International Workshop on
The Present and Future in Health Monitoring

Bauhaus-University Weimar, Germany, September 3^{rd}-6^{th}, 2000

HEALTH MONITORING OF ARCH DAMS
RECENT DEVELOPMENTS

by Eng. Matteo Bianchi and Dr. Eng. Roger Bremen
Lombardi Engineering Ltd, Minusio (Switzerland)

July 2000

TABLE OF CONTENTS

Health Monitoring of Arch Dams – Recent Developments

Matteo Bianchi
Consulting civil engineer

Lombardi Engineering Ltd., Via R. Simen 19, CH – 6648 Minusio, Switzerland

ABSTRACT
Due to the considerable damage potential in case of failure, arch dams are among the most systematically monitored of civil structures. Although the first monitoring instruments were installed in arch dams more than 70 years ago, new approaches and methods are currently being developed concerning the management, analysis and evaluation of monitoring data.

After the presentation of some basic concepts, the characteristics, advantages and limits of deterministic and statistic monitoring models are discussed.

Two case studies will be presented illustrating modern practice in arch dam monitoring. In particular, the role of monitoring in the early detection of abnormal structural behaviour will be discussed.
Some actual limits and needed developments in health monitoring applied to arch dams will complete the presentation.

KEY WORDS
The relevancy of the following aspects will be pointed out:
Health monitoring of dams - Strategies for assessing dam behaviour - Statistical, deterministic and combined models - Reference deformation

1. INTRODUCTION

Being well aware of its responsibility in the domain of dam safety, the Swiss Government has put in place a rigorous, global safety concept for dams and entrusted the Federal Office for Water and Geology (FOWG) with the supervision of it.

Before addressing the main topic of this paper, it is appropriate to recall that the **Swiss dam safety concept** is based on the three following main aspects:

- **structural safety**;
- **monitoring**; and
- **the emergency concept**.

It is well known that the goal of dam safety is to provide the best possible protection for the population that would be affected in case of failure. We can say, in a few words, that structural safety, based on an appropriate design, is intended to minimise the risk of danger, whereas both monitoring and the emergency concept to help master the remaining risk.
This latter condition can only be achieved by an accurate and systematic assessment of the condition of the dam and, in particular, of its behaviour. And in addition, emergency measures must be prepared beforehand in order to act appropriately and promptly in case a threat is recognised.

The scope of this paper is to present a number of remarks and comments on modern health monitoring of concrete dams, which is of primary importance – but is not the only aspect – within the entire safety concept.

2. ELEMENTS OF DAM HEALTH MONITORING

The goal of monitoring is to identify, as soon as possible, any abnormality which could be a forerunner of some upcoming danger in order to allow sufficient forewarning for the implementation of appropriate corrective measures.
To accomplish this, the following tasks are needed (**Fig. 1**):

- **regular assessment of dam condition and behaviour**; as well as
- **periodical safety evaluations**.

Regular assessments serve, in particular, to monitor the current "health" of the dam, whereas periodical safety evaluations serve to analyse long-term behaviour in order to detect abnormal trends.

To identify the existence or the appearance of an anomaly, both of the following types of observation are necessary (Fig. 1):

– **visual inspections**, direct/on-site or remote; and
– **measurements**, including manual readings (on-site), i.e. instrument readings during the regular measurement round, and/or automated readings (remote), i.e. electronic recordings.

In addition, operating tests are needed from time to time to verify the condition of gates and valves.

