PERFORMANCE OF STATISTICAL MODELS FOR DAM MONITORING DATA

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ABSTRACT

In general, dams are subjected to three external factors: the hydrostatic load from the reservoir, air temperatures, and time (or irreversible effects). Effects from the hydrostatic load and temperature are assumed to be reversible, while time effects are considered irreversible. Reversible effects are usually less of a concern from a dam safety perspective since they represent the normal behavior of the dam. Irreversible effects can be associated with creep and shrinkage effects but may also be associated with unanticipated changes in material properties, damage due to unanticipated loads, deterioration or damage accumulation.

The Hydrostatic-Season-Time (H-S-T) model has been widely used for analyzing monitoring data of dams, and has proven to be a powerful tool for data analysis of concrete dams and in particular for global displacements. A simulation model was used to develop guidelines on the applicability of the model to different types of dams as a function of the frequency of readings, the length of measurement records, uncertainty associated with different types of measures and dam pathologies. These guidelines were then evaluated by comparing the predicted and actual performance of the models for several thousands of different types of instruments commonly used in dams. Recommendations are formulated for the use and limitations of the models for each type of instrument.

KEY WORDS

Monitoring, statistical analysis, decision making, dam safety.

INTRODUCTION

Monitoring of structures is a research area that has seen many new developments in the last few years (Feknous et al. 2001). These have been driven by the need to improve the reliability and optimize the maintenance of existing infrastructures and the development of new monitoring devices. Several issues need to be addressed when making the decision to deploy such devices: 1) how many devices are required, 2) where should they be located on the structure, 3) what is the frequency of readings 4) and how long should be the period of observation to obtain a statistically significant model. The first two issues are specific to each structure and phenomena that is monitored and are not statistical in nature. The last two

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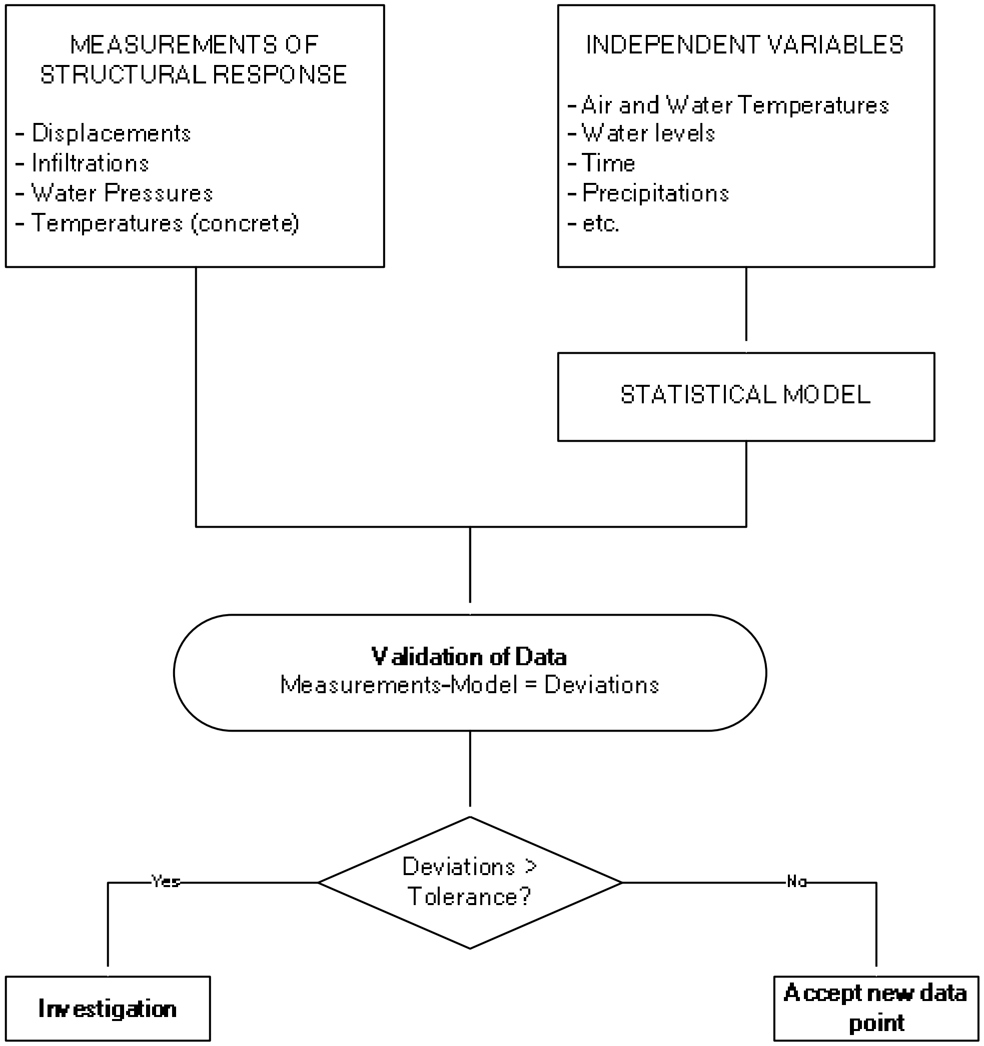
issues are important first to limit the number of observations that need to be collected in a specific application and obtain a sample that provides information that is adequate to estimate statistically significant and accurate models. These latter issues are addressed in this article by using dam monitoring data. Dams are among the few structures that have been instrumented historically and lessons learned from this experience are very useful as many other types of structures (e.g. bridges and buildings) are considered for long term monitoring.



