1. INTRODUCTION

In order to guarantee the long-term safety of dams, one of the most important procedure is the regular monitoring of their behaviour. A proper monitoring device must at least take into account the loads acting on a dam due principally to the water pressure and the temperature, and render its response to these loads. The latter can be distinguished between global responses, such as the displacements in a certain point or the seepages, and local responses, such as the stresses, the uplift pressures, or the rotations of the structure. The local responses are most influenced by local effects and are not as representative of the actual behaviour of the dam as the global ones.

In order to interpret adequately the behaviour of a dam, it is possible to establish a mathematical model, which refers to a given response to the acting loads. With the interpretative models it is possible to verify immediately after a measure has been taken whether the behaviour of the dam corresponds to the expected behaviour for a given operative condition.

The problem is well known since the interpretative models are commonly used for the interpretation of the displacements. For the interpretation of seepages and uplift pressures it is less common to adopt interpretative models, probably due to the fact that such readings depend mostly on the water level in
the reservoir. Their interpretation is therefore relatively easy even without using specific instruments. However, displacements depend on both the water level and the thermal state; consequently, the manual interpretation of the dam behaviour could become quite a complex task.

This paper deals with the interpretative models for concrete dams, showing the various drawbacks and the possibilities to address them.

2. GENERAL DESCRIPTION OF THE INTERPRETATIVE MODELS

An interpretative model is a very useful tool to analyze the dam monitoring data in order to assess adequately the dam behaviour. It is normally integrated in a monitoring software, in order to analyze systematically and automatically all the new readings.

The analysis and the interpretation of displacements have a fundamental importance. Displacements can easily be measured and reflect the overall behaviour of the structure. Every abnormal behaviour in the foundation or in the dam body itself has some effects on the displacements.

As a whole, the interpretative model could be subdivided into three main parts as shown in “Fig. 1”:
- first part: definition of the thermal loads from the thermometer readings;
- second part: calculation of the displacements in some selected points of the structure due to impounding and temperature variations;
- third part: final treatment and result analysis.

The term “interpretative model” refers often only to the second part, i.e. the calculation of displacements, while the present paper will consider the pre-treatment of thermal data as integral part of the model. In fact, this first part assumes a great importance for the accuracy of the prediction of the dam behaviour. The last part is considered to be complementary.

The first part is usually considered in association with deterministic models. By using statistical models the thermometer readings are frequently directly linked to displacements without paying attention to the construction of the continuous thermal field within the structure.

The definition of the thermal loads was a necessity with the traditional beam methods (as arch-cantilever method) and remains of a great advantage for the physical comprehension of the dam behaviour.
Using finite element method it is possible to calculate the displacements for unitary variations of temperature at various measuring points in order to link directly the displacements to single thermometers. This procedure does not seem to present many advantages. Even if theoretically correct, it contributes to a general complication of the system. As a first step the determination of the thermal loads should be favoured in order to provide a general overview of the dam behaviour.

The calculation of the displacements - the second part of the interpretative model - is mainly based on the superposition principle. This principle allows a simple summing up of the effects of the acting unit loads and is applicable for
linear elastic structures. Appropriate coefficients of influence permit to quantify the effects of the different loads on the displacements.

If the definition of the influence coefficients is based on a structural analysis, the interpretative model is called deterministic model. In case it is based on a statistical analysis of past measurement data, then the model is called statistical. Between deterministic and statistical models there are different combined or hybrid models, as the Hydrostatic-Seasonal-Time Model (HST) proposed by the French school, based on a deterministic evaluation of the water level and a seasonal variation as approximation of the temperature.

In the category of the hybrid models it is also possible to include deterministic models calibrated in using a statistical analysis. However, if the optimisation can modify every single coefficient of influence with no connection to other coefficients, the final model will be virtually a statistical one. To avoid an excessive optimisation process, it is preferred to modify only some single parameters, such as the overall elasticity modulus or the coefficient of thermal expansion, and consequently to change the influence coefficient. In this case the final model will be an optimized deterministic one.