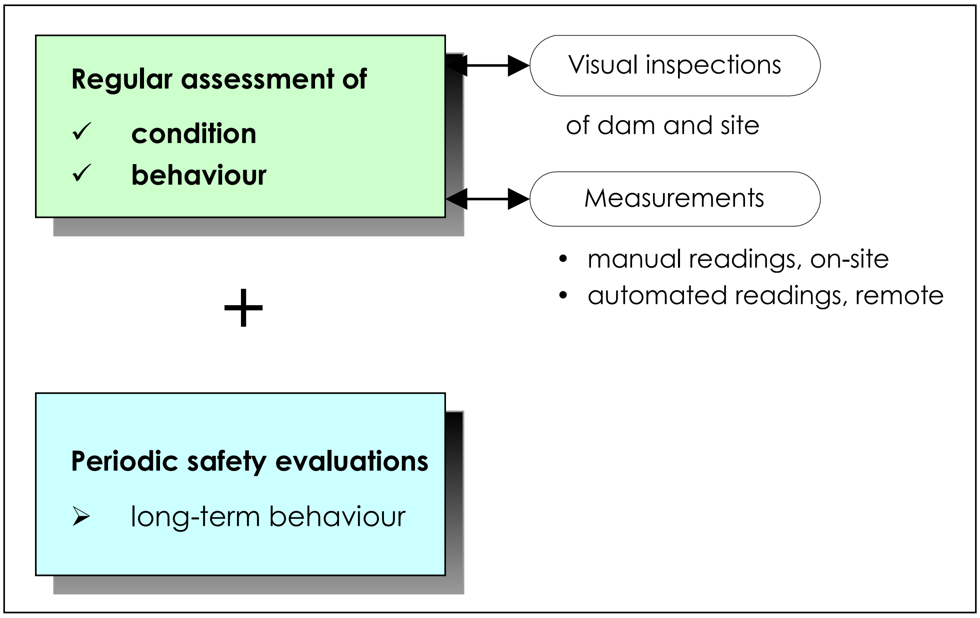

Fig. 1: Elements of health monitoring for dams

3. GENERAL STRATEGY FOR DAM MONITORING

The supervision of the structural behaviour is ensured, in principle, by the following procedure:

- Acquisition of the monitoring information, i.e. instrument measurements as well as qualitative information from visual inspections;
- Interpretation and assessment of the information;
- Taking decisions;
- Archiving the results.

The aim of the timely detection of any abnormal behaviour of the dam or of the monitoring instrumentation does not necessarily imply frequent monitoring or the collection of a great deal of data. It is, rather, of primary importance that information be representative of the behaviour of the dam and of its foundations and, above all, that it be accurately interpreted.

First of all, an immediate series of plausibility checks of the measurements obtained from instruments is required. This aims to avoid interpreting and archiving erroneous or incomplete data. Once the data have been checked and validated, they can be processed, analysed and finally interpreted. This operation should be done not only by the dam wardens but certainly also by an experienced civil engineer.

The interpretation of the available information is, in fact, the keystone of the health monitoring. Particular effort - both brain power and financial resources - should be devoted to this fundamental phase.
Two opposing dangers have, in fact, to be taken into account:

– underestimating a real problem, i.e. being satisfied with the collected values too early; or
– overestimating any deviation with respect to the expected value and hence predicting imminent dam failure.

Both erroneous assessments could result as a consequence either of an excessively optimistic or pessimistic nature of the person in charge – in conjunction with a lack of critical ability – or of deficiencies in the numerical model used for the interpretation.
No doubt that the latter source of wrong assessments is the most important and for this reason it will be focused on in the next section.

4. INTERPRETATION OF MONITORING INFORMATION

The only way to assess the available monitoring information is by comparing it with a set of references, or to be precise, with the numerical model of the dam. Appropriate analytical tools are thus needed.

There are two well-known philosophies for the interpretation of monitoring information:

- **the statistical model**; and
- **the deterministic model**.

The statistical model establishes relationships between the present and the past behaviour of the dam. The accuracy of this approach depends on the amount and reliability of the available data. Due to lack of data, this approach is thus unable to assess dam behaviour during its initial operation or during uncommon operating conditions.

This method provides an answer to the question: *Does current dam behaviour correspond to behaviour observed in the past?*.

The deterministic model compares the actual measured behaviour with that of a theoretical model set up beforehand. This model may be adapted later on, should it be preferable. Or enhanced on the basis of experience gained during years of operation.

Since the deterministic model is independent of any statistical approach, it represents a powerful tool for the identification of long-term non-reversible deformations, as well as extremely low or high impounding levels or uncommon temperature conditions. Moreover, it can be used immediately during the first filling of the reservoir, which is – as is generally recognised – the most delicate period in the life of the dam.

This method provides an answer to the question: *Does current dam behaviour correspond to what it should be?*

Arch dam response to loading is, in general, expressed in form of a deformation. This dam deformation – recorded by the monitoring instruments, usually by pendulums – is really to be considered as a result of the superposition of different effects. For arch dams, the main factors of influence for such effects are:

- **the reservoir level** and
- **the thermal distribution** within the concrete.