determine if the observation is tainted by a bad measurement or faulty instrument or if it is associated with a change in structural response.

For the purpose of this article, only instruments that monitor global displacements in dam are considered. Global displacements offer the benefit of being usually linear as a function of independent variables and are thus ideally suited for this type of analysis. The analyses were performed for the HST model, which is widely used in the industry for this type of measurement.

HST MODEL

The Hydrostatic-Season-Time (H-S-T) model was first proposed by Ferry and Willm (1958) Wilm and Beaujoint (1958). It has since been widely used for analyzing monitoring data of dams, and has proven to be a powerful tool for data analysis of concrete dams and in particular for displacements. The model is based on the assumption that displacements are associated mainly with three factors: hydrostatic loads, external temperatures (air and water), and time effects.

$$MB_j = f_1(H_j) + f_2(S_j) + f_3(t_j) + r_j$$

where:

MB_j: measurement of effects (e.g. deformation) at time t_j

$f_1(H_j)$: response due to hydrostatic load at time t_j

$f_2(S_j)$: seasonal response due to temperature at time t_j

$f_3(t)$: irreversible response at time t_j

r_j: residual at time t_j

The hydrostatic effect is usually expressed as a polynomial function of degree 3,

$$f_1(H_j) = a_0 + a_1 \cdot Z + a_2 \cdot Z^2 + a_3 \cdot Z^3$$

where a_0, a_1, a_2, a_3, are constants. and Z is the relative value of water level defined as:

$$Z = \frac{H_{\max} - H_j}{H_{\max} - H_{\min}}$$

where

H_{max}: the maximum historical reservoir water level

H_{min}: the minimum historical reservoir water level

H_j: the reservoir water level at time t_j

The seasonal effect and is used when data on temperature is incomplete or not available. It represents the cyclic component of displacements.

$$f_2(S_j) = a_4 \cdot \sin(T_j) + a_5 \cdot \cos(S_j) + a_6 \cdot \sin^2(S_j) + a_7 \cdot \sin(S_j)\cos(S_j)$$

$$S_j = \frac{2p\,(t_j - t_0)}{365}$$

where t_0 is the initial reference date for the data. Several mathematical expressions have been suggested for irreversible effects, the most common one for concrete gravity dams that have been in operation for a number of year, is

$$f_3(t_j) = a_0 + a_1 \cdot (t_j - t_0)$$

The sample of observations used for estimating model parameters must be obtained under similar conditions for the dam and the monitoring system (Draper and Smith 1981). Consequently, a preliminary step is the anlysis of historical records to determine if any significant modifications were performed on the dam (cutting of a dam affected by alkali-aggregate reaction, installation of prestressed cables, etc.) or on instrumentation (change of wires for pendulums, change in benchmark for topographic surveys, etc.). Once a period of observation is selected, a further screening of the data is performed to eliminate apparent outliers which are usually influential points. Figure 2 shows an example of outliers in manual data while Figure 3 shows an example of outliers in automatic data. Formal statistical tests are availabe to identify outliers but in most cases, these can be identified viusally directly from the time series (Montgommery et al. 2001).