When creating a new model using a statistical analysis, it is possible to include various causes to simulate the desired effect. Typically for displacements, it can be considered the effect of water level, temperatures and seasonal effects as reversible components and the drift as an irreversible one. An overview of the possible formulations may be found in [1]. If the dam behaviour indicates a drift, it is mandatory to include, when creating a new model, the non reversible component in order to avoid an important source of errors that may disturb the analysis of the reversible one.

The third and last part of the interpretative model simply calculates the residuals (or differences) between measured and calculated displacements. The correction of the measured displacements with the various factors of influence should be limited to the reversible components, in order to adequately put in evidence the presence of a drift in the residuals.

In the deterministic models, the residual corresponds physically to a reference displacement. In fact, by correcting the measured displacements with the effect of water level and thermal variations, the final displacement corresponds to a theoretical displacement of the dam at fixed reference conditions of operation.

In the deterministic models it is possible to choose the reference load condition and thus to define the constants of the various influence functions according to this choice. In the statistical models the constants reflect instead the arbitrary origin of the displacements.
3. MONITORING AND INTERPRETATION OF DAM LOADS

3.1 WATER LOAD

The hydraulic load is simply defined by the water elevation. The displacements of a point of the dam are generally simulated by a polynomial function as following:

$$\delta_w = a + bx + cx^2 + dx^3 + ex^4 + ...$$  \[1\]

where $x$ is the water elevation and $\delta_w$ is the displacement at a reference point due to the water load.

The order of the polynomial function may be selected according to the expected behaviour. For gravity dams, characterized by a transmission of the loads in the vertical direction, the displacement at a certain point is defined analytically by a polynomial function of third order related to the water elevation. The behaviour of arch dams is more complex, but it could be considered, as an example, that the total water load acting on the structure is also defined by a polynomial function at least of third order.

For practical purposes (reasons related to numerical calculation) it is useful to define the variable $x$ of the polynomial function not directly as the water elevation above see level or the water head in m above the dam base, but as a normalized function ($x/H$) of the water elevation. This allows maintaining the different coefficients of the polynomial expression more equilibrated.

The assumption of an elastic behaviour is sufficient in the most cases and should be the initial assumption when defining a new interpretative model. For the Contra arch dam, it could be observed, after the basic interpretative model has been optimized, that the actual behaviour of the dam is not linear-elastic, but elastic-viscous. For a sudden change of the water elevation the dam behaviour is more rigid in comparison to slow variations. The interpretative model has been thereafter improved with a viscous-elastic law and it was found that almost 80% of the displacements were elastic while 20% are viscous [2].

The case of Contra dam should represent more a particular case then a general rule, since it is a significantly high (220 m), thin and slender arch dam [3], [4]. For dams with lower stress levels, the viscous part of the water displacement should be less important.
3.2 THERMAL LOADS

3.2.1 Determination and analysis of thermal loads

In order to analyze the effect of the internal temperature it is necessary to differentiate between the various types of thermal loads, i.e. recognize the main contributors of thermal deformation “Fig. 2”:

− The mean uniform temperature across the wall thickness determines the lengthening or shortening of a structural element.
− The temperature gradient across the wall thickness, also called thermal moment, determines the rotation of a structural element.
− The non-linear part, i.e. the difference between the actual temperature field and the linearized temperature, modifies the local stresses but is of secondary importance for the overall displacement of the dam.

![Fig. 2](image)

Definition of thermal loads
Définition des charges thermiques

The thermal loads that generate the deformations in the dam are linked to the continuous thermal field in the dam body. Since the temperature can not be measured in each location of the dam, it is important to consider some approximations. The first step is hence the reconstruction of the continuous thermal field from the discrete information provided by the installed thermometers. This task is frequently under evaluated in practice and can be considered one of the principal causes of imperfections of the deterministic models.

