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An analytical model for the monitoring of pore water pressure inside embankment dams

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ABSTRACT

The hydraulic behaviour of embankment dams is influenced by many factors, such as hydrostatic loads and settlement. Particularly, the delayed response due to the diffusion phenomena plays a crucial role in the interpretation of the monitoring data gathered in embankment dams. The paper describes a statistical analysis model named EFR (EFfet Retard - Delayed effect), based on the HST (Hydrostatic-Season-Time) model, for the monitoring of pore water pressure inside embankment dams. The model allows separating the influence of the most important factors and takes into account the delayed hydrostatic effect. The use of this model leads to a better estimation of the irreversible trend and enables an earlier detection of abnormal pore water pressures. An application of this model to a French embankment dam is provided in the second part of the paper. Based on this application, the influence of different diffusion models, calculation methods for the equivalent reservoir water levels and the irreversible term versions on the EFR analysis results are discussed.

1. Introduction

According to the ICOLD (International Commission on Large Dams), the majority of failed dams either did not have any monitoring system or had a system that was out of order [1]. This finding therefore demonstrates the importance of inspection and an appropriate monitoring system for regular observation of dam performance. The objective of dam monitoring, which plays a significant role in the concept of dam safety, is to provide data in order to evaluate dam performances throughout its whole life cycle. The typical safety control variables could be classified into 3 categories: mechanical effects (deformation, displacement), hydraulic effects (seepage flow rate and pore water pressure) and environmental effects (reservoir water levels, precipitation and temperature) [2]. Such variables are quantified by means of monitoring instruments installed in dams.

Once the monitoring data is collected, it is necessary to analyze it inside and in the vicinity of the dam for the purpose of determining and understanding the dam's behaviour. Changes in the behaviour of dams in response to thermal or seasonal effects and to variations in the reservoir water level are mostly reversible. By separating the hydrostatic effect induced by the impounding variations and the thermal effects induced by the temperature variation, some aspects can be better understood. It should be noted that the thermal effects are negligible for embankment dams, and thus can be neglected for analyzing the measurements collected in such dams. Multiple correlation methods are used to draw up models for the following-up and surveillance of monitoring measurements. Over the last fifty years, the increase of knowledge in the field of data analysis has led to the development of analytical methods which can exploit these databases, yielding excellent results [3]. The first physical-statistical model which statistically determines the effects of hydrostatic and thermal loads was formulated in 1967 [4,5]. This HST model accounts for mechanical behaviour, by using a statistical regression technique to find out correlations between causes and quantified effects. It is based on a mean seasonal thermal reference curve for the phenomena observed on dams and it enables one-year periodic variations to be identified according to the reservoir level and time. After many years using this model, its limitation was revealed by the phenomena which are sensitive to variations of temperature because it cannot take real temperature into account. In 2004, a new model named HST-T (-T for thermal) [6] was developed after the heatwave of 2003 to better consider the influences of harsh thermal conditions.

Concerning embankment dams, the monitoring of pore water pressure is crucial because it is the main indicator of internal erosion and seepage problems and has a significant role in the stability of geotechnical works [7–9]. Pagano [10] focused on these pore water

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pressure measurements at different stages of the dam lifetime. The authors collected measurements, particularly during the consolidation process within the dam, in order to detect the effectiveness of measurements, in revealing watertightness problems. These problems are influenced by various external factors due to the fact that the effects of variations in reservoir water levels are not instantaneous since the flow inside the dams are delayed by the low hydraulic conductivity of the materials constituting the embankment. Bonelli and Royet [11] described a model, using a linear dynamic system, to perform delay analysis on pore water pressure measurements. The authors assumed that the delayed effects depend on the convolution of numerical integral of the impulse response and the loadings. However, only the non-ageing factors are modelled in the model. The irreversible trend of measurements therefore cannot be quantified. Lombardi et al. [12] suggested an equivalent formulation of delay analysis to [11], but for thermal response in concrete dams. For more information about the delayed effect analysis of dam behaviour, readers are referred to Salazar et al. [13], in which a review of statistical models for the prediction of dam behaviour is presented.

In order to tackle the problems mentioned above, the EFR model was developed for the analysis of pore water pressure measurements in embankment dams [14]. It allows taking into account delayed hydrostatic effects and obtaining the pore water pressure under identical loading conditions by identifying and separating the influence of the most important factors (ageing and non-ageing factors). The model is able to quantify the delayed hydrostatic effects and leads to a better estimation of the irreversible trend induced by sensors ageing, foundation settlements, soil consolidation and engineering works, etc. Abnormal pore water pressures evolution can be earlier detected with the model, especially in the case of low hydraulic conductivity and for the sensors located far from hydrostatic loads.

