8th European Workshop On Structural Health Monitoring (EWSHM 2016), 5-8 July 2016, Spain, Bilbao
www.ndt.net/app.EWSHM2016

Assessment of the structural behaviour of concrete dams based on wavelet transforms

Juan MATA [1], João Pedro SANTOS[2]

[1] Concrete Dam Department, LNEC jmata@lnec.pt
[2] Structures Department, LNEC josantos@lnec.pt
Portuguese National Laboratory for Civil Engineering (LNEC)
Avenida do Brasil, 101, Lisbon 1700-066 PORTUGAL

Key words: Feature Extraction, Condition monitoring, Statistical analysis, Wavelet transform, Structural health monitoring, Concrete dam.

Abstract

The safety control of large concrete dams, involving monitoring data and numerical modelling, is an important challenge being faced by all stakeholders involved in the exploration and safety of these structures with high social and economic value. In this context, the main concern is the detection of possible malfunctions as early as possible so as to ensure the real-time assessment of the structural behaviour under operation conditions. The structural response observed in large concrete dams is generated by the combination of the effects imposed mainly by the hydrostatic loading and by the temperature variations. The assessment of the observed structural responses, like displacements, is usually performed through its comparison with values obtained by statistical models, also known as quantitative interpretation models, or by numerical models, composed of finite elements or other. The purpose of the research work presented herein is the development of a new methodology, coupled with a computational application, capable of properly assessing the structural behaviour of large concrete dams. This methodology is based on computing quantitative interpretation models and wavelet transforms from monitoring data obtained on site and in relating this type of information, extracted from variables related to the actions' effects and to the structural responses. The testing and validation of the proposed strategy is carried out using data acquired hourly from several years in a large concrete dam. In particular, the relations between the values of displacements and the main loads (water level and temperature) are presented and analysed using multivariate statistical methods and wavelets transform. From this analysis it is shown that the consideration of data in the time frequency domain, based on wavelets, can be of great use for real-time estimation and assessment of dams' structural response.

1 INTRODUCTION

Structural safety control is based on making decisions during the different phases of a dam's life through safety control activities. Thus, the main aim of structural safety control is the assessment of the expected dam behaviour based on models, and on measurements and parameters that characterise the dam's behaviour and its condition. It takes into acount the capacity of a dam to satisfy the structural behaviour requirements under the loads and other influences associated with the construction and operation, even under exceptional events, and consists of assessing the real and actual dam behaviour, under exploitation conditions, in order to detect possible malfunctions as early as possible.

During the dam's life, the performance and dam safety conditions are reassessed for the several accident and incident scenarios, and for other scenarios "suggested" by the observed behaviour through the analysis of relevant parameters (such as self-weight, water level and temperature variations, among others), Fig. 1. Typically, these parameters will describe: the loads or operating conditions to which the system may be subjected, the materials from which the structure is constructed, the materials upon which the structure is to be founded, and the structural response of the dam.

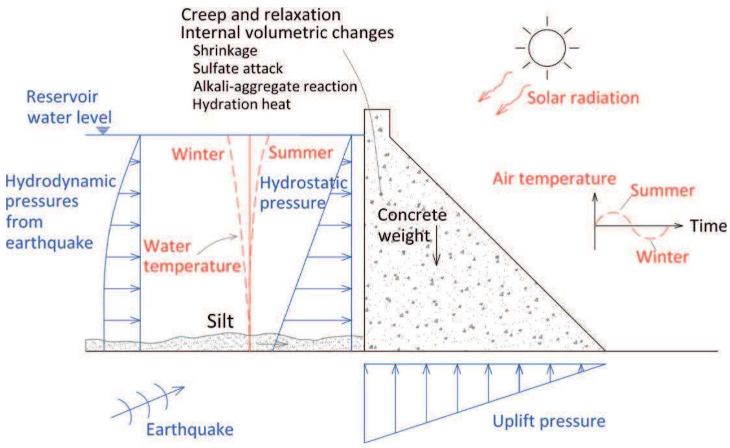

Figure 1: Some parameters usually analysed for the assessment of dam safety and performance.

In terms of the structural dam behaviour, if the results obtained from dam behaviour models (that represent the normal behaviour) and from the observed behaviour (measured) are divergent, then some hypothesis/es which support the model might be no longer valid, and the reason for this change must be identified to assess the consequences.

Over the years, new developments in monitoring systems of concrete dams, namely those based on the implementation of automated data acquisition systems, have increased the capability of measuring the structural response and the main loads at dams, with the desired frequency. The use of automated monitoring systems for supporting the safety control activities has allowed for the integration of the activities related to monitoring, the analysis and interpretation of the dam's behaviour, and dam condition assessment into a near real time process.

The analysis in the time domain is commonly used in dam engineering to study time series related to data obtained from monitoring systems in order to interpret the dam's behaviour. The time evolution of each physical quantity observed is analysed and multivariate relations between the structural response and the main loads are usually performed through quantitative interpretation models (usually based on multiple linear regression analysis), being these models validated over time.

The analysis in the frequency domain is complementary to the time domain. In particular, by spectral analysis, to study the importance of different frequencies in the univariate behaviour and to assess the relation between the variables in terms of frequency are possible. For example, in Mata [1] a procedure is presented for the analysis of the daily variation of structural response due to the daily temperature variation through the application of a Short Time Fourier Transform over the residuals from the traditional quantitative models.

