediate proximity of the measuring point.

Pneumatic and electric pressure cells (for concrete dams)

Reference number 2.302–1

1. Measuring device

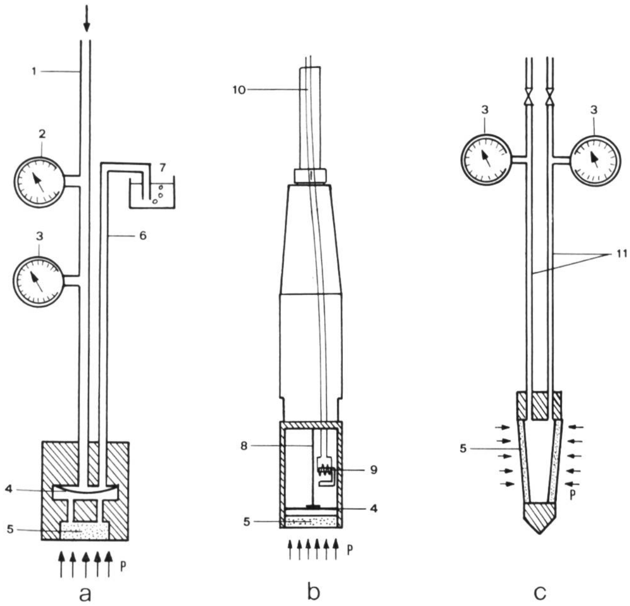
The cells measure the water pressure in the rock foundation. They are installed in the boreholes, at the desired level, and connected by small tubes or electric cables to the measuring station, which most often is a central station.
The cells measure the local pressure of the water indirectly, most often by the deformation of a membrane.
For pneumatic cells, the pressure in the cell is progressively increased by means of a gas (e.g. nitrogen), or more rarely by means of oil, up to the point where there is a balance between the internal pressure and the existing external pressure. This pressure balance causes a valve to open and gives a corresponding reading at the measuring instrument.
The electric cells are based either on the principle of the measurement of resistance or on that of the frequency of a vibrating cord.

2. Appraisal

All the measuring systems are well proven; they require, nevertheless, very careful choice of products, and equally careful installation of instruments and pipes (cables).
The cells mentioned have a short reaction time, and for this reason they are recommended for use in rock with low permeability. The use of electric cells is particularly simple; in addition measurements can be taken over very long distances.
Alteration of the results of measurement as well as loss of the cells due to silting up of the filters are not unfrequent.

3. Possible problems and measurement errors

At the time of installation a cell is occasionally lost from the beginning as a result of its blockage by the grouting works necessary in the borehole.
With careless installation, a pipe (or a joint) can fail to be watertight or an electric cable can be defective.



Reference number 2.302. Types of piezometric cells. (a) The pneumatic piezometer, (b) Vibrating wire piezometer, (c) Twin-tube hydraulic piezometer; 1 Gas supply tube, 2 Gas flow gauge, 3 Pressure gauge, 4 Membrane, 5 Porous filter, 6 Return tube, 7 Gas flow indicator, 8 Vibrating wire, 9 Electrical coil, 10 Signal cable, 11 Twin plastic tubes containing deaired water.

According to the chemical composition of the water, the filters of the cells can silt up either more or less rapidly, leading to loss of the cell.
The presence of air in the filters leads to inaccurate measurements.
Water circulating along the pipes or cables can lead to a balancing of the pressure in two or more measuring sections, resulting in false readings.
As a result of careless installation the pneumatic measurement can be disturbed by the presence of condensation or foreign matter in the pipes.
With respect to the electric cells, false results can be caused by different influences, for example drifting of the "zero" point, ageing of the cables, oxidation of the electric contacts, defects in the measuring instrument. Loss of cells as a result of overvoltage (lightning) are not uncommon.

