MONITORING AND INSTRUMENTATION STRATEGIES FOR NEW AND EXISTING DAMS

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ABSTRACT

Regular monitoring assisted by instrumentation measurements is of paramount importance for ensuring the safe operation of dams. The monitoring and instrumentation program should be part of the dam design. The principles that define the monitoring requirements and the design of the necessary instrumentation system include the understanding of the dam behavior during construction and operation, the early definition of probable failure mechanisms, the longevity of the instruments, the ability to replace the critical ones etc. In order for the monitoring and instrumentation system to be effective it should be concise, easy to follow and interpret, adopted to site conditions, and providing the ability for early warning. No instruments should be installed without full substantiation of their necessity. The article presents an overall classification of instruments and the key requirements during construction and during operation. It briefly discusses the case of old dams. It presents some cautionary tales and demonstrates things that can go wrong with instrument placement such as inadequate sealing of cable ditches, inadequately sealed standpipes, cross wiring of electrical instruments etc. Finally it presents briefly the case of instrumentation for existing dams as part of their safety upgrade. Three examples are presented for a very old concrete gravity dam, a rockfill dam with upstream asphalt concrete deck and a high rockfill dam with central core.

1. INTRODUCTION

The frequent surveillance is of paramount importance for the safety and normal operation of a dam. Surveillance is foremost done by visual observation and is assisted by monitoring parameters that provide information on the “health” of the dam. These parameters are measured through instruments.

It is very often that more attention is paid on instrumentation rather than on visual surveillance regardless of the advice given, among others, by Peck (2000).

Over the last 25 years, the advance of instrumentation systems regarding both the abilities of each instrument and the ease of measuring, presenting and transporting data is spectacular.

Unfortunately, the progress in the design of appropriate instrumentation systems to assist dam surveillance and monitoring has not advanced proportionally. Regardless of the importance that is recently placed on monitoring failure mechanisms, the vast majority of dams are fitted with instruments placed mainly on geometrical patterns, without a clear role and purpose. Poor understanding of dam behavior results often in great omissions while at the same time a large number of unnecessary instruments are installed.

This becomes apparent when reviewing a usual dam design report. The relevant chapters are normally exhausted with describing the types and locations of the instruments without any substantiation as to their purpose. Also, in most cases, the Monitoring and Instrumentation Manual is not part of the design but comes later near the completion of construction.

Further still, the lack of understanding the importance of the installation details often leads to situations that can have serious repercussions on the safety of the dam and/or create undue false alarms.

Finally, the Engineer often has the challenge to design a monitoring and instrumentation system as part of the safety upgrade of old dams. These dams often have heavily damaged instruments or no instruments at all. Fitting them with the appropriate system, that will also be able to provide early detection and warning, is critical for their safety upgrade.

The article discusses initially some key principles of surveillance and instrumentation. It then presents some examples highlighting things that can go wrong. Finally, it presents briefly some case studies where old dams had to be fitted with an instrumentation system as part of their safety upgrade.

This article deals only with instruments relating to the safety monitor of a dam. It does not deal with the instruments required for the operation of the dam.

2. PRINCIPLES OF MONITORING AND INSTRUMENTATION

2.1 General

On the monitoring and instrumentation issues there have been many publications and guidelines, the most relevant being those of the International Commission on Large Dams (ICOLD) Bulletins No 60, 68, 87, 104, 118, 138 and 158, the United States Bureau of Reclamation Manuals on Embankment Dams (1987) and on Concrete Dams (1987), the book on Geotechnical Instrumentation by Dunicliff (1993), the United States Federal Energy Regulatory Commission (FERC) Engineering Guidelines for the Evaluation of Hydropower Projects (2018), the Indian Central Warehousing Agency (CWA) and the American Society of Civil Engineers (ASCE) guidelines (2018).

The ASCE publication appears to incorporate the latest trends and state of the art on the matter.

A short but fundamental presentation on the approach to monitoring and instrumentation was made by the late Ralph Peck in 2000.