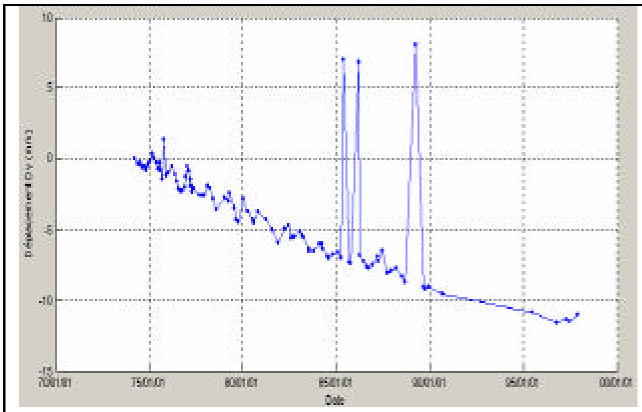


Figure 2 Example of outliers in manuel data.

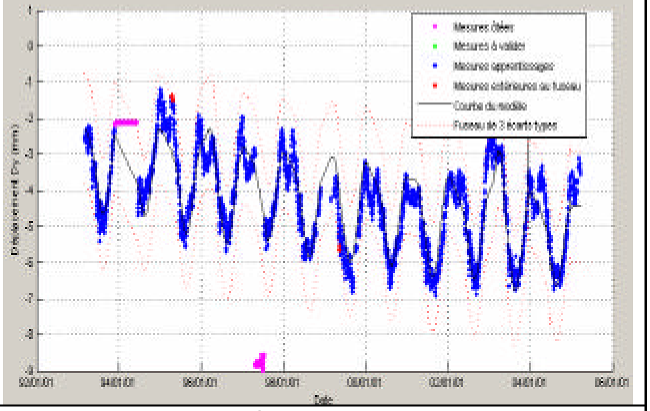


Figure 3 Example of outliers in automatic data.

ANALYSIS OF MONITORING DATA USING THE HST METHOD

Monitoring data from pendulums were analyzed with the HST method after removal of outliers and the identifiaction of an homogeneous sample of observations. The HST model provides good results for most of pendulums. Figure 4 gives an example of results using the HST model. On the graph, the observations, the predictions from the HST model, and the predictions for each effect (hydrostatic, seasonal, and irreversible) are shown simultaneously. In this example, the coefficients of determination are respectively $R^2 = 0.88$ in the x-direction (along the axis of the dam), $R^2 = 0.90$ in the y-direction (+ downstream, - upstream), and $R^2 = 0.94$ in the z-direction (vertically). The seasonal effects are the most important components of the deformations, followed by irreversible effects. The effect of reservoir water level is relatively small and does not appear to be very important for this particular pendulum.