4. Technical requirements

For all types of cells:
The installation is difficult and must only be carried out by specialists.
In order to avoid air entrainment the filters must be saturated with water before installation.
In a given borehole, each cell must be embedded separately, or possibly together with a cell in reserve, in a suitable sand, generally quartz. In order to prevent the circulation of water along the borehole, the segments of the borehole between the measuring sections must be waterproofed with cement grout.
The most suitable type of filter must be determined as a function of the chemical composition of the water, before proceeding with the installation work. (At present, there are filters in ceramic or porous metal, as well as in quartz sand. For these filters either natural quartz sand or artificially manufactured quartz sand [silica] is used. Different materials are used as a binder.)
If an obstruction of the filters is to be feared it is necessary to provide a rinsing system for the cells.
To compensate for the loss of some of the cells, it is necessary to install the cells in excess numbers. It is equally advantageous to combine different measuring systems.
For pneumatic cells:
Because of the considerable difference in levels which normally occurs between the cells and measuring station, oil is not normally used. Gas must be used instead.
To prevent the formation of condensation it is necessary to dry the pipes completely at the time of installation.
The pipes must be accessible for checking over the longest length possible (checking for leaks).
For electric cells:
The cables must be completely waterproof and of high mechanical resistance. There must be no spliced joints between the cell and the junction box or the measuring equipment.
Great importance must be placed on protection against overvoltage (shielded cable, earthing, protection fuses).
In order to overcome the problem of the drifting "zero" point, it can be useful to install pairs of cells in each measuring section (the results of the two cells being checked against each other).

5. Checking of operation and maintenance

For all types of cell:
In order to insure a long life for the cells provided with a rinsing system, they must be rinsed out periodically without fail, in view of the fact that cells too heavily silted up can normally no longer be descaled.

For pneumatic cells:
At each measurement check if the maximum pressure can be maintained. If this is not the case, the pipework is not airtight at some point and must be repaired.
In order to eliminate humidity in the pipes, periodic drying out can be necessary.
For electric cells:
The electric contacts and measuring instrument must be cleaned regularly and protected against oxidation.
The measuring instrument must be verified periodically by means of a calibrating instrument or by the manufacturer.

6. Redundancy

A fair amount of redundancy is achieved by comparing the results obtained at several measuring points spread out over the whole foundation.
It is recommended to arrange groups of measuring points in several transversal sections of the dam.

7. Remarks

For the installation of instruments during the operation of a dam, the restrictions on space available should be taken into account as well as the exact position of the surface of the foundation (topographic record of excavations carried out during construction).
When choosing the sections for measurement it is necessary to take into consideration the geotechnical properties of the rock foundation.
The boreholes must be of the rotary type with withdrawal of cores. It is recommended to measure the permeability of the concrete and rock before installation of the measuring equipment.
In cases where the pressure decreases progressively over the course of time, in spite of periodic maintenance of the measuring systems, or when the pressure stays constant with a variable level of the reservoir, new measuring equipment should be installed in the vicinity of the old ones. This will show if the whole rock foundation is being silted up, or only a local zone near to the measuring sections.

Pneumatic, hydraulic or electric pressure cells (piezometers for embankment dams)

Reference number 2.302–2

1. Measuring devices

The pressure measurement cells (piezometers) measure the pore water pressure in a dam or in foundations. They are installed in dams during the placing of fill, as soon as the dam has reached the required height. In foundations, piezometers are installed in boreholes. The piezometers are usually connected by means of flexible tubes or electric cables to a central recording station.
There are principally three types of piezometric cells:
Hydraulic cells: The cell consists of a porous element (filter) connected to the measuring station by two flexible tubes filled with deaerated water. The pore water pressure is measured either directly with a manometer or indirectly by a pressure probe with electric indicator.
Pneumatic cells (membrane valve cells): The pressure within the cell is raised by means of a gas such as nitrogen, or more rarely using oil, to the level at which it is equal to the external pressure to be measured. A valve then opens to equalize the pressure in the outflow and return-flow pipes connecting the cell with the measuring point, at which this pressure is indicated.
Electric cells: The pore water pressure acts on a membrane fixed in the cell. The deformation is transmitted to the measuring station as an electric current which varies in proportion to changes in either the resistance or vibrating frequency of a thin wire as a function of the tension in the wire.

2. Appraisal

All three types of piezometer cells operate reliably and accurately, providing that they have been correctly selected and installed. They have a short reaction time and are therefore particularly suitable for material of low permeability.
Hydraulic piezometers have been in use the longest. However, compared with the other two types they require most care in operation and maintenance, and therefore there is an increasing trend towards use of electrical and pneumatic piezometers.
One of the advantages of the hydraulic cells is the possibility, thanks to their twin tubes, of flushing the filter of any air which has entered it, a particularly useful operation for cells placed in non-saturated clay material. On the other hand, a disadvantage of this type of cell is the need to place the tubes below the level corresponding to the pore water pressure.
The electric cells are simple to use and can be read from a long distance.
For cells of all three types, a high rate of failure with time must be expected.