Clearly separating the effects of different causes is an important difficulty for an interpretation model, even more so if it is based on a purely statistical approach, and, in particular, if the effects are cyclic and more or less synchronous.
The two following operating circumstances are intended to show the limits of a purely statistical approach:

- a simple, unusual combination of the main factors of influence (for example, unusual temperature conditions for a given season, or extremely low water level due to reservoir cleaning) would generate unexpected dam deformations. The deformations would find no correspondence with historical values, thus giving cause for an incorrect assessment.
- on the other hand, a dam deformation value within the plausibility ranges might hide an anomaly, that could only be identified (too) late.

There is no need to belabour the point that insufficient analysis at this stage would likely lead to erroneous assessments. Therefore, detailed examination of the data is required. And this should be carried out immediately after any regular set of measurements.
We do clearly prefer a deterministic approach. Or, better said, as we will discuss later on, we advocate a combined approach to measurements, including both advanced probabilistic and deterministic analyses.

Table 1: Features of interpretation models in brief

Statistical model	**Deterministic model**
Established "a posteriori"	Established "a priori"
Not available during initial dam operation	Available during dam initial operation
Numerical basis	Physical basis
Self-adaptable	Adaptable from time to time
Unusable in case of uncommon operating conditions	Usable in case of uncommon operating conditions

→ **MIC**

5. BASIC PRINCIPLES OF MIC

In light of the previous remarks, we have adopted and developed an advanced approach to monitoring measurements, called **MIC**. Specially designed for the monitoring of concrete dams, MIC is based on a combination of probabilistic and deterministic models.
Dam health assessment is thus carried out through a sequence of careful analyses (**Fig. 2**).

The evaluation of manually or automatically acquired monitoring data is preceded by a series of tests to avoid the storage of:

- erroneous or incomplete data – such as reading or writing mistakes as well as troubles with automated data acquisition or transmission – or
- implausible readings, such as concrete temperatures unlikely for the season.

Filters, user-defined plausibility limits based on statistical analyses of historical values, and immediate plotting tools offer the possibility of identifying anomalous values quickly.

As demonstrated in the previous section, drawing a conclusion about apparently anomalous dam deformations by simply comparing them with previous measurements is definitely a difficult and hazardous task.
For this reason, MIC provides, at this stage, a deterministic tool which allows the continuous comparison of the measured dam behaviour to expected behaviour.

MIC's basic concept is easily explained: for given impounding and temperature conditions, the previously established structural dam model computes the static and thermal effects on the dam deformation. These effects are thus deducted from the measured deformation so that a normalised deformation results, a so-called **reference deformation**.

In the absence of additional items of influence, i.e. in a normal situation, the computed reference deformation is almost constant over time. Otherwise, should an important deviation with respect to the expected value exist, this can be identified immediately and then the experienced engineer is asked to perform a thorough assessment.
However, due to unavoidable imprecision in the measurements or of the structural model, a certain deviation is usual. In fact, a tolerance range is defined as the maximum allowed deviation between the expected and the measured dam behaviours.

Moreover, the interpretation of the temporal evolution of these deviations represents an absolutely powerful tool for the assessment of long-term behaviour, i.e. non-reversible deformations.

This relevant study should be carried out every 5 – 10 years and be appointed to an expert that will evaluate the causes of such phenomena.

