Experiences from the installation of geotechnical instruments in dams

Expériences par l'installation des instruments géotechniques dans des barrages

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ABSTRACT
The paper presents experience gained with geotechnical instruments installed in several Greek dams that were built during the last few decades. The encountered problems and the applied practices are addressed. A list of many issues faced during installation and operation, according to the instrument type, is presented. Proposals are made in order to improve instrumentation practice.

RESUME
Ce papier présente les expériences obtenues par l'installation des instruments géotechniques dans plusieurs barrages grecs, construits pendant les dernières décennies. Les problèmes rencontrés et les pratiques appliquées se sont rapportés. Une liste des plusieurs cas affrontés pendant l'installation et l'opération est présentée, selon le type des instruments. Des propositions sont faites pour améliorer la pratique d'instrumentation.

Keywords: geotechnical instruments, damsDams, geotechnical instruments, monitoring

1. INTRODUCTION

Dam engineers are aware of problems associated with malfunctions of geotechnical instruments installed in dams, which have in some cases led to false alarms, or, even worse, failed to provide early warnings about developing instabilities. Most of these problems could have been avoided if the whole procedure (design, installation and monitoring) did keep in line with guidelines provided by the manufacturer, as well as by the technical literature available [Dunicliff, 1993; USBR, 1987; ICOLD bulletins].

This paper presents in brief some of the problems concerning instrumentation, encountered in several earth and rockfill dams that were erected recently in Greece. The current practice is discussed, and, where appropriate, proposals are made on how to improve current practice.

2. PROBLEMS AND PROPOSALS

Table 1 presents important issues to be addressed for various measuring devices. A reference code is being assigned to each case that is commonly a source of problems, with the first letter referring to the relevant project phase (i.e. design, installation or operation).

2.1 Design Phase (D)

Most of the problems encountered could have been avoided by careful consideration, during the design, of every aspect of instrument installation and operation. The following present some broad guidelines on the design of dam instrumentation:

- Instruments should be placed in order to measure parameters critical for dam safety at places of specific interest, taking into account the size and importance of the project and the ground conditions. Instrumentation should be oriented towards providing answers to specific questions concerning dam safety, and not just proving the validity of well-established geotechnical theories (Peck, 2001).
- Instrument placement is often a nuisance during construction. The instrumentation layout has to be simple and robust. When possible, instruments that obstruct construction should be avoided.
- The number and type of instruments placed should conform to the human resources (number and training of the personnel) available on site during construction and operation.

The aforementioned principles may apply into the design practice as follows:

Specifying the instrument type necessitates the estimation of the minimum and maximum values to be recorded (pore pressure, deformation, settlement etc). The measuring range usually also dictates the accuracy/sensitivity (**D1**). The range of interest during construction may differ from that during dam operation. At Papadia dam (67m high rockfill dam), a 35m deep cut-off diaphragm wall (D/W) was constructed under the dam core in pleio-pleistocene deposits down to the sound bedrock. Numerous vibrating wire piezometers were installed in order to monitor pore pressures developing in the foundation during reservoir filling and project operation. However, pumping tests were performed in order to test the water tightness of the D/W, before fill placement. During these tests a significant number of the instruments provided erratic data (Fig. 1), necessitating cross-checking of their records by installing several new standpipe piezometers and repeating the pumping tests.

The erratic measurements were mainly attributed to the fact that the pore pressure values were close to the sensitivity of the vibrating wire piezometers, since their measuring range and sensitivity was selected to conform to the high head conditions established in the foundation after reservoir filling. A better choice would have been to provide two groups of vibrating wire piezometers: one with a low range to assess the effectiveness of the D/W, and another with a high range to provide information during first filling and operation.

Selection of the suitable piezometer type is also a matter of debate (**D2**). Vibrating wire piezometers tend to be more and more popular, but their use is not always justified.

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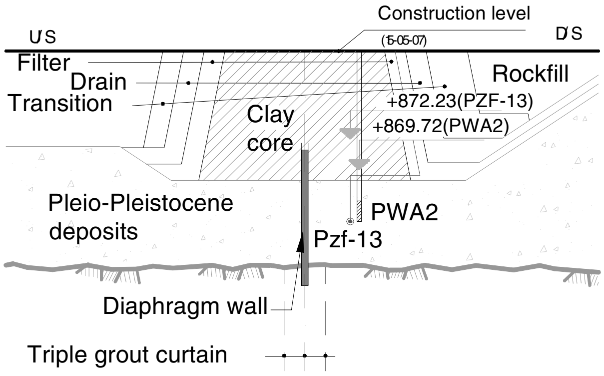