3. Possible problems and measurement errors

If carelessly placed, a tube can leak or a cable can be damaged.
Tubes and cables can be stretched or can shear as a result of differential settlement where they cross the boundaries between different zones of material.
If not very carefully installed, pneumatic cells can give incorrect readings due to the presence of condensation water or of foreign bodies in the tubes.
Various factors can lead to incorrect readings of the electric cells. These are for example the ageing of the cables, oxidation of contacts, defects in the measuring instruments, displacement of the zero point of the measurement indicator. Voltage surges (lightning strike) can also put electric cells out of action.
The accuracy of measurements can be affected by air penetrating the filter.
The failure of a piezometer cell can also be provoked by chemically aggressive water.
During installation in a borehole a cell can be accidently grouted and this can result in never functioning satisfactorily.

4. Technical requirements

The placing of piezometer cells is a delicate procedure and must only be carried out by specialists.
In the fill of the dam, the cells must be placed in separate niches of the trench excavated for the tubes or cables, and carefully surrounded with fine material. However, when the cells are placed in the impermeable zone of a dam they must not be surrounded with sand.
To prevent damage, the cables and tubes must be placed in zig-zag form in the trenches in order to allow reserve for deformation of the dam. Particular attention must also be given to the placing of cables in difficult zones such as boundaries between different fill materials or entry into control galleries.
Joints in flexible tubes or splicing of electric cables must be avoided in all inaccessible locations (buried in fill, boreholes).
Piezometers placed in boreholes must be surrounded with material similar to that through which the hole is driven. To

prevent any vertical percolation, a plug of impermeable material must be placed above the cell and the borehole must be refilled over its entire length.
When selecting the material for the filter of the piezometer cell the chemical analysis of the water must be taken into account.
To allow for failures, it is advisable to install an adequate number of piezometers. There are also advantages in combining several different measurement systems.
When hydraulic piezometer cells are used, the entire instrumentation system must be placed where it will not be affected by frost.
To provide the necessary internal pressure for the pneumatic piezometer cells a dry gas is used (nitrogen).
The flexible tubes for the hydraulic and pneumatic cells must be air and water-tight. The cables for the electric cells must also be water-resistant and must be protected against voltage surges and of high tensile strength.
The electric and pneumatic cells must be saturated during their installation in order that all air is expelled from the filter. If any risk exists of a filter being blocked, it should be equipped with a means of flushing.

5. Checking of operation and maintenance

Hydraulic cells: The cells and connecting tubes must be periodically flushed with deaerated water in order that the system remains free of air (during flushing excessive pressures should be avoided).
By means of raising and lowering the water level, correct functioning of the cells can be checked.
The readings of the manometers must be regularly compared with those of a standard manometer.
Pneumatic cells: During each measurement a check must be made that the increase in pressure takes place normally, and that the pressure can be maintained. If this is not the case, the pipes are not air-tight and, whenever they are accessible, must be repaired.
To eliminate humidity it may be necessary periodically to blow gas through the piping.
The filter body should be periodically flushed, providing a means of flushing has been provided.
Electrical piezometer: The contacts on the measuring equipment and cable boxes must be regularly cleaned and protected against oxidation.
The reading equipment must be periodically checked with a calibrated cell or by the manufacturer.

6. Redundancy

Certain redundancy is achieved by comparing the readings of a large number of dam or foundation piezometers. It is advisable to locate piezometers in a dam along several cross sections.

7. Remarks

Failed piezometers in a dam can be replaced by means of boreholes. When doing this very great care must be taken to ensure that the pressure of the drilling mud does not result in hydraulic fracturing and crack formation in the dam body.
When piezometers are installed in foundations, it is advisable to carry out appropriate water pressure tests during the drilling of the necessary boreholes.
If despite regular maintenance of the measurement system the measured pressure slowly diminishes with time, or if it remains constant for varying reservoir levels, new measuring equipment should be installed near to the existing equipment. This makes it possible to determine whether general colmatation has occurred or whether this is limited only to the measurement points.