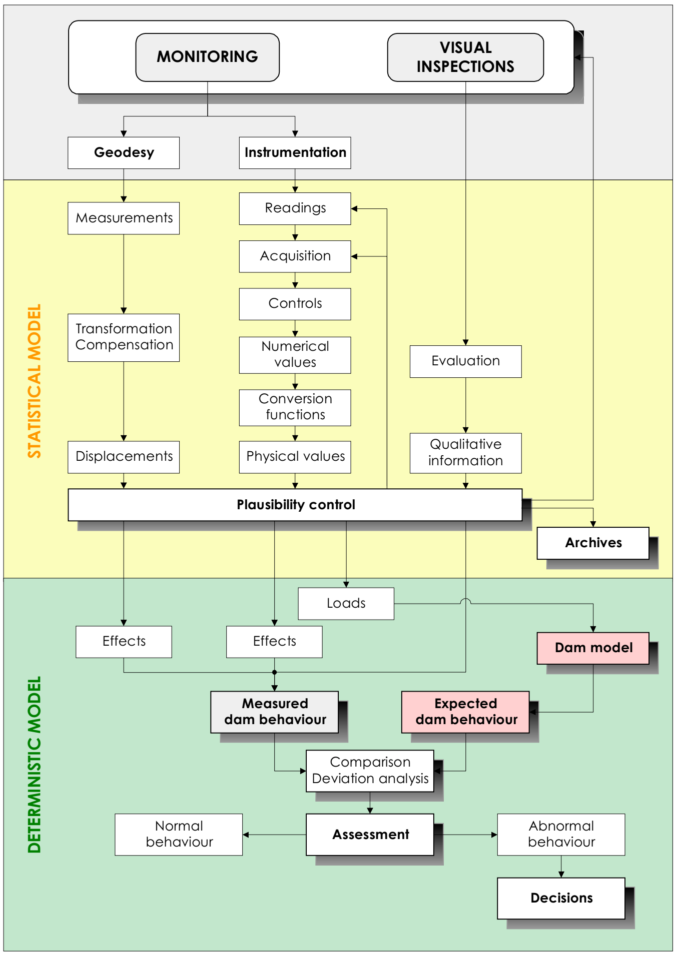

Fig. 2: MIC - general flow chart of dam monitoring

The discussed analysis steps included in MIC may be summarised as follows:

1. immediate diagnosis of the collected readings using statistical tools;
2. deterministic core analysis based on the comparison “Measured – Expected”, using a structural model which considers static and thermal effects;
3. probabilistic long-term analysis in order to quantify dam behaviour over time and to monitor its eventual rate of change, i.e. the long-term trend in behaviour.

All of the procedures presented have been integrated into a scientific, client-oriented software product that is currently meeting considerable interest from dam owners, as well as from specialised engineers. MIC is now being used in dozens of dams worldwide.

6. CASE STUDIES

Two representative cases have been selected to present different note-worthy situations:

- **the Ferden arch dam (Switzerland)**, testimony of an extraordinary event; and
- **the Roggiasca arch dam (Switzerland)**, messenger of a long-term irreversible trend.

FERDEN (Switzerland):

On February 23, 1999, following exceptional snowfalls, a huge 250-300'000 m^3 avalanche came down onto the Ferden arch dam and its basin. About 2/3 of the avalanche formed a 300 m-long cone-like body downstream, while the remaining part reached the reservoir. Downstream, the snow cover reached a height of 30 m, thus leaving only the upper third of the dam free.

Most of the associated structures located on the downstream side of the dam were strongly damaged or even destroyed. All the monitoring instruments, including the water level indicator, were inaccessible or out of order due to power failure.

Corrective measures were immediately implemented – such as drawing down, exploiting the maximum utilisable flow and obviously informing the authorities –, in order to evaluate dam safety and hence to re-establish it as soon as possible.

Although clear damages to the structure itself were not observed, a final assessment of the dam health could not be made until the monitoring instruments were repaired, i.e. by the beginning of April, about 5 weeks later.
Then, according to the new measurements, it was seen that a crest dam displacement of about 11 mm had occurred – as shown in **Fig. 3**. However, during the 5 week-long period the temperature within the concrete and the impounding level had varied so that a careful evaluation of the exceptional loading conditions was needed.

The on-site installed MIC enabled the engineer in charge to carry out the assessment by evaluating the reference deformations (illustrated in Fig. 3 in blue together with the tolerance limits). The reference deformations appeared almost unchanged both before the avalanche and after the break period, confirming normal dam behaviour.

From the middle of June to the end of July, the reference deformations were clearly outside the usual values. Investigations revealed that during instrument repair faulty connections were applied, causing erroneous data acquisition.
It may be observed that this type anomaly cannot be clearly identified based solely on the measured deformations.

The concept of a reference deformation, related to the deterministic model, therefore proved to be a powerful tool for a quick evaluation of the dam behaviour, even in the presence of an extraordinary condition.