It is now well established that visual surveillance and instrument measurements should focus on probable failure mechanisms. The probable failure mechanisms should therefore be established and ways of monitoring them should be defined. Instruments could assist in monitoring and providing early detection of developing problems. The reading procedures, the longevity of the instruments, the ability to replace the critical ones etc. are critical considerations during design.

In the case of new dams a detailed report on instrumentation is needed as part of the design, together with a draft Surveillance and Instrumentation Manual covering construction, first filling and operation. The finalization of the manual should be completed before the start of the first impoundment. Incidents that occur following the first impoundment might require additional instruments.

A complete presentation is not possible within the space of an article. In the following paragraphs there are some notes that the author finds useful when designing or rehabilitating monitoring and instrumentation systems.

2.2 Instrument classification with respect to area of measurement

Instruments can be broadly be classified with respect to the information they provide as:

[a] Point Information. That is when the measurement of a parameter represents only the local condition, such as a vibrating wire piezometer or an earth pressure cell installed in the core of an embankment. The information provided by "point" instruments can be used as spot checking in order to investigate the behavior of a construction or foundation material during placement, impoundment and operation. Only by chance they can provide overall information on developing problems during operation. It should be noted that it is the combination of the type of the instrument and its location that makes it a "point" instrument.

[b] Area Information. That is when the measurement of a parameter represents the behavior of a broader area as in the case of a seepage weir at the toe of a dam, a column of magnetic settlement plates in the dam body, a vibrating wire piezometer installed at the base of a chimney drain within the drainage zone, or a fiber optic cable running along a drainage blanket.

This classification is not always obvious and in many cases a "point" instrument provides some area information. It is nevertheless a useful classification to keep in mind when it comes to designing a monitoring system.

2.3 Instruments useful during construction

During construction the instruments serve mainly the following purposes:

[a] Validate design assumptions, such as pore water pressure development, foundation and dam settlements etc.

[b] Assist finalization of design, such as need for additional drainage blankets etc.

[c] Control construction by measuring parameters to ensure design assumptions, such as pore water pressure development in embankment dams, temperature development in mass concrete pours etc.

[d] Check effectiveness of construction, such as watertightness of a diaphragm wall etc.

[e] Provide baseline behavior at the end of construction, such as pore water pressure in the dam body, pore water pressure at the foundation, seepage through the abutments and foundation, verticality of structures etc. This will assist the interpretation of the measurements during operation.

As Peck (2000) noted there is no further need to prove well established theories. A complete site and laboratory investigation can provide very reliable information, particularly for materials over which there is extensive international experience.

Some instruments installed during construction pose a considerable strain on the construction activities, resulting in delays, frequent damages, and defects embedded in the structure. Cable trenches and pipes and cables rising with the dam are the most notable examples.

According to Peck (2000) "… the fundamental rule today should be that no instrument should be installed that is not needed to answer a specific technical question pertinent to the safe performance of the dam."

Exceptions of course should be allowed for research purposes, particularly when dealing with materials or construction technics that are not well documented.

In any case, there is no need to install instruments for reading the obvious. Some redundancy is required but it is good to keep in mind that more is not necessarily better. It easy to be lost in an ocean of instrument readings and difficult to concentrate on the useful and important ones.

The establishment of "zero readings", which is the conditions at end of construction, is extremely useful in the understanding of the measurements during first filling and operation.

2.4 Instruments useful during the operation stage

During the operation stage, the instruments should assist in the safety of the dam by providing key monitoring parameters. The instruments should be able to:

[a] monitor probable failure mechanisms by measuring key indicators,

[b] provide early warning on the development of conditions that could jeopardize the safety of the dam,

[c] check the efficiency of critical components of the dam, such as upstream concrete decks, diaphragm walls, grout curtains, pre-stressed anchors etc.

The simplicity of the instrumentation system and the clarity on the purpose and meaning of instrument readings should be the aim of a good designed system.