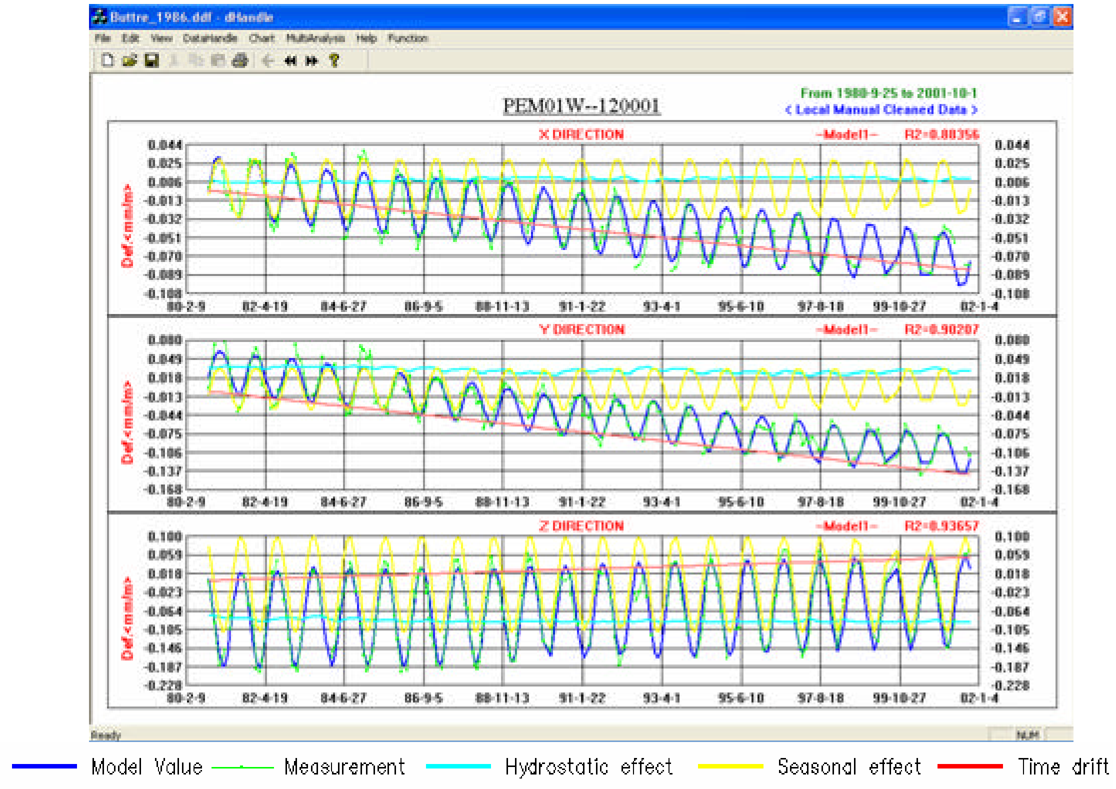


Figure 4 An Example of H-S-T Model Analysis Results.

FREQUENCY OF READINGS AND LENGTH OF RECORDS

The analysis of the performance of the HST model was performed in two steps. First, simulation was used to evaluate the performance of the model as a function of the frequency of readings and the total observation period. Second, the actual performance of the model was evaluated for different types of measurements and dams using a representative sample from several dams.

Simulations were performed with a simplified model that included the seasonal and irreversible displacement components. The hydrostatic effect is generally not as important for Hydro-Quebec dams since most are run-of-the-river dams. Only a few of the reservoir dams exhibit large seasonal variations of the water level. In these cases, part of the dam response to water level fluctuations are captured by the seasonal effect. The first series of simulations was performed for a seasonal component without irreversible displacements. The simulations were performed for a period of 40 years and unit amplitude for the seasonal variation. The period of 40 years was selected since it represents the maximum record length for the monitoring data base on dams. Noise was added to the signal to represent the influence of short term variations in air temperature, measurements uncertainty and other effects not captured by the HST model. The noise level is modeled as a normally distributed random variable with zero mean and a standard deviation defined as a specified percentage of the amplitude of the base signal. Each run consists of 1000 simulations of a daily record over a 40 years period. Samples are obtained from each simulation using a given sampling rate, sampling strategy and length of record, and model parameters are estimated and compiled. Mean values and 90% confidence intervals are obtained for each of the model parameters as well as for the coefficient of determination.

Results for the simulation are discussed for the analysis of global displacements. These are measured using either topographical surveys or pendulums (inverted or simple). Surveying data is obtained at frequencies that may vary from once every two years to up to once a month. The higher frequencies are usually during the first fill-up of the reservoir and the lower frequencies are usually for older dams. Sampling frequencies on pendulums are higher and may vary from 4 to 12 per year for manual data, and to daily readings in the case of automated devices. Simulations were performed for frequencies varying between 1 to 12 per year. Higher frequencies were investigated and showed that there was no significant gain in the accuracy of the models for frequencies greater than 12 per year. This conclusion applies to global displacements and may not be valid for other types of measurements that are exhibit high short term variability.

For low sampling frequencies (= 2), the timing at which readings are obtained is critical for the coefficient of determination. The coefficient of determination can be significantly affected by the time of the first reading for a sampling frequency of twice a year. The simulations indicate that the seasonal model can be estimated accurately as long as the observations correspond to the region close to the maximum and minimum seasonal values. In this simulation, the neutral point corresponds to a sampling date of 0 and the maximum at a sampling date of 90. In this case, high coefficients of determination can be obtained with observations within 60 days of seasonal highs and lows. Note that these cases correspond to sampling schemes that are repeated at the same dates every year, and that the coefficient of determination is for predictions at the same dates. The errors of predictions for observations away from the sampling periods can be quite large. For these reasons, the better practice in structural monitoring is to obtain observations under similar seasonal conditions. Given the proper sampling scheme, Figures 5 and 6 indicate that high coefficients of determination can be obtained with relatively small samples (> 30 observations) for the seasonal model.