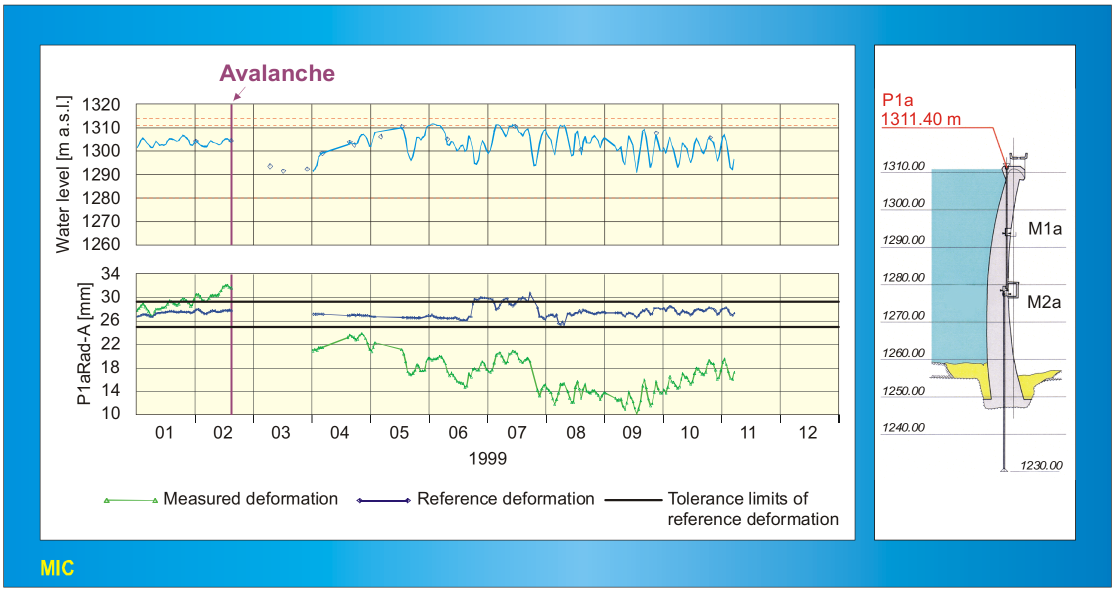

Fig. 3: Ferden arch dam: Impounding level, radial deformation and computed reference deformation of the uppermost measuring point (P1a) before and after the avalanche event

ROGGIASCA (Switzerland):

With regard to periodical safety evaluations (as discussed in Section 2), the Swiss dam safety concept requires an appraisal every 5 years, at least for major concrete dams. An expert is especially asked to perform the evaluation of the long-term behaviour of the dam in question.

As appointed experts for the Roggiasca arch dam, in 1999 we introduced – in agreement with the dam owner – the MIC system for the management of dam monitoring.
An advanced static model was implemented, enabling us to consider, in particular, a higher placed measuring point and its behaviour.
It should be stated that until 1999, no abnormality in the behaviour and condition of the dam had been identified or reported.

An abnormal trend in the behaviour of the Roggiasca dam was, however, overlooked.
To assess the long-term behaviour of the dam accurately, MIC offers the possibility of plotting the development of reference deformations over a long period, e.g. over the last 20 years as illustrated in **Fig. 4.** This figure clearly shows that, if up to 1990 the dam presented a perfectly normal behaviour, something abnormal has been occurring over the last years. In fact, at the elevation of the dam crest (point L1), a non-reversible radial displacement of about 4-5 mm towards the lake has occurred from 1990 up until the present. This trend has also been confirmed by the geodetic deformation measurements of November 1999.
A careful evaluation of this phenomenon is currently in progress.