In most cases, the most important "instrument" is the measurement of seepage through the dam and the foundation. A well designed system should be able to measure not just total seepage but local seepage through various components of the dam and its appurtenant structures, e.g. drainage under the spillway, drainage through galleries, seepage under upstream membranes etc. Where possible, spatial differentiation should be made in order to detect the source of probable excessive leakage, e.g. separation of seepage through abutments, parts of the valley floor etc. The advances in fiber optic techniques will assist greatly in the detection of the seepage location. Seeping water should be regularly analyzed for sediment content.

Second most important is to measure the movements of the dam and its appurtenant structures. Surface monuments and targets are easy to install, repair and supplement if necessary. Often critical is also the monitoring of abutments and reservoir slopes. The advances in remote sensing using GPS technology is probably the future into monitoring surface movements.

Measurement of water levels in the abutments and the dam body, measurement of pore water pressures, measurement of internal movements etc. also assist in the verification of the dam safety.

Strong motion accelerographs assist in understanding the behavior of the dam during earthquakes and should be installed in high and very important dams.

2.5 Old dams

In designing an instrumentation system for an existing dam, the same principles as above should be followed. Defining the most probable failure mechanisms is the starting point. Known deficiencies and poor performance issues should be closely monitored, particularly when it is difficult to remedy.

In 9 out of 10 cases when dealing with moderately high dams, fitting seepage (and turbidity) monitoring devices and surface monuments on the crest will be the only required instruments.

In the case of high dams and/or high risk dams a more elaborate system might be needed, including stand pipes and point piezometers, tilt meters, inclinometers, extensometers etc.

An interesting and difficult to handle case is that of old large dams where the instrumentation system has been severely damaged by neglect, vandalism, or aging. Although it is tempting to try to restore and replace so that the initial instrumentation is re-instated, this is in most cases unnecessary and potentially hazardous. In such cases it is better to design a new system following the above mentioned principles.

It is again noted that the entity responsible for the operation of the dam and its safety surveillance should be able to handle the installed instrumentation. It is strongly recommended that if the dam operators do not have the capacity and the expertise required for monitoring the safety of the dam, they should employ the appropriate consultants for the job.

3. CAUTIONARY TALES

Some cases where problems occurred with instrumentation are included in this chapter with the hope that they will act as cautionary tales.

3.1 Inadequately sealed cable ditches

Ditches for instrument cables that cross part of the core, or other impermeable zones, have to be extremely well filled and compacted with appropriate clay material. If either the filing material or the compaction is sub-standard, then a path that the water will easily go through is left across part of the core. In ditches with vertical walls there is potential for arching causing low total stresses along the ditch. Then the reservoir water can pass through by hydraulic fracture.

This condition is met in many earth dams where the cables of instruments installed near the upstream face of the core (piezometers, earth pressure cells etc.) are carried through ditches to the upstream filters and then rising towards the crest.

An example of a 60m high earth dam from Europe is presented in Figures 1 and 2. Vibrating wire piezometers installed at the upstream part of the core register reservoir pressure with practically no delay. Piezometers located at the center of the core respond with considerable delay registering pressures corresponding to the theoretical flow net.

In Figure 1, piezometers Pz6 and Pz9 follow closely the reservoir level because their cables go through apparently not well sealed ditches to the upstream face where full reservoir pressure acts. Piezometers Pz7 and Pz11 whose cables are taken towards the downstream face of the core exhibit the expected behavior for a low permeability core.

In Figure 2 a similar behavior is observed with piezometer Pz17, while piezometer Pz 18, located at the downstream part of the core and linked to the downstream face shows very little response.

Just seeing piezometer readings, without noting the route of the cables, can create the wrong impression on the permeability of the core and the safety of the dam.

This behavior has been observed in many dams and one wonders if no instruments should be installed at the upstream half of the core with cables driven towards the upstream face.