Interpolations between thermometers and extrapolation toward the structure boundaries, i.e. crown, faces and foundation, are required to estimate the continuous thermal field. The quality of the results depends primarily on the locations of the thermometers. A rational disposition of thermometers should consider the following:

− In the horizontal bank-to-bank direction, the thermal conditions are relatively uniform if the dam thickness is more or less constant at a given elevation. The placement of thermometers only in the central vertical section is generally sufficient. In arch dams the central section is also representative for the mean orientation of the structure regarding solar radiation.
In the vertical direction, besides of the variation of the dam thickness, the thermal conditions are also influenced by the impounding level. In order to define correctly the continuous temperature field in the vertical direction, it is recommended to place thermometers in a sufficient number of elevations. The optimal number may not be defined unequivocally. Two elevations seem to be few, 8 are a lot. A number between 3 and 5 should be adequate for the majority of dams.

The most important thermal flux occurs in a normal direction to the faces (for a dam in the upstream-downstream direction). The placement of thermometers across the wall thickness is very sensitive and often source of imprecision of interpretative models. It is very important to have enough and well-distributed measurement points in order to be able to calculate the representative thermal loads (mean uniform temperature and thermal moment). In particular near both faces, where the temperature gradient may increase significantly, the distance between thermometers should be progressively reduced in comparison to the distance in the central part of the wall. The optimal placement of thermometers across the wall thickness may be verified and optimized with a one-dimensional thermal analysis by assuming realistic external conditions. The thermal loads calculated with a limited number of points should be the same as those calculated with the continuous thermal field (that is known).

The consequence of an inadequate placement of thermometers is that the thermal loads are incorrectly determined and consequently the dam displacements are imprecisely simulated by deterministic model (an interpretative model based on a structural analysis).

A thick wall with two thermometers placed near the centre represents an extreme case that permits to explain clearly the phenomenon: in springtime the external temperature increases and the structure starts to move. The heat flow from outside needs time to reach the deeper part inside the concrete body and the mean uniform temperature corresponding in this case to the average of the measures provided by these two thermometers is wrongly determined. The delay between the actual thermal loads and the loads determined from the temperature readings can not be corrected neither by a new static calculation nor in adapting some influence coefficients. The information obtained by the thermometer readings is thus insufficient.

The same would happen with only two thermometers placed each one at a dam face. In this case the calculated uniform temperature would be in advance in comparison to the actual one.

Figure 3 shows a more realistic example for the case of an 83 m high arch dam in Switzerland.
Case A: The thermal field within the dam is determined with 4 sections with each 3 thermometers across the wall thickness

Case B: The thermal field within the dam is determined with a upper section with 3 thermometers and 3 lower sections with each 5 thermometers across the wall thickness

1. Measured displacement
2. Effect of water level on displacements
3. Displacements after correction of water effect
4. Effect of temperature for Case A
5. Effect of temperature for Case B
6. Reference displacement for Case A (=displacement after correction of water and temperature effects)
7. Reference displacement for Case B

Cas A: L’état thermique dans le barrage est déterminé à l’aide de 4 sections avec 3 thermomètres chacune

Cas B: L’état thermique dans le barrage est défini à l’aide de 1 section supérieure avec 3 thermomètres et 3 sections inférieures avec 5 thermomètres chacune

1. Déplacement mesuré
2. Effet de l’eau sur les déplacements
3. Déplacement après correction de l’effet de l’eau
4. Effet de la température pour le Cas A
5. Effet de la température pour le Cas B
6. Déplacement de référence pour le Cas A (=déplacement après correction des effets de l’eau et de la température)
7. Déplacement de référence pour le Cas B

Fig. 3
Analysis of radial crest displacements of an arch dam
Analyse des déplacements radiaux en crête d’un barrage-voûte
The behaviour of the dam is little influenced by the hydraulic pressure, since the water level remains more or less constant. The displacement of the dam follows therefore mainly the internal temperature changes.