Figure 1: Papadia dam - Cross-checking of vibrating wire piezometer Pzf-13 erratic readings with standpipe piezometer PW-A2

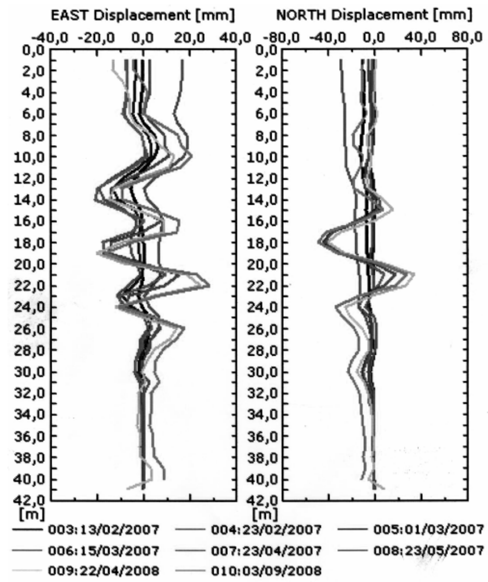

Figure 2: Typical inclinometer deformation pattern indicating inadequate grouting around the casing

In the case of the 21m high Aghia Barbara earthfill dam on a permeable foundation, the design provided for a number of vibrating wire piezometers, in the foundation. As variations of the water table after construction were anticipated to be rather small, and having in mind the Papadia experience, it was decided during construction to replace vibrating wire by standpipe piezometers. The performance of these piezometers was proved to be very successful, adequately recording water table fluctuations during reservoir first filling and operation and providing useful information for the effectiveness of the cement-bentonite diaphragm wall in the foundation.

Seepage is probably the most critical parameter concerning dam safety and operation and the simplest and most reliable way to measure it is by means of collector pipes and measuring weirs (Peck, 2001). These devices can provide very important information (such as the exact quantity of seepage though the dam and foundation, the clarity of the seeping water etc.) and should be installed in every dam. In Smokovo (rockfill dam, 109m high), a measuring weir was not provided by design. The embankment was built 5 years before first filling, and skepticism was expressed concerning dam safety, mainly due to inadequate construction records available. A seepage measuring weir was deemed necessary and was constructed right before reservoir filling, providing confidence during first filling.

When measurement of vertical settlements in the core is considered of paramount importance (**D3**), settlement gauges (hydraulic or other type) might be a safer, although more expensive, solution than combined inclinometer – settlement gauges (referred to herewith as IDEL instruments). At Ilarion (a 130 m. high earthfill – rockfill dam), where both types of instruments (IDEL - hydraulic settlement gauges) were placed close to each other, settlements recorded were quite similar. Leakage paths may form along the IDEL casings, due to inadequate compaction around them (Peck, 2001; Dunicliff, 1993). If such instruments are damaged and inoperable, it is better to fully plug them with suitable grout before filling the reservoir.

Drawings and specifications should include details and instructions to ensure correct installation. Efficient grouting around instruments installed in boreholes is essential; otherwise gaps may permit ravelling or collapse of the borehole walls, resulting in deformations and false records (**D4**). Unreliable records of movements in inclinometers, of the zigzag pattern depicted in Figure 2, are quite often (here from the abutments of Thissavros, a 172m high rockfill dam). When installing these instruments in highly disturbed rock, pre-grouting the hole, re-drilling and water testing should be the recommended practice.

For nested piezometers (multiple piezometers installed in one borehole), insufficient grouting means insufficient sealing of each piezometer tip, leading to identical readings (**D5**). In order to avoid this, each instrument can either be placed in a separate hole or, for diaphragm type piezometers, the fully-grouted method (Dunicliff, 2008) can be applied. The effectiveness of the traditional method of sealing with bentonite pellets above the sand-pack is lately disputed especially in jointed rockmasses, due to the tendency of the bentonite pellets to arch part-way down the borehole.

To avoid couplings in electrical piezometers cables and hydraulic settlement gauges tubes and minimise bends, cable and tube routes and the total length for each individual instrument should be clear in the drawings (**D6**).

In order to give reliable measurements, surface monuments and in particular strong motion recorders need a stable foundation, preferably anchored (**D7**).

Access roads and facilities for the measuring crew (as well as to a buggy, if necessary) must be ensured in the design (**D8a**). On the other hand, instruments should be, as far as possible, not easily detected or accessible by unauthorized people, in order to be protected against vandalism. Moreover, the location of the instruments should be safe against natural hazards (rockfalls, slides etc – **D8b**).

The time of installation must also be clearly specified particularly in relation to works that might harm them (**D9**). At Papadia dam, the additional grouting that had to be done close to installed vibrating wire piezometers, resulted in destroying some of them.