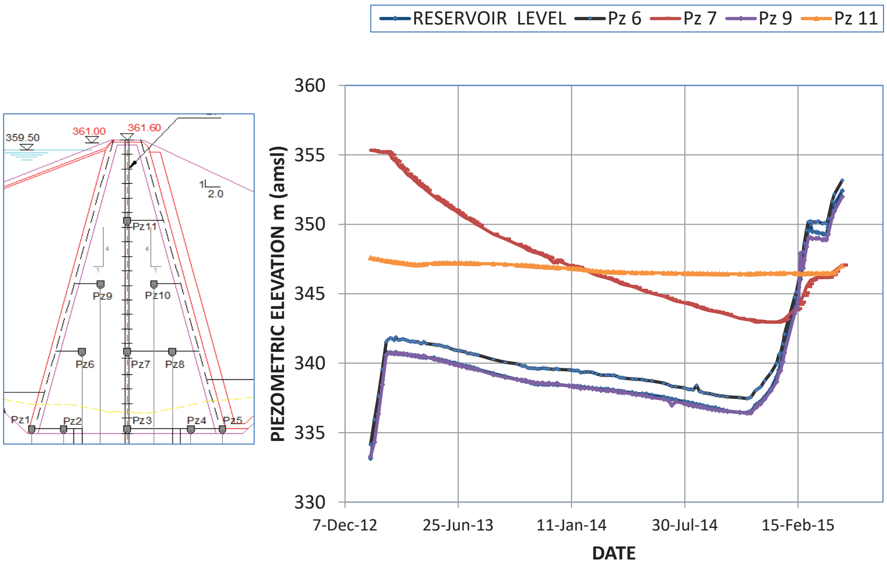

Figure 1 : Pz6 and Pz9 linked to the upstream face of the core, Pz7 and Pz11 linked to the downstream.

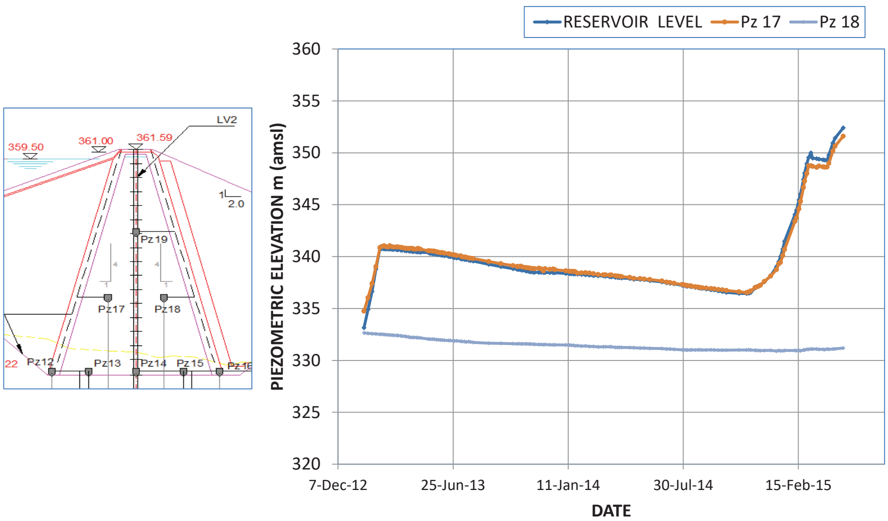

Figure 2 : Pz17 linked to the upstream face of the core, Pz18 linked to the downstream.

3.2 Inadequately sealed standpipes

When the top few meters of the borehole for an observation well or a standpipe is not properly sealed rain water can seep through and fill the pipe giving false readings of very high water levels.

This is very common but it is frequently overlooked. It has occurred in a few dams creating false alarms. In a 135m high earthfill dam with central core in Europe there were three locations where very high water levels were reported that after close examination were caused by incomplete sealing:

[a] At a stabilized landslide on the right abutment just upstream of the dam water level close to the surface was reported indicating very low factors of safety against sliding. It was proved that actual water level was considerable lower.