The temperature is measured at 4 elevations with 3 thermometers at each section (Case A). The thermometers are placed at regular distances across each horizontal section, including the distances toward both faces (for a wall thickness of 14 m the distance between the thermometers is 3.5 m). With the information provided by the existing thermometers, the thermal displacement was determined quite roughly. As a consequence, the reference displacement showed a residual seasonal variation.

The precision of the predicted displacement could only be improved with two additional thermometric points situated at a deep of 1/16 of the wall thickness from both faces (Case B). With this improvement the standard deviation of the residuals could be further reduced by 34%. The additional thermometers allowed anticipating the thermal loads by 15 days.

The given example shows the difficulty to determine the thermal loads from internal temperature reading. After defining the continuous thermal field, the determination of the thermally induced displacements results by analyzing the effect of unitary temperature variations. Independent unit thermal loads with specific spatial shape are introduced and calculated in a structural analysis. The superposition of the unit thermal loads forms the continuous thermal field, or at least the significant part, which contribute to the displacements.

As already mentioned in Chapter 2, it could also be possible to calculate the displacements, even with a structural analysis, directly as function of the thermometric points, avoiding the intermediate step of the definition of thermal loads. The final results and the problems are similar for both approaches, since the difficulties do not arise from the definition of the thermal loads, but from the reconstruction of the continuous thermal field from a limited number of thermometers. The advantage of dividing the analysis in two steps (defining first the thermal loads and than the displacements) is that the thermal state of the dam may be synthesized and therefore better analysed.

3.2.2 Optimisation of the thermal loads

In a new dam under construction it is suggested to install the thermometers according to the recommendations exposed in the previous chapter. The advantage of placing a sufficient number of thermometers is that the thermal loads can be established directly from thermometers readings, in using a linear combinations, without the need of complex calculations procedures. The second advantage of a direct definition of the thermal loads is the possibility to monitor at the initial period of dam operation the dissipating hydration heat of the cement.
In an existing dam, in case of insufficient temperature reading points, there are various solutions. Some possibilities are listed below:

- installation of new thermometers;
- interpolation of the temperature within points between two existing thermometers, for example, when an intermediate thermometer is out of service [5];
- calculation of the internal temperature distribution starting from the outside temperature readings (air and water) or from thermometers placed in the concrete near both faces;
- extrapolation of internal temperature readings toward the dam faces;

The one-dimensional calculation of the internal temperature distribution may be solved with several methods. A procedure based on the finite difference explicit method was adopted for example for Pian Telessio dam [6]. Laplace transform algorithm represents also an adapted procedure [5] as well as several other methods found in the literature [7], [8].

The advantage to start from thermometers placed in the concrete near both faces instead of using outside temperatures is that the boundary conditions are constant: the effect of impounding water, solar radiation and wind are already included in the temperature readings. Furthermore, the daily variation of external temperature is filtered and strongly reduced if the first internal thermometers are placed at round 80 cm from the face.

The extrapolation of the internal temperature towards both dam faces represents also a possibility to complete the thermal field across a horizontal section. The extrapolation should be carried out only for a limited distance, since deeper located thermometers contain less information then the external one and this information can not be recovered by any calculation procedure. A possibility to extrapolate the internal temperatures may be found from the equation governing the one-dimensional heat transfer in the finite difference explicit methods [9]:

\[
\Delta T_i = a^2 \cdot \frac{dt}{dx^2} \cdot (T_{i+1} + T_{i-1} - 2T_i)
\]  

[2]

where \(a^2\) is the thermal diffusivity, \(dt\) the time step, \(dx\) the element size, \(T_i\) the temperature of element \(i\) and \(\Delta T_i\) the temperature variation for a time step \(dt\).

The equation [2] may be changed as follows:

\[
T_{i-1} = \frac{1}{a^2} \cdot \frac{dx^2}{dt} \cdot \Delta T_i + 2T_i - T_{i+1}
\]  

[3]

In equation [3] the temperature of element \(i-1\) depends only on the temperatures of the internal elements \(i\) and \(i+1\).