Instrument materials may also be critical and should be specified in the design (**D10**). Plastic tubes and casings were found generally preferable to metallic ones, since they are more durable, lighter, more flexible and easier to install or remove (if re-drilling of the hole is needed). They have, though, to be protected against rodents attack. Aluminium inclinometer casings were subject to corrosion attack problems, either by groundwater or by cement grout. At Thissavros dam, corrosion of aluminium casings close to the water table occurred a few years after instrument installation. At Smokovo dam, the aluminium casings were destroyed so quickly that no measurements were ever taken.

Vertical instrument cables must be placed in segmental corrugated pipes (ARMCO type), preferably coming in nestable half sections (**D11**). The diameter of these riser pipes depends partly on the number of cables, but should be large enough to be filled with sand and to resist excessive deformations.

Table 1: Important issues to be addressed for various measuring devices

	Flow measuring weir	Vibrating wire piezometers	Open standpipe piezometers	IDEL instruments	Inclinometers	Strong motion recorders	Settlement Gauges	Extensometers	Surface monuments	Load Cells
Instrument range and sensitivity (D1)		•		•		•	•	•		•
Selection of instrument to measure pore pressures (D2)		•	•							
Selection of Measuring settlements in the dam core (D3)				•			•			
Grouting for stabilisation (D4)			•		•	•		•		
Grouting for water sealing (D5)		•	•							
Avoiding cable couplings (D6)		•					•			
Stable anchoring (D7)						•			•	
Safe access and protection (D8 a & b)	•	•	•	•	•	•	•	•	•	•
Succession of construction works (D9)		•	•	•	•		•	•	•	•
Selecting instrument material (D10)			•	•	•					
Protective ARMCO type pipes (D11)		•				•				
UPS provision (D12)						•				
Anti-lightning protection (D13)		•				•				•
Use of telescopic couplings (D14)				•						
Protecting casings in rockfill (D15)				•						
Scheduling measurements (D16)	•	•	•	•	•	•	•	•	•	•
Installation record, labelling and signalling (I1)		•	•	•	•	•	•	•	•	•
Verticality of installation (I2)				•						
Referencing instrument to a stable point (I3)				•						
Ensuring water tightness (I4)		•	•							
Avoiding reading errors (Om1)	•	•	•	•	•	•	•	•	•	•
Attributing measurements to the correct instrument (Om2)		•					•	•		•
Avoiding errors in piezometer measurements (Om3)		•								
Avoiding effects of traffic on measurements (Oa1)									•	
Provision of assessment software (Oa2)				•	•					
Assessment assumptions (Oa3)				•						

Strong motion recorders should be provided with UPS, as the memory of the recorder fills up in case of successive power supply interruptions (**D12**). All electrical instruments have to be protected against lightning during construction and operation of the project. A number of malfunctions in vibrating wire piezometers (Loutros, a 50m high rockfill and Papadia dams) have been attributed to that reason (**D13**).

For IDEL instruments telescopic couplings are preferable, since they provide better guidance for the wheels of the measuring probe in the slots and allow higher settlements without casing breakage (**D14**). Settlement collars should be placed right below the couplings, allowing free sliding, compatible with the settlements of the fill. Malfunctions due to inadequate available sliding margins have been recorded in Messochora (a 150m high CFRD dam) and Evinos (a 126m high earthfill dam). In the latter case, all casings in the core broke at almost the same elevation, probably under the same strain conditions.

The casings of IDEL instruments placed in rockfill have to be well protected by enveloping the casing with several co-centric filter layers, with gradually increasing particle sizes (**D15**), a difficult task as it has to be done by hand. Moreover, metallic cross-arms of a significant length must be attached to the settlement collars, well embedded in the fill, so that the settlements measured should be that of the embankment and not of the filter column surrounding the casing.

The frequency of measurements should be defined by the design, as well as by the alert-alarm limits for every instrument (**D16**). The frequency of measurements should be adjusted so that production of big volumes of data, and the consequent demand for assessment, is avoided. The decision on the provision of an automated data acquisition system must be made by considering, among other factors, the human resources available and the number and importance of instruments to be monitored. These systems are still very sensitive and set false alarms, but their advantages with respect to continuous time-histories, real time monitoring and low operational cost, will render them common practice in the near future.

2.2 Installation phase (I)

The installation of instruments should be done according to the design and the instructions of the manufacturer, under close supervision and in cooperation with the design team. Where practicable, the manufacturer should train the personnel and supervise installation. Instruments installed in the dam body, and in particular in the core of embankment dams, should be placed with great care, since their restoration or even replacement in case of malfunction is much more difficult and in some cases not possible.