For displacements that are dominated by irreversible displacements, Figure 7 indicates that for sampling rates as low as two observations per year, high coefficients of determination can be achieved irrespective of the date of sampling when the rate of irreversible displacements and the length of the record combine such that the seasonal component of the displacements become less significant. A sampling scheme at the peaks of the seasonal displacements can be used to estimate both the seasonal and irreversible components of displacements while a sampling scheme at the neutral point can be used to estimate only the irreversible component of displacements. Consequently, the importance of sampling rates and sample size decrease with the rate of irreversible displacements as well as with the length of the period of observation. For structures that are severely affected by the alkali-aggregate reaction, the dominant component of long term displacements becomes linear, and seasonal as well as hydrostatic components become less significant for predicting the overall behavior of the structure (Figure 7).

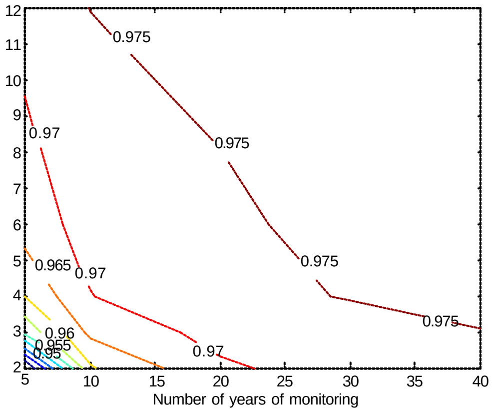


Figure 5 Coefficient of determination as a function of length of record and sampling rate for a seasonal component.

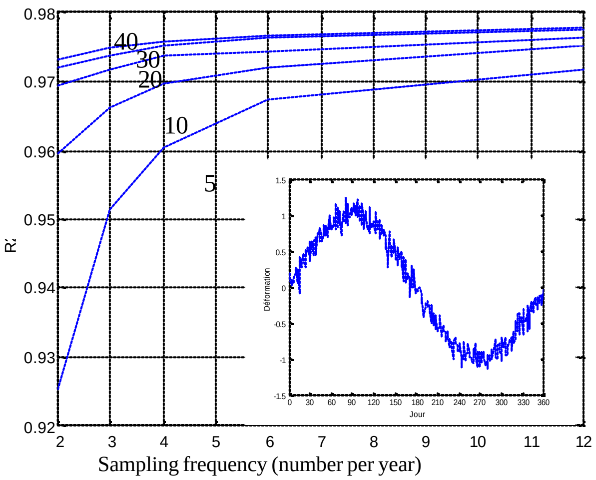


Figure 6 Coefficient of determination as a function of sampling frequency and length of record for a seasonal component.

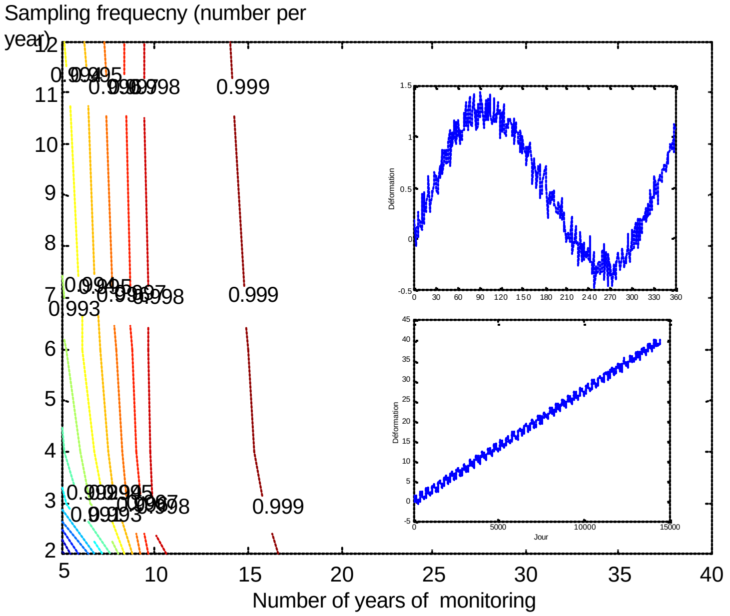


Figure 7 Coefficient of determination as a function of sampling frequency and length of record for seasonal and irreversible components.