As final recommendation it is suggested to optimize carefully the thermal part before starting to search for more causes that may influence the displacements, as (e.g.) the non linearity of the structure (for example when a crack opens), its viscosity, the uplift pressure, etc.
4. DETERMINISTIC OR STATICAL MODEL

4.1 QUANTIFICATION OF INFLUENCE COEFFICIENTS

In the deterministic models the relationship between loads and displacements are clearly defined by the structural behaviour, while in statistical model the coefficients of influence are established according to arbitrary relationships. The unique condition is that the time histories of the causes have similar shape with the chosen effect. The air temperature may not have an important influence coefficient on a smooth nearby sinusoidal displacement, since the air temperature readings are characterized by important higher frequencies as daily and weekly variations. The shapes of both time histories (air temperature and smooth displacement) are not compatible.

With a statistical analysis it is theoretically possible to find a relationship between the radial displacements of a dam and the numbers of food menus served during the weekend to visitors in a nearby restaurant. Obviously there is no physical relationship between the sold menus in the restaurant and the displacements of a dam, but by nice warm weather there are more tourists visiting the dam and eating in the neighborhood.

What occurs with monitoring data is not so far from the previous example. With statistical analysis it is quite possible to find a strong relationship between a thermometer near the foundation, and the crest displacements even when the actual thermal variation near the foundation has a negligible effect on the crest displacements. The problem when using such a model to analyse the future monitoring data is that, if the temperature near the foundation changes for any reason, the interpretative model indicates a variation of the displacement, while the actual displacement does not change in the same proportion.

The previous chapter has clearly illustrated that in many cases the thermal loads are wrongly determined, i.e. they are out of phase in relationship to the actual thermal loads. Since the deterministic model (the central part of Fig. 1) cannot compensate and correct this time delay, it produces unsatisfactory results. The particularity of statistical analysis is, instead, that any time delay will be easily corrected if there are at least two causes that are compatible with a chosen effect. The phenomenon can be showed with a theoretical example “Fig. 4”.

The statistical analysis (simple linear combination of two thermometers) is able to define appropriate coefficients of influence \( k_1 \) and \( k_2 \) in order to predict almost exactly the measured displacement for every time delay of thermometer 2. This result demonstrates the flexibility and the self-adapting capacity of statistical models. As illustrated in “Fig 4”, the influence coefficients may assume any value, positive and negative. Furthermore when both temperature effects have nearly symmetric (same delay time) or asymmetric time histories, the coefficients
arise to high absolute values indicating a singularity. One speaks in this case of multi-collinearity. The interpretative model becomes unstable (e.g. for $t_0=0.2$ or 0.7).

$$
\begin{align*}
\delta_{m} &= 3 \cos(2\pi t-0.8) \quad [\text{cm}] \\
T_1 &= 4 \cos(2\pi t-0.7) \quad [\text{°C}] \\
T_2 &= 5 \cos(2\pi t-0.8) \quad [\text{°C}] \\
\delta_{c} &= k_1 x T_1 + k_2 x T_2
\end{align*}
$$

<table>
<thead>
<tr>
<th>DISPLACEMENT (DEPLACEMENT)</th>
<th>THERMOMETER 1 (TERMOMETRE 1)</th>
<th>THERMOMETER 2 (TERMOMETRE 2)</th>
<th>MODEL (MODELE)</th>
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<tr>
<td>$\delta_{m} = 3 \cos(2\pi t-0.8)$</td>
<td>$T_1 = 4 \cos(2\pi t-0.7)$</td>
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<td>$\delta_{c} = k_1 x T_1 + k_2 x T_2$</td>
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STATISTICAL OPTIMISATION (OPTIMISATION STATISTIQUE) $\sum (\delta_{m} - \delta_{c}) \rightarrow \text{MINIMUM}$

**Fig. 4**
Quantification of influence coefficients with a statistical analysis
_Détermination des coefficients d’influence par une analyse statistique_

From the simple theoretical example as exposed above, it is possible to imagine what happens with actual readings of, for example, 6 thermometers, for which all the temperatures are more or less similar, i.e. indicating a strong multi-collinearity. With statistical analysis it is therefore very common to obtain arbitrary influence coefficients and thus a correct thermal effect as a whole but a wrong effect of each single temperature.