A detailed installation record should be kept for each instrument. Immediately after installation, instruments should be named for future reference (this holds especially for extra instruments, not provided by the original design), be properly labelled, marked and protected, in order to avoid damages by the construction plant (**I1**).

IDEL instrument casings, which are raised with the fill, should be kept as vertical as possible during installation (**I2**), in order to prevent bending due to the unavoidable deformations that occur during fill construction. In the case of Ilarion dam, the significant deviation from verticality rendered them, very soon, impossible to measure. Moreover, the precise coordinates (x,y,z) of each new settlement collar should be recorded immediately after installation, with reference to a stable positioning monument, well outside of the dam body. This helps greatly if the IDEL instrument casing is sheared or obstructed at some intermediate point, making the lowest magnetic plate (which is usually taken as a reference point) not accessible (**I3**). Malfunctions of this type were recorded in several dams (i.e. Messochora, Thissavros, Gratini, and, more recently, Ilarion and Papadia).

It is essential to stop precipitation and surficial water from entering the piezometer tube in standpipe piezometers (**I4**). This is the case if the instrument head is not well isolated (not embedded in concrete or when the casing is not protruding adequately out of the soil). Careful filling of the annulus between the borehole and the casing with cement mortar or grout, up to the very top is also essential.

2.3 Operation phase(O)

2.3.1 Measurements (Om)

Erroneous readings are a common problem. If recording “manually”, measurements should be double-checked and compared to the latest ones, when on site. Usually, readings are not expected to greatly vary without good reason, this being more so after dam completion. The recording crew should check carefully such cases and the information should be immediately passed on for data assessment (**Om1**).

A common error is the recording of the wrong instruments (**Om2**). When allowed by the advances in technology and the budget of the project, a data logger system helps to avoid these errors. However, during construction, many cables or tubes tend to end up in the same place, usually bearing just a small non – waterproof, hand-written label with the instruments name. This label can be easily damaged and be possibly replaced erroneously. A request should be addressed to the manufacturers in order to provide these instruments with a digital signature so that they can be accurately detected.

For standpipe piezometers (**Om3**), it is quite common to get erroneous measurements due to moisture that is present on the walls of the casing or on the measuring device, so producing a wrong signal. Another problem, commonly observed, is getting erroneous readings due to using measuring tapes that were cut and subsequently clumsily restored, missing some centimetres or even meters that the measuring crew was unaware of.

If instruments heads are left uncapped, some peculiar problems may arise. This was the case at Thissavros dam, where insects (wasps) had entered uncapped extensometer slots, constructing nests in them, so affecting measurements.

2.3.2 Data assessment (Oa)

Data assessment demands the participation of experienced and trained personnel that will consider all the conditions applying during the measurement and investigate all possibilities to avoid wrong conclusions. The data assessment team should be in contact with the design team and be aware of the concepts of the design. For example, if an instrument stops functioning they should be able to judge whether the information it provides is significant and if has to be replaced.

Data assessment should start right after instrument installation, so that the reliability of the instrument is assessed as soon as possible and false alarms by problematic instruments are avoided during operation. Even the cause of the failure or the malfunction of an instrument should be assessed because it may give valuable information. For example, vibrating wire piezometers readings may drift off when their cables are sheared (if they are not given enough slack) when passing from intensely deforming zones.

Surface monuments placed close to roads are commonly influenced by pavement construction works and heavy traffic (case reported in Pramoritsa dam). This problem can be solved by taking measurements right before and after the works (**Oa1**).

For inclinometers and IDEL instruments, where the measuring points are numerous, the manufacturer should supply an appropriate presentation and evaluation software (**Oa2**), compatible with the commercially available ones (spreadsheets etc).

For IDEL instruments placed in a compressible foundation (weak rocks should also be considered as such), the elevation of the lowest settlement collar should not be considered to be fixed (especially if under a high embankment like Ilarion dam), unless the embedment depth in the underlying sound bedrock is significant (**Oa3**). In order to overcome this problem, as far as possible, settlements should be double checked with reference to the elevation of the upper settlement collar (taken by surveying methods).

Finally it should be noted that contrary to experience from other dams, load cells installed in Greek dams (Thissavros and Evinos) appear to work well, providing reasonable measurements.

3. CONCLUSIONS

Facing numerous incidents concerning instrumentation problems in Greek dams provided the experiences outlined. The manufacturers should note that the dam instrumentation will benefit a lot from:

- Provision of a way to identify each electrical instrument, e.g. a unique signal response
- Automated data loggers for all instruments
- Development of instruments that will minimise obstruction to construction activities (wireless signals?)

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