The HST model was evaluated for a large sample of pendulums and topographical surveys. Figure 8 shows the scatter plot of the sampling frequency and length of record for pendulums which exhibits a very wide range of samples. Typically, the sampling frequency varies during the service life of a dam. Sampling rates are high initially during first filling of the reservoir and decrease with the number of years of service life. The effect of varying sampling rates does not affect the coefficient of determination. High initial sampling rates are beneficial to establish as early as possible the seasonal and hydrostatic dependency of the structural response. Both of these dependencies are usually linear and reversible. Lower sampling rates after several years of operation are acceptable for structures that do not exhibit significant deterioration and are sufficient to monitor the rate of irreversible displacements. The histogram for the coefficient of determination for the sample indicates that a very large proportion of the pendulums are very well represented by the HST model. The cases where low coefficients of determination were obtained are mainly associated with instruments that exhibit erratic measurements due to instrumentation malfunctions. Low coefficients of determination are also associated with instruments that are affected by short term variations in air temperatures that cannot be modeled with the seasonal effect.

The HST model was also investigated for its application to local displacements, infiltrations and pressure. However, these measurements are subject to nonlinear behavior and cannot be modeled accurately with the HST model. For these instruments, length of record and sampling frequency has to be higher in order to estimate accurately the nonlinear components of these models (Chouinard et al. 1995). Preliminary results also indicate that nonlinear structural responses are often functionally related. For this reason, multivariate statistical analysis procedures are better suited as prediction models. High sampling rates can be beneficial for those cases in order to capture transition points in behavior and to develop accurate multivariate models.

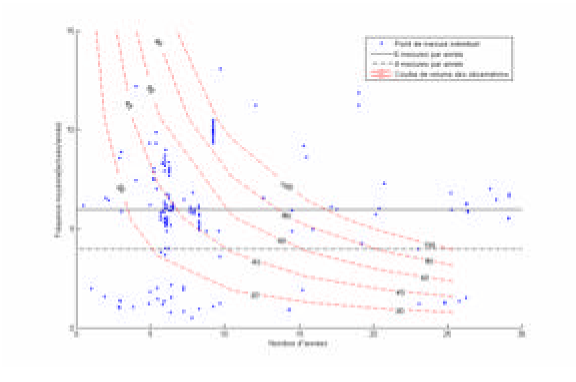


Figure 8 Frequency of sampling and length of record for a sample of pendulums.

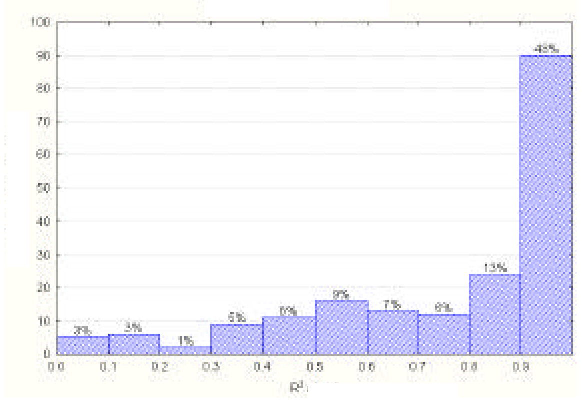


Figure 9 Histogram of the coefficient of determination for a sample of pendulums.

CONCLUSIONS

Structural monitoring is increasingly used as a tool to implement optimal maintenance and management strategies for infrastructures. Dams are among the few structures that have been instrumented and monitored over long time periods and provide a wealth of historical data to develop optimal monitoring and surveillance strategies. One the main issues in developing monitoring programs and fitting linear regression models to structural responses is the effect of sampling frequency and length of record. Both issues were examined for monitoring global displacements in concrete gravity dams using simulation. Global displacements in concrete dams can be separated into hydrostatic, seasonal (thermal) and irreversible effects. Seasonal effects are usually dominant on a yearly basis; however, irreversible effects can easily dominate when the structure is affected by the alkali-aggregate reaction as the length of the historical record increases. The results of the simulation indicate that sampling rates greater than 6 times a year do not significantly increase the good-of-fit of regression models for dams that are mainly subject to seasonal effects. For dams that are affected by the alkali-aggregate reaction, irreversible effects become increasingly dominant with the length of the historical record. Sampling rates in this case do not need to be as frequent since the main purpose of monitoring is to estimate the rate of irreversible displacements.

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