In order to limit the problem of multi-collinearity, the easiest and usual way is to eliminate some thermometers from the statistical analysis. The final model is not necessarily more robust, since the deformations are simulated with only few and probably arbitrary parameters. A better way could be the definition of ranges of acceptability for each coefficient of the thermal influence. In an arch dam it does not make sense that a temperature increase moves the dam downstream. So the influence coefficients should be at least limited to the right signs.
Similarly, the thermometers placed near the downstream face of a gravity dam move the dam upstream.

A certain multi-collinearity could exist also between temperatures and the water level due to a seasonal operation of the reservoir. However a proper period of calibration can limit this problem. In general the two types of loads can be better separated as the single thermal contributions due to the different shape of their time history. Multi-collinearity can appear also between the different terms of the polynomial function used to describe the effect of the water level. This multi-collinearity has no consequences, since the various variables are not independent each other but depend all from the same water level.

The only element that needs to be verified by the water level, is that the polynomial function should not present a minimum deformation at a certain intermediate level and increasing values for higher and for lower water levels “Fig. 5”.

The problem shown on Figure 5 can happen as a consequence of a multi-collinearity between hydrostatic and thermal loads or as consequence of too few measures by lower water levels, which do not have sufficient weight in the calculation of the standard deviation of residuals. This phenomenon can be somewhat limited by defining a variable weight of the measures as function of the water level.

Fig. 5
Excessively intense optimisation process
*Optimisation trop poussée*
4.2 GENERAL CONSIDERATIONS ON INTERPRETATIVE MODELS

The statistical model is a mathematical tool that permits to simulate the variations of a measure with time as function of presumed factors of influence. The relationships between causes and effects are fully arbitrary, since the geometric shape and the physical laws are not considered at all by the statistical analysis.

The deterministic model is a model that permits to simulate the behaviour of a dam, or in general of a structure. By using a deterministic model it is possible to optimise the structural analysis and to verify the main material parameters. If a deterministic model does not work satisfactorily it is necessary to investigate the physical reason of this imprecision and, thank to this analysis, to better understand the actual behaviour of the dam. In a deterministic model there are no shortcuts: the deterministic model is satisfactory only if the dam behaviour is correctly simulated in all his parts.

All type of interpretative models help answering the question whether the monitoring data are regular or whether there is in the dam behaviour something new. But the fundamental question if the dam behaviour is regular and satisfactory, can only be answered by a deterministic model. It is clear that the presence of regular monitoring data allows also concluding about the current behaviour of a dam, but only by assuming that the past behaviour was regular and satisfactory.

The problem with the statistical models is that they loose their reliability when the operational conditions change from the conditions existing during the optimisation time. An extraordinary example is represented by the case of the huge 250'000 m\(^3\) avalanche during the winter of the year 1999 that reached the 67 m high arch dam of Ferden, in Switzerland [10]. About 2/3 of the avalanche formed a 35 m high downstream snow cover, while the remaining part reached the reservoir. Most of the structures located on the downstream side of the dam were strongly damaged and all monitoring instruments were inaccessible or out of order. First measurements came only almost 5 weeks later. During that period the water level was partially drawn down “Fig. 6”.