[b] At the center of the core of the dam, the inclinometer column was registering high water levels that were initially attributed to connection with the reservoir, causing concerns on the integrity of the core. The top of the column was not properly sealed and examination of nearby vibrating wire piezometers showed that the core was impermeable and in good condition.

[c] At the downstream right abutment an observation well showed water level close to the surface. When replaced by a properly sealed standpipe the measured water levels were considerable lower.

3.3 Improperly installed inclinometer columns

Installing vertical columns that are raised together with the dam is a difficult operation affecting construction. Placement of combined inclinometer casing with magnetic rings/settlement plates is very common in earth dam construction. Extreme care is required in order to protect the column from the moving plant and to compact adequately around it with small compaction equipment. Key elements for a successful construction of these columns in order to ensure longevity are:

[a] Use of long telescopic joints, fully extended when fixed to the casing segments.

[b] Perfect verticality of the column.

[c] Adequate protection with high well marked scaffolds.

In many dams not all three above conditions are met resulting in frequent breakage of the casing. In one particular high dam a column had to be replaced to full depth twice during construction and still the final column is not operational at full depth.

Most of these combined inclinometer-settlement plate columns serve mainly to provide information during construction. It is very seldom that inclinometer measurements are meaningful in the long term, mainly due to difficulties in maintaining a well calibrated reading unit. Magnetic settlement plates though are easier to read and can provide very useful information long term.

On Figures 3 and 4 there are examples of two earth dams in Europe where considerable damage to the columns occurred because not all three of the above conditions were met. In Figure 3, for a 75m high dam with central core and shoulders made of relatively soft shales, nearly all columns are blocked at relatively small depth. Not even the thin probe for detecting the magnetic settlement plates can pass.

On Figure 4, for a 125m high earth dam with central core and river gravel shoulders the first column placed in the core is blocked at a depth of 32m and its replacement is blocked at 42m depth.

In both cases the maximum settlement in the core during construction exceeded 1m.

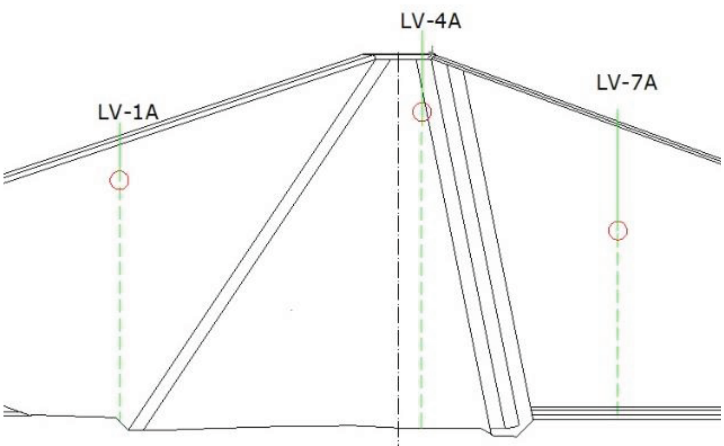

Figure 3 : Earth dam 75m high. Inclinometer tubes blocked LV1A at 9m, LV4A at 11m and LV7A at 22m

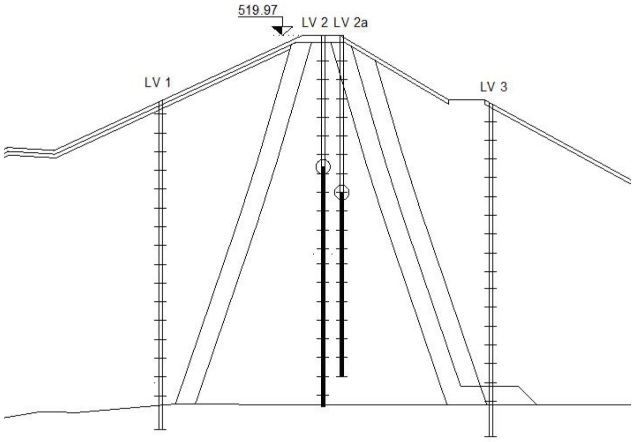

Figure 4 : Earth dam 125m high. Inclinometer tubes blocked LV2 at 35m and LV2a at 42m depth.