Settlements

Vertical settlement gauge

Reference number 3.101

1. Measuring device

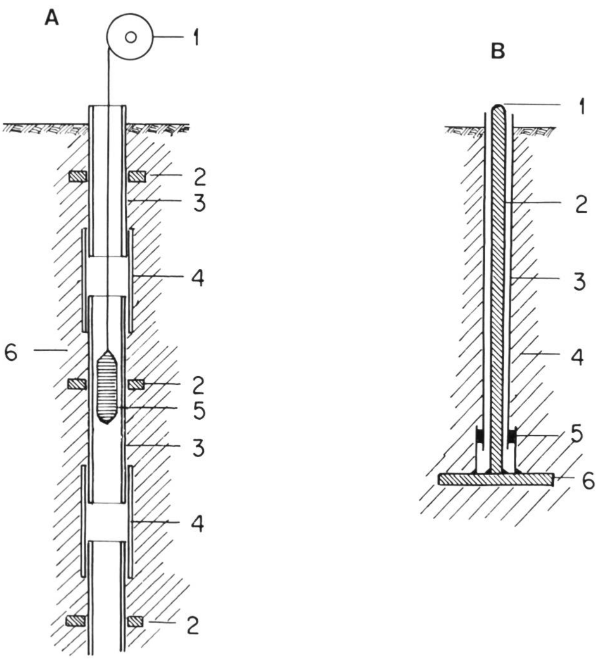
This is a vertical plastic tube of which the successive sections are raised as the placing of fill progresses. At suitable intervals (3 to 10 m) metallic settlement plates or rings (of steel or aluminium) are placed horizontally around the tube. They are set in the fill and can move vertically around the tube. Their relative position can be determined by an induction probe, the distance being measured relative to the flange at the upper end of the tube. Methods of indication are acoustic (whistle) or optical (maximum induced current measured at the recording apparatus). In the case of foundations in loose material, the gauge can be extended in a borehole of up to 50 m depth. In this case the metal settlement rings are embedded in the sand used to refill the borehole. Settlement gauges can also be placed inclined or horizontally to measure non-vertical deformations. In these cases the probe can be moved by means of a cable running over a pully at the end of the gauge, or alternatively the probe can be introduced into the tube with rods.

2. Appraisal

This instrument functions without problems in homogeneous, fine to gravelly fill of up to 50 m, exceptionally 100 m height. The effectiveness of steeply-inclined or horizontal installations is questionable.

3. Possible problems and measurement errors

Entry of material or foreign bodies into the tube.
Deformation of the tube due to large horizontal deformations of the dam, in particular very high structures. This can result in the probe getting jammed in the tube.
Rupture of the tube under the effect of high earth pressures.
Shearing of the tube where it passes through the contact zone between different fill materials.
Overstressing of the connecting sleeves of the tubes.



Reference number 3.101. Examples of vertical settlement gauges. (A) left: Settlement gauge (not to scale), 1 Measuring cable and recording instrument, 2 Metallic plates, 3 Guide casing, 4 Sleeve, 5 Probe, 6 Fill. (B) right: Settlement plate, 1 Measuring point for levelling, 2 Measurement rod, 3 Protection pipe, 4 Fill material, 5 Sliding sleeve, 6 Settlement plate.

The settlement plates can become jammed against the vertical tube (sliding sleeves should be provided between the plate and the tube).
Influence of a magnetic field on the probe (to be determined on site).
Friction between the measurement cable and the side of the tube (in particular at changes of direction) can lead to stretching of the cable and incorrect measurements.
Stretching of the suspension cable of the probe.
Spatial deformation of the tube can complicate the correct interpretation of the measurements (to be combined with an inclinometer, etc.).