Although clear damages to the arch dam were not observed, a final assessment could be made also by evaluating the results obtained with a deterministic model: the reference deformation after the break period appeared to be inside the tolerance limits, confirming the normal behaviour of the dam. With a statistical model the same conclusion would have been hazardous. One should have doubt that the behaviour of the dam was anomalous and the statistical model did not works correctly under said exceptional loading conditions. The reference deformation could have stood inside the tolerance limits due to a fortuitous combination of various factors.
Behaviour of the Ferden arch dam before and after the avalanche event

Comportement du barrage-voûte de Ferden avant et après l’avalanche

A. Measured radial crest displacement
B. Reference displacement (=radial crest displacement after correction of the water and temperature effects)
C. Tolerance limits for reference displacement
D. Avalanche

1. Gallery with pendulum measuring station (broken by the avalanche)
2. Direct pendulum
3. Inverted pendulum
4. Maximum snow elevation
5. Thermometers

When the operation conditions are regular, all type of interpretative models can work, but for exceptional loading conditions, only the deterministic model maintains its full reliability. Within this framework, one would ask whether not the anomalous situations that necessitate mostly a reliable interpretative model to assess the dam behaviour.
There are finally some limits to consider for both types of interpretative models (deterministic or statistical).

- If the relationship between causes and effects is structurally or physically not clearly defined, as in the case of uplift pressures or drainage water by concrete dams, the unique way is to refer to statistical models.
- A statistical analysis requires sufficient number of measures in the past to be tuned. The establishment of a statistical model is therefore not possible for a dam during its initial period of life. It must also be considered that at this time it is mandatory to ascertain that the behaviour is regular and the dam is safe. In this case only deterministic models come into consideration. After a long period of satisfactory behaviour, i.e. by old dams, the assessment becomes easier.

Whatever interpretative model is adopted, a serious and complete analysis of the monitoring data, including the validation of all new collected values, is essential. An automatic acquisition of readings from a large amount of instruments is not sufficient for a good monitoring. In more than one case the practice has shown unfortunately that more the collected monitoring data are large less they are carefully interpreted and even interpretable. The general tendency of large automatic data systems should be considered with more prudence, also in respect to a long-term maintenance.

5. CONCLUSION

Interpretative models are currently used in order to verify the monitoring data. It is possible to differentiate between:

- deterministic models, where the relationship cause-effect are established on the base of a structural analysis,
- statistical models, where the relationship between presumed causes and effects are established on the base of a statistical analysis of previous readings, and
- hybrid models, a combination of both.

The creation of a fine tuned deterministic model requires a good knowledge of the physical laws governing the dam behaviour. The thermal part is often the cause of major imprecision. The construction of the continuous thermal field within the dam body from discrete information provided by the thermometers is a quite delicate task.

With a deterministic model it is possible to assess the dam behaviour during the whole life of the structure. After having created a deterministic model, there are no reasons to periodically update the model, beside of a calibration during the initial period. Needs for updating are limited to cases of an actual change in rigidity or in case of a structural modification (heightening).
Deterministic models provide satisfactory results only if the whole physical process is correctly interpreted: accurate definition of loads, adequate structural model and representative material parameters.

Statistical models are apparently easier to be established than deterministic ones. This fact is due to a fundamental difference: in the deterministic approach the model determines the quality of the prediction, while in the statistical approach the optimization of the prediction determines the model. The relationship cause-effects are, with the latter, both empirical and subjective. This fundamental difference should be strongly kept in mind.

A robust model is easier to be established by the deterministic approach than by the statistical approach. The minimization of prediction errors is not a reliable criterion to judge the quality of a model. At the contrary, an excessive intense optimization facilitates the establishment of unstable models.

Obviously all types of models allow to answer the question whether there is something new in the dam behaviour, but only the deterministic models can really give an answer whether the dam behaviour is regular and satisfactory or not.

Because statistical models do not necessitate a robust and proper definition of the thermal field, there is the risk of a long-term deterioration of the related instrumentation. The temperature remains in any case an essential element for understanding the actual behaviour of dams.

Clearly the type of the interpretative model can be chosen in relation to the dam to be monitored. A deterministic model may be considered as a luxurious solution for a small dam and certainly a statistical model is better than nothing.

REFERENCES

SUMMARY

The paper deals with dam monitoring and in particular with the interpretative models adopted to verify the structural displacements of concrete dams.