3.4 Cross wiring

When dealing with a large number of electrical instruments installed in the dam body, one has to be extremely vigilant with proper marking of the cables in order to avoid cross wiring and therefore erroneous readings.

When analyzing instrument readings you often come across to peculiar measurements that seem out of place, make no sense or even be alarming. This situation usually arises during construction and during first impoundment and is normally resolved thereafter.

A frequent reason for this is cross wiring. Two examples from Europe are presented in Figures 5 and 6. In Figure 5 piezometer Pz18 records built up of high construction pore pressures in the upstream clay shales shoulders of the dam well beyond the time that the full overburden was constructed over the instrument. Such high built up of pore pressure is only possible in the core, where high placement water content was used and load was continuously placed above the instrument (similar to Pz101) till the end of construction.

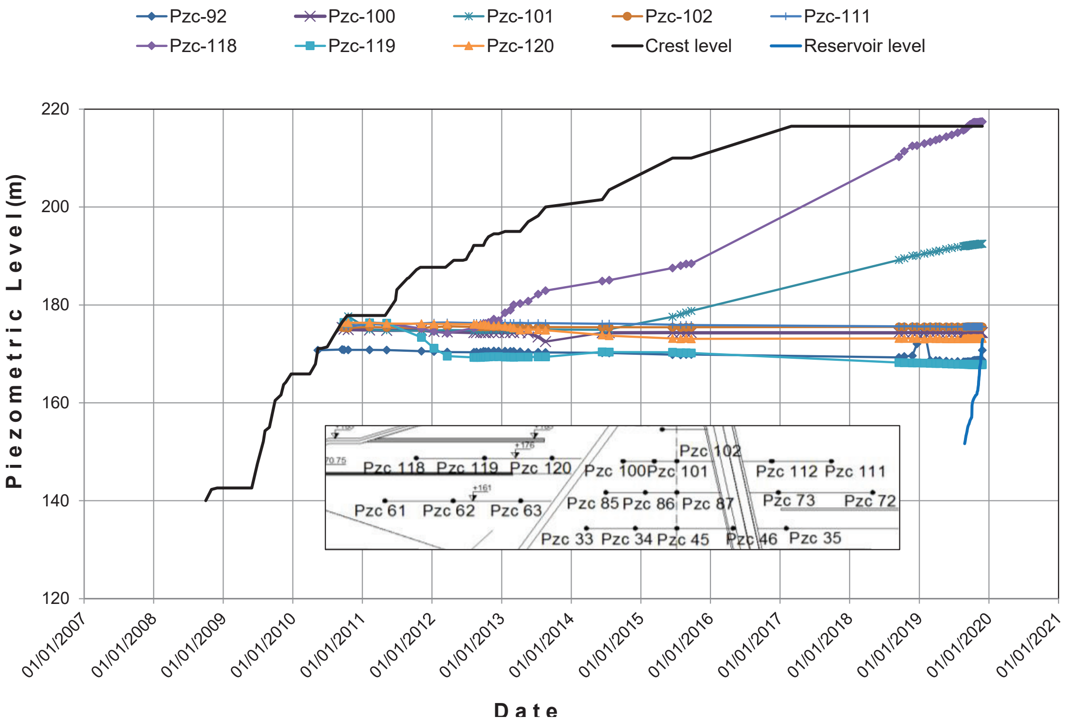

Figure 5 : Piezometer Pz18 clearly cross wired with a piezometer from the core.

In Figure 6 piezometer Pz35 records built up of high construction pore pressures at the downstream clay shales shoulders of the dam. Again and for similar reasons as above it must be cross wired with a piezometer from the core.