4. Technical requirements

Installation

The length of each section of tube must not exceed 6 m. The connecting sleeves must be sufficiently long (up to several decimeters) to allow settlements of the fill to be followed. These connecting sleeves must be surrounded by rubber sleeves to prevent the ingress of fill material. When installing the tube its verticality must be checked continuously during the placing of fill material, and must be corrected if necessary. The tube should be bedded by hand in suitable material and this must precede the main fill by a depth of 0.5 to 1 m. That part of the tube which extends above the surface of the fill must be well-protected and indicated by easily visible signs, or guarded, in order that risk of damage by the earthmoving machines is avoided. The upper end of the tube must always be closed with a cap. As an alternative the tube can be installed in a shaft excavated in the newly-placed fill.
A free space must be left at the lower end of the tube, i.e. the lowest plate must not be placed at the very bottom of the tube.
For dams of great height ($>$ 100 m), on completion of construction, a number of additional settlement gauges should be placed in boreholes, adjacent to those installed during the construction, in order to record subsequent settlements.

Measurements

The position of each plate must be measured when lowering and when raising the probe. The elevation of the upper edge of the tube must be surveyed at the time of every measurement. For very deep tubes the weight of the probe must be increased to ensure that its cable is always under sufficient tension.

5. Checking of operation and maintenance

Frequent checking of the electric functioning of the probe and the recording equipment. Occasional checking that the cable has not been stretched.
At least two identical probes and sets of the recording equipment should be provided for each structure and the compatibility of this equipment must be verified. This requirement applies also during the construction period.

6. Redundancy

A damaged tube is almost invariably a complete loss. Therefore, several measuring sections, at least three per dam should be provided with settlement gauges. Redundancy can be achieved with hydraulic settlement gauges and series of extensometers (see 3.102 and 2.120–2), and should be provided for in critical cases, e.g. in zones where serious differential settlements are to be expected which could lead to over-stressing or even cracking of the material. If needed, further redundancy is obtained by levelling along the control gallery to the roof of which the settlement gauge tubes extend. This levelling is essential whenever the gallery is situated on loose material.

7. Remarks

Settlement gauges can usefully be combined with an inclinometer if the tube has the necessary internal guide grooves. Evaluation of horizontal deformations of the gauges makes possible a noticeably more reliable assessment of the settlement of the dam.
If the settlement plates have to be in rock fill, tubes and plates must be surrounded by well-graded gravel.
In simple cases for small dams a plate fixed at the lower end of a double-tube can serve as settlement gauge.
The USBR mechanical probe is today no longer in general use.

Hose levelling device (hydraulic settlement gauge)

Reference number 3.102

1. Measuring device

The hose levelling device or hydraulic settlement gauge operates on the principle of interconnected vessels. It consists of a cell which contains the overflow crest of an open hydraulic system. This cell is placed in the fill material and surrounded by sand, and is connected with the measurement points by three tubes:
- A supply tube for deaerated water which is connected to the overflow.
- A drainage pipe leading from the bottom of the cell.
- An aeration pipe which leads from the top of the cell and which ensures that the pressure in the cell is always atmospheric.

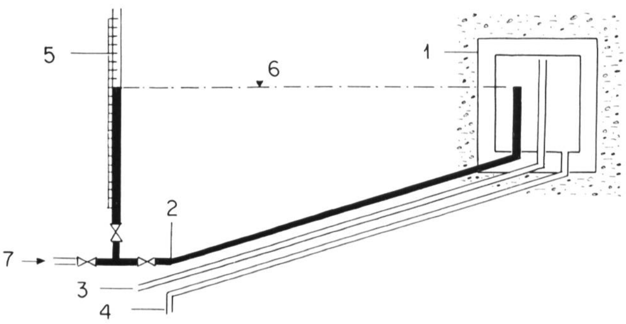
The water level in the cell can be read on a graduated glass tube fixed at the measurement point, and possibly filled against mercury counterpressure.

2. Appraisal

This system is adaptable for all fill dams, in particular where placing of a vertical settlement gauge is not possible, e.g. in the upstream shoulder of a dam. The measuring point must be situated at a lower level than the cell in order that the difference in elevation of the cell with respect to the measuring post can be defined by the hydrostatic pressure (relative to the overflow crest).
As the elevation of the measuring point with respect to the cell must be known with precision the system is somewhat complicated.

3. Possible problems and measurement errors

Entry of foreign bodies into the measuring pipes.
Inadequate deaeration of the measuring water.
Rupture of the tubes due to differential settlements where they cross two types of material in adjacent zones. This limits the use of the system to embankments of moderate height.