The article is organized into two parts. The first part consists in presenting the EFR model in detail, including the principle and calculation of “equivalent reservoir water level” (ERWL). The second part provides an application of the model to a French embankment dam. The underlying diffusion model, the numerical computation method for the ERWL and the irreversible term versions are discussed in this part.

2. Description of EFR model

The EFR model is an extension of the conventional HST model. It is designed for the monitoring of pore water pressure measurements in embankment dams and is able to account for delayed hydrostatic effects. For this reason, a general description of the HST model is provided at first in the section. It is followed by the development of the EFR model.

2.1. General description of the HST model

The HST model was initially proposed by Willm and Beaujoint [5] for the monitoring of global displacements in concrete dams. The model has been widely used for analyzing monitoring data of dams and has been turned out to be a powerful tool for data analysis in dams [15].

The model is based on the assumption that the displacements are mainly explained by three factors: a reversible effect of hydrostatic loads, a reversible seasonal thermal influence and an irreversible term due to the evolution response of dams over time. It consists in a multiple linear regression function Y given in Eq. (1) which is the sum of an average value a_0, different functions modelling independently the three specific factors ($f_{hydro} f_{ther} f_{irre}$) and ϵ a residual error [16].

$$Y = a_0 + f_{hydro} + f_{ther} + f_{irre} + \epsilon \tag{1}$$

The function f_{hydro} is usually a polynomial function of degree 4 to model hydrostatic effect:

$$f_{hydro}(Z) = a_1 \cdot Z + a_2 \cdot Z^2 + a_3 \cdot Z^3 + a_4 \cdot Z^4 \tag{2}$$

where Z represents the relative trough.

$$Z = \frac{RN-R}{RN-R_0} \tag{3}$$

where RN, R_0, R are respectively the full, minimum and real reservoir water level.

The function f_{ther} depends on temperatures, represented by the sum of four sine functions.

$$f_{ther}(\varphi_S) = a_5 \cdot \cos(\varphi_S) + a_6 \cdot \sin(\varphi_S) + a_7 \cdot \cos(2 \cdot \varphi_S) + a_8 \cdot \sin(2 \cdot \varphi_S) \tag{4}$$

where the season is taken into account using the angle φ_S between 0 radian (1st January) and 2π radians (1st January of the next year).

The function f_{irre} is used to model the time-variant and irreversible response due to the sensors ageing, foundation settlements, soil consolidation and engineering works, etc. (the time unit is the year and the time zero corresponds to the 1st January of the studied period) [16]

$$f_{irre}(t) = a_9 \cdot e^{-\frac{t}{t_0}} + a_{10} \cdot t \tag{5}$$

where t_0 (in year) is a constant of exponential damping time. It can be given by users or determined automatically. It should be noted that some authors used other algebraic forms to model the irreversible term [13]. For the sake of simplicity, a simple linear term is adopted in the following described EFR model which is commonly employed in practice [17]. A further discussion on the different irreversible term versions is provided in the later part of the article.

Although this model has been commonly and successfully used in various dams [18–20], it has some limitations in different aspects:

1. The real temperature is not taken into account for the modelling of thermal effects. A term φ_S representing the season is introduced to approximate this effect,
2. The delayed hydrostatic effect, which is important for some cases of monitoring, is ignored in this model,
3. Rainfalls, which have not been taken into account by the HST model, may influence leakages,
4. The governing variables are supposed to be independent, although it has been shown that some of them are correlated [21].

For the particular case of analyzing pore water pressures in embankment dams, the limitation of using the HST model is that the delayed hydrostatic effect is not taken into account. This model considers that the effect of variations in reservoir water levels on pore water pressure is instantaneous, while it is in fact non-instantaneous and is delayed by the low hydraulic conductivity of materials constituting the embankment. In addition, modelling of the thermal effects, as done in the HST model, is not necessary since the effects are negligible in embankment dams.

2.2. EFR model

The EFR model, that represents an improvement of the HST model, was designed to analyze the pore water pressures (PWP) for homogeneous earth dams considering a constant hydraulic conductivity. The principle of the model is first to create a new series of the reservoir water level, named equivalent reservoir water level (ERWL), accounting for the hydrostatic effect induced by the previous impounding levels. Second, the HST model is applied to pore water pressure data, using this new water level series as variable. Compared to the conventional HST model, the thermal term disappears, since the effect is negligible inside embankment dams. Thus, the EFR model only accounts for two effects: the irreversible trend and the hydrostatic load which is modelled by using the ERWL. In summary, the following expression gives the algebraic formulation of the EFR model:

$$PWP = a_0 + a_1 \cdot t + a_2 \cdot Z_e(T_0) + a_3 \cdot Z_e(T_0)^2 + a_4 \cdot Z_e(T_0)^3 + a_5 \cdot Z_e(T_0)^4 + \epsilon \tag{6}$$