This dam is now filled for the first time. The situation will most probably be clarified and corrections will be made.

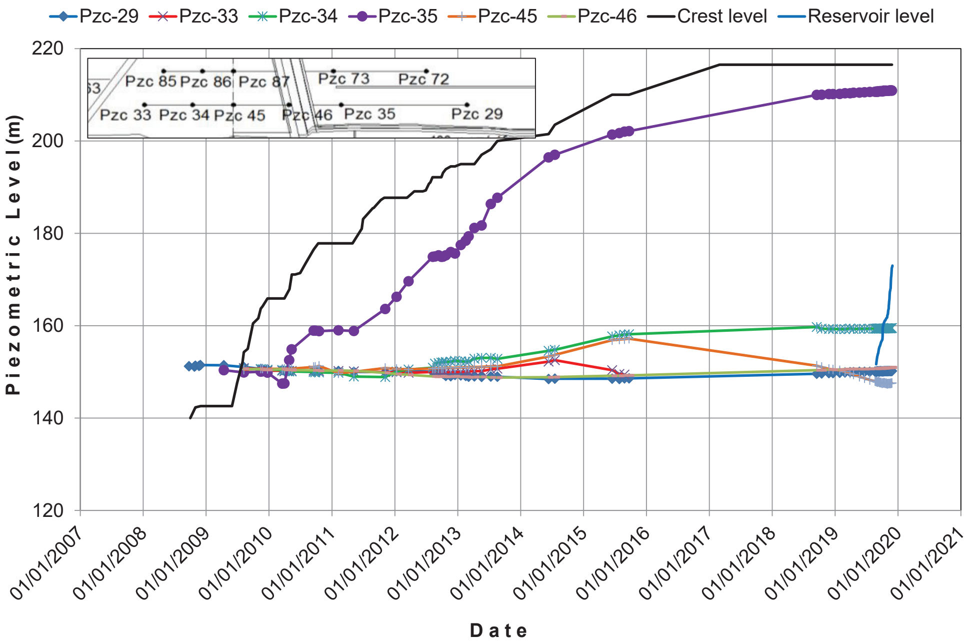

Figure 6 : Pz35 most probably cross-wired with one of the core piezometers.

3.5 Poor surveying of surface monuments

High precision topographic survey is needed when measuring surface monuments. Simplified methods of triangularization give very poor results often appearing as noise when plotted with time.

One would assume that with the available high quality hardware and software, results with an accuracy of, let's say, 1cm or less would be commonly achieved. It is nevertheless frustrating at times when the results plot as random numbers.

In many dams, surface monument survey has stopped a few years after construction. But earth dams settle forever and gravity dams move following the reservoir fluctuations, leaving a tiny permanent displacement.

The need to know the current crest elevation and to exclude the possibility of development of alarming displacements, makes it crucial to measure the movements of the dams at least once a year with high accuracy methods.

3.6 Orphan accelerographs

Arrays of strong motion accelerographs are installed in high dams for many decades, particularly in highly seismic areas. During dam safety inspections performed over the last two decades it was noticed that in the majority of dams the operation of accelerographs was problematic. There were long periods of no readings, failing thus to record strong seismic events, and occasional complete failure of some or all of the instruments.

The main reason for the problems was that the dam operators lacked the expertise required into caring for the instruments, download the readings and interpret them Understandably it is not feasible for many dam operators to have in-house capabilities for maintaining and using properly the accelerographs.

In some cases new instruments were installed and the dam operators were advised to employ an agency specializing into monitoring and research of earthquakes for the management of their accelerographs. These agencies are often willing to assist in the placement of the instruments and are better to be employed early on, before the finalization of the construction.

4. CASE STUDIES OF OLD DAMS

4.1 A very old gravity dam

As part of the safety upgrade of a very old 60m high concrete gravity dam in Europe, the question of instrumentation was raised. There were no instruments installed on the dam.