Reference number 3.102. Schematic of hose levelling device or overflow gage. 1 Measurement cell, 2 Water overflow tube, 3 Vent tube, 4 Drain tube, 5 Fixed graduated transparent tube, 6 Liquid level to be measured, 7 Supply of deaerated water to cause overflow in the cell.

4. Technical requirements

If possible the measuring cell should be placed on a base plate. The tubes (three per cell) must be continuous, without sleeves or other fittings between the cell and the measurement point. There should always be a continuous slope without high points between the cell and measurement point. The nylon supply and drainage tubes are of 3 to 4 mm internal diameter. The aeration pipe should have an internal diameter of 6 to 7 mm.
The pipes must be placed in the fill on a bed of sand. During placing the pipes must be clearly identified (for instance using colored plastic bands). The entire installation must be fully protected against frost.

5. Checking of operation and maintenance

The tubes must be regularly cleaned and flushed.
Measurement water must be boiled to remove all air.
The reference levels of the fixed graduated tubes must be regularly checked.

6. Redundancy

Redundancy can be obtained by installing an adjacent vertical settlement gauge or by placing at the same point two hydraulic cells with independent systems of tubes.

7. Remarks

This system is relatively expensive compared with the vertical settlement gauges.

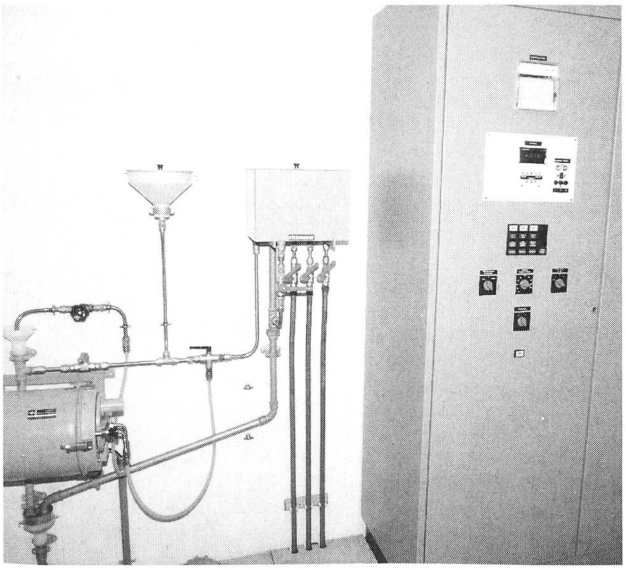
Physical or chemical alterations of seepage water

Turbidimeter

Reference number 3.301

1. Measuring device

This instrument allows the suspended material in infiltration water to be measured at selected points (points of high infiltration outflow or collection points for total infiltration discharges). The turbidity is measured with the aid of a photoelectric cell by the continuous comparison of the diffused light in the infiltration water and in a standard solution (formaline or diatomaceous earth). The standard solution can be introduced into the measuring equipment in different concentrations.



Reference number 3.301. Turbidimeter. Measuring equipment (on the left) for 3 drainage water samples introduced by the 3 supply pipes in the center. The boxes on the right contain the control and monitoring equipment.

The turbidity values (as percentages of that of the standard solution employed) are plotted on a paper band.

2. Appraisal

This is a sensitive instrument which requires frequent checking. It should only be installed where it is really meaningful and where it can be fully protected. However, its records give complete information on the development of the process associated with solids transport by infiltrating water (erosion phenomena, outwashing of grout material, etc.).

3. Possible problems and measurement errors

Obstruction of the supply pipe. Soiling of the reflecting mirror. Defective bulbs. Interruption of the electricity supply. Entry of air into the water sample. Icing up. Introduction of foreign bodies into the infiltration water.

4. Technical requirements

A continuous infiltration flow of 0.2 to 0.5 l/min must be drawn off. Electricity for heating and lighting is required. Protection against condensation, splashing and spray is essential. Where necessary, a coarse settlement basin and ventilation must be provided.

5. Checking of operation and maintenance

Checking the correct advance of the paper strip.
Checking and periodic changing of the bulb.
Cleaning at least once a month of the reflecting mirror.
Checking for obstruction of the ventilation system as well as of the supply pipe (monthly).
Occasional checking by measurement of the standard solution.

6. Redundancy

Periodic chemical analysis in the laboratory of samples of the infiltration water.

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* texte également en français