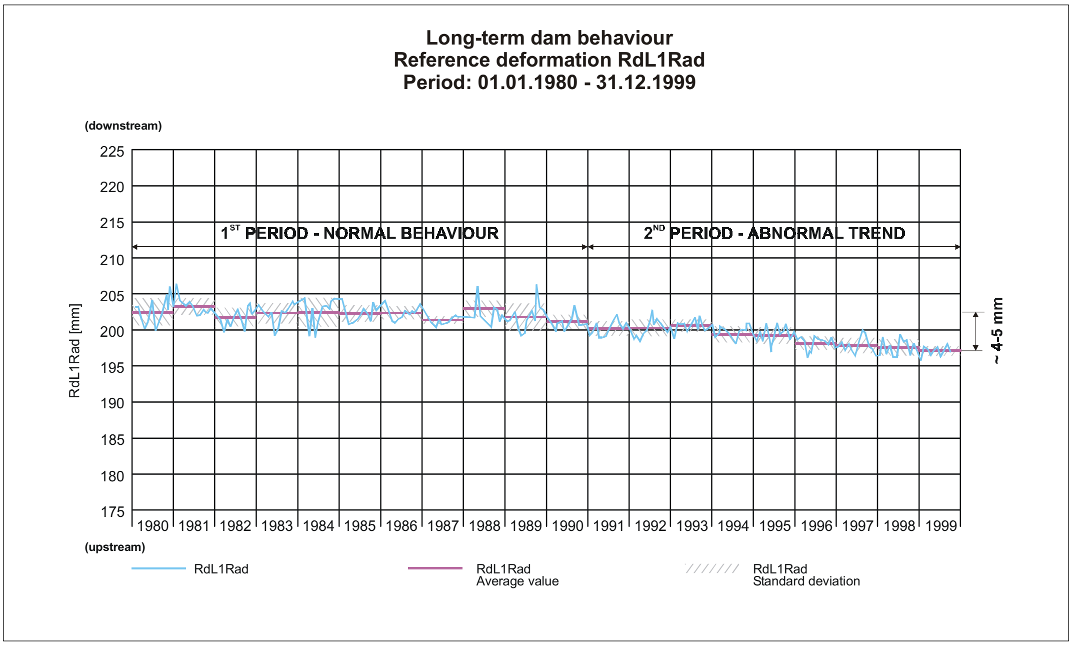

Fig. 4: Roggiasca arch dam: Reference deformation of the uppermost measuring point for long-term analyses.

7. NEED FOR DEVELOPMENTS

In spite of the advantages exposed in previous sections, the combined model and its efficiency still presents a certain need for further research and development.
In particular, the following points deserve consideration:

- Improving the instruments' precision and reliability, as well as that of the data transmission.
- Better suiting the structural model to the specific monitoring features.
- Better co-ordinating the relationship between automated and manual data, in particular by better managing schedules and acquisition requirements.
- Better reducing some additional seasonal influences that occasionally occur in the deterministic analysis.
- Better separating of significant information from mundane information.

8. CONCLUDING REMARKS

From measurement acquisition to the final assessment of dam behaviour, the keystone of the entire dam health monitoring procedure is the interpretation of the available information.
It is right at this point that the main efforts – economical, also – have to be concentrated, in order to detect any abnormal behaviour of the dam or of the monitoring instrumentation quickly and accurately and consequently to ensure dam safety.

The analytical tool used plays a fundamental role. In our opinion, an advanced deterministic model is to be preferred over a statistical approach.

Two case studies were presented to show how an advanced deterministic approach led to reliable explanations of and solutions to extraordinary situations.

Minusio, July 2000 Lombardi Engineering Ltd.
Bia

9. BIBLIOGRAPHY

Theoretical aspects

G. Lombardi: *L'informatique dans l'auscultation des barrages*, Comité National Suisse des Grands Barrages, "Wasser, Energie, Luft", **83**, Heft 1/2, pp. 2-8 (1992)

G. Lombardi: *Concrete Dams and their Foundation - Evaluation for static Loading*, International Workshop on Dam Safety Evaluation, Grindelwald, Switzerland, Volume 4, pp. 77-90 (1993)

G. Lombardi: *On the limits of structural analysis of dams*, Symposium on Research and Development in the field of dams, Crans-Montana, Switzerland, Hydropower & Dams, Volume Three, Issue Five, 1996, pp. 50-56 (1995)

R. Biedermann: *Safety concept for dams: development of the Swiss concept since 1980*, "Wasser, Energie, Luft", **89**, Heft 3/4, pp. 54-72 (1997)

G. Lombardi: *Traitement et analyse des données*, "Wasser, Energie, Luft", **75**, Heft 1/2, pp. 7-11 (1983)

G. Lombardi: *Barrages en béton. Détection et solution de problèmes*, Société canadienne de génie civil, Conférence du 20 octobre 1993, Montréal, (1993)

G. Lombardi: *Auscultación y monitoreo de presas de fabrica*, ENEE, Conferencia del 9 de marzo de 1999, Honduras, (1999)

Ferden Dam

R. Bremen, G. Como, H. Salzgeber: *Wiederinstandsetzung der Staumauer Ferden*, "Wasser, Energie, Luft", **91**, Heft 3/4, pp. 291-294 (1999)