The dam is in very good condition without discernible deformation and very little seepage through the dam body and the foundation. Its location, a few kilometers upstream of a city, makes it a high hazard dam.

Two main failure mechanisms were considered. The first involves high seepage through the abutments destabilizing the structure. The second involves damage due to very big earthquake that will cause failure of concrete blocks near the abutments.

An instrumentation system was designed comprised of:

[a] Five (5) seepage measuring chambers located at the toe of the dam, one on each abutment, inside the central dam drainage gallery and at the exit of two tunnel in the abutments.

[b] Thirty (30 in total surface deformation monitoring targets on the dam body, at the abutments, on the spillway and the intake tower.

[c] Seventeen (17) tilt meters on drainage and inspection shafts, some one and some two dimensional.

[d] Eleven (11) crack meters at the block joints inside the drainage and inspection galleries.

[e] Five (5) strong motion accelerographs.

With the exception of the surface markers and some crack meters, all other instruments are fitted with transducers linked wirelessly to the central dam service building. There, a data logger will be programmed to make immediate assessment of the measurements and transmit automatically alert signals.

A rather large number of instruments were designed due to the high hazard classification of the dam.

4.2 An old rockfill dam with asphalt concrete deck

Instrumentation has to be designed as part of the safety upgrade of an old 56m high rock fill embankment dam with upstream asphaltic concrete facing, located in Eastern Africa.

The construction of the dam included an instrumentation system comprising of:

[a] surface monuments and markers along the crest and the abutments,

[b] water level observation wells on the abutments, and

[c] seepage chambers to measure the water coming from the dam underdrains.

The seepage collection and measuring arrangements were very carefully designed and well-built, but suffered from vandalism and neglect. The observation wells were all blocked and therefore inoperable. The surface monuments were not measured for many years.

The dam body was in a good condition overall, the total seepage was very small for the size of the dam. There were no discernible deformations along the crest and the dam slopes.

The failure mechanisms considered involved high leakage due to damage of the upstream deck either by a strong earthquake or due to deterioration of the asphalt concrete.

It was decided to reinstate the original instrumentation system, as it was in the original design and to not add additional instruments.

The site is well managed by the dam operators and frequent surveillance together with the instrumentation will ensure the safety of the dam.

4.3 A high rockfill dam with clay core

A very interesting case was presented during the safety upgrade of an 110m high and 850m long rock fill embankment dam with central core, located in Eastern Africa.

This is a well designed and constructed dam with an extensive array of instruments installed consisting of electric piezometers (Maihak vibrating wire), standpipe piezometers, earth pressure cells, vee-notch seepage measuring weirs, settlement gauges (USBR type), extensofor borehole extensometers, surface monuments, main dam distometer monuments, seismographs etc.

Unfortunately, with the exception of the vee-notch weirs, no instrument was operational due to either vandalism or lack of the appropriate readout units. Nearly all vertical casings were fully blocked (standpipes, settlement columns, borehole extensometers). The instrument houses collecting the electrical instruments appeared in good order but the readout units were missing. Extensive vegetation had developed at the toe of the dam prohibiting free drainage and easy access to measuring units.

Two main failure mechanisms were considered. The first involves internal erosion of the core of the dam escalating into piping. The second involves slope failure and or excessive settlement due to extreme earthquake.

The following actions were recommended for the instrumentation:

[a] rehabilitate all instruments in the dam body that are not completely damaged,

[b] rehabilitate all seepage measuring chambers by removing vegetation, draining, cleaning and fitting properly installed rulers,

[c] acquire the suitable probes and readout units for measuring the installed instruments,

[d] rehabilitate or replace the seimographs, and

[e] re-evaluate the situation in 5 years.

No new instruments were proposed to be installed in the core to replace the damaged ones. The total seepage was estimated at 4lt/sec, a value very satisfactory for the size of the dam. As the overall condition of the dam and its performance is very good, there is no need to risk damage by installing rather unnecessary instruments.

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