In order to assess the cyclic displacements of a dam, it is primarily necessary to consider the effects of water level and temperature. If the first could generally be analysed without major problems, the thermal part is quite difficult to manage. This latter is often the main source of imperfections by deterministic models. The temperature is measured in single points, but the dam responds to the continuous thermal distribution, which is in fact unknown. Interpolations are thus required. In this context, the position of the thermometers in the dam body becomes an important task.

Since the deterministic model, where the relationship between the loads and the dam response has been clearly defined by a structural analysis, cannot compensate and correct any imprecision in the definition of the loads, it produces unsatisfactory results. However, the reason for the said imprecision may clearly be identified and corrected. If a deterministic model does not work satisfactorily it is necessary to investigate the physical reasons of this lack of precision and therefore to improve the knowledge one has of the dam.

By using statistical models, this improvement is not possible. The particularity of statistical analysis is that any time delays may be easily corrected if there are at least two causes that are compatible with a chosen effect. The consequence is that with a statistical analysis it is very common to obtain arbitrary influence coefficients and thus a correct thermal effect as a whole but a wrong effect of each single temperature.
With small effort a statistical model may appear more precise than a deterministic one, but it is certainly not more reliable.

RÉSUMÉ

La thématique traitée dans le présent article s’inscrit dans le cadre de l’auscultation des barrages et plus spécifiquement des modèles interprétatifs utilisés pour vérifier les déformations des barrages en béton.

Afin de pouvoir interpréter les déplacements cycliques d’un barrage, il est essentiel d’analyser en premier lieu les effets de la poussée de l’eau et des températures. Si généralement la poussée de l’eau ne pose pas des problèmes majeurs, l’analyse de la partie thermique est bien plus difficile à maîtriser. Dans plusieurs cas cette dernière s’est révélée être comme l’une des causes principales de l’imprécision des modèles déterministes. La température est mesurée en un nombre limité de points, mais le comportement du barrage est défini par l’état thermique complet, qui est finalement inconnu. La définition de l’état thermique doit se faire par des interpolations entre les thermomètres, dont la disposition dans le corps du barrage joue un rôle déterminant pour la précision des résultats. Selon le besoin on pourrait faire recours à des procédures de calcul plus ou moins complexes pour permettre d’améliorer la situation.

Dans un modèle déterministe les relations entre les charges et les déformations sont clairement définies par une analyse structurelle de l’ouvrage. Puisque ce type de modèle ne peut pas corriger et compenser librement les imprécisions dans la définition des charges, il peut produire des résultats insatisfaisants. La raison d’une éventuelle imprécision est pourtant physiquement explicable. On pourra ainsi la corriger permettant d’améliorer l’interprétation et la compréhension des phénomènes qui déterminent le comportement d’un certain barrage.

Avec les modèles statistiques ces approfondissements ne sont pas possibles. La particularité des modèles statistiques est qu’il arrive à corriger toute sorte de décalage de la partie thermique, à condition d’avoir au moins deux tracés de température plus ou moins compatible avec la courbe de déformation. La conséquence est que dans les modèles statistiques les coefficients d’influence sont définis totalement par hasard. La déformation thermique est quantifiée correctement dans la totalité, mais l’effet de chaque thermomètre peut être manifestement incorrect. Le modèle interprétatif peut devenir ainsi instable.

Avec peu d’efforts un modèle statistique peut apparaître plus précis qu’un modèle déterministe. Ce caractère est lié à une différence fondamentale entre les deux méthodologies : dans le cas de l’approche déterministe, le modèle définit la précision de la prédiction, dans le cas de l’approche statistique par con-
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tre, l’optimisation de la prédiction définit le modèle. Dans ce dernier, les relations causes-effet sont pourtant totalement empiriques.

La minimalisation de l’erreur n’est pas un critère fiable pour évaluer la stabilité d’un modèle, au contraire, une optimisation trop forcée peut facilement conduire à un modèle instable.