Wavelet analysis reconciles both time domain and frequency domain. This study shows that relevant information for safety assessment and for dam behaviour interpretation can be extracted from the residuals with a time–frequency analysis based on wavelets transforms.

All mathematical calculations and the graphic representations presented in this work were developed using the R project software [2] and the WaveletComp package [3].

2 SAFETY CONTROL OF CONCRETE DAMS

To ensure that structures are safe (prevent accidents) and meet their performance specification (avoid incidents) are the goals of dam engineering. This has to be achieved without threat to the environment and at acceptable cost in terms of construction, operation and maintenance. Part of the elements used in the activities related to the safety control of concrete dams begins to be developed during the design phase as is the case of the definition of each structure's monitoring plan [4]. The monitoring plan must pay attention to the hypotheses and critical aspects considered in the project, taking into account the assessment of potential risks, and the definition of the necessary resources to guarantee the safety control and the dam functionality over time, and the timely detection of any abnormal phenomena. The monitoring plan is established for the entire life of the dam, however, it must be understood as being dynamic and must be revised and updated, if necessary.

To be effective, dam safety control must be considered as an ongoing process. The assessment of the dam's structural behaviour and condition through the use of monitoring systems is a continuous improvement process based on three activities: monitoring, data analysis and interpretation of the dam's behaviour, and dam safety assessment and decision-making.

During the dam's life phases, the models used for the assessment of the dam behaviour are updated to take into account the observed dam behaviour through the monitoring systems. This is the case of quantitative interpretation models, whose parameters can be updated based on the measured dam response over time. In the following section, the main principles of this type of model are explained.

2.1 Analysis of the structural response with quantitative interpretation models

Quantitative interpretation models for the prediction of the structural response of concrete dams are statistical models based on the estimation of parameters, and on several simplifying assumptions concerning the behaviour of materials, such as:

(i) The analysed effects refer to a period in the life of a concrete dam for which there are no relevant structural changes.

(ii) The effects of the regular structural behaviour for normal operating conditions can be represented by two parts: a part of elastic nature (reversible and instantaneous, resulting from the variations of the hydrostatic pressure and the temperature) and another part of the inelastic nature (irreversible) such as a time function.

(iii) The effects of the hydrostatic pressure, temperature, and time changes can be evaluated separately.

HST models (Hydrostatic, Seasonal, Time models) are the traditional quantitative interpretation models usually used. HST models consist in approximating the shape of the deterministic indicators through simple functions which are easier to manipulate [5]. It is considered that the effects associated with a limited time period at a specific point can be approximated by Eq. (1),

$$\delta(h,\ \theta,\ t)= \delta_h+\delta_\theta+\delta_t+k \qquad (1)$$

where $\delta(h, \theta, t)$ is the observed structural response; δ_h is the portion of the structural response due to the elastic effect of hydrostatic pressure; δ_θ is the elastic portion of the structural response due to the effect of temperature depending on the thermal conditions; and δ_t is the portion of the structural response due to the effect function of time considered irreversible.

The separation of effects requires the consideration of a constant k due to the fact that the structural response, measured on the reference date, has a value different from zero.

The portion of the structural response due to the effect of hydrostatic load, δ_h, is usually represented by polynomials depending on the height of the water in the reservoir h, Eq. (2).

$$\delta_h(h)=\beta_1\times h+\beta_2\times h^2+\beta_3\times h^3+\beta_4\times h^4 \quad (2)$$

The portion of the structural response due to the effect of the temperature changes can be considered as a proportional function of the environmental temperature changes, with a phase shift, depending on the depth into the section. The portion of the structural response due to temperature changes is considered as instantaneous with respect to the temperature field in the dam body, but they are deferred with respect to the measured air and water temperatures.

Usual HST models do not use temperature measurements because it is assumed that the thermal effect δ_θ can be represented by the sum of sinusoidal functions with a one-year period [5 to 9]. Thus, the effect of temperature variations is defined by a linear combination of sinusoidal functions which only depends on the day of the year, Eq. (3).

$$\delta_\theta(d)=\beta_5\times sin(d)+\beta_6\times cos(d)+\beta_7\times sin^2(d) \quad (3)$$

where $d = 2\pi j/365$ and j represents the number of days between the beginning of the year (January 1) until the date of observation ($0< j < 366$).

To represent the time effects, t, it is usual to consider the functions presented in Eq. (4), where δ_t is the number of days since the beginning of the analysis.

$$\delta_t(t)=\beta_8\times t+\beta_9\times \varepsilon^{-t} \quad (4)$$

4 CASE STUDY

The Varosa dam (Fig. 2) is located in Portugal and has as its main water line the Varosa River in the Douro hydrographical basin. The Varosa dam consists of a double curvature arch. The construction completion date was 1976. The dam started operating in November 1976 and the maximum reservoir water level was achieved in December 1977. The maximum dam height is 71 m and the total crest length is 213 m. The maximum reservoir water level is 264 m, with a total capacity of 14.5×10^6 m^3.

In accordance with best technical practices, the monitoring system of the Varosa dam aims at the evaluation of the loads; the characterisation of the rheological, thermal and hydraulic properties of the materials; and the evaluation of the structural response.

Figure 2: Downstream view of the Varosa dam.

The monitoring system of the Varosa dam consists of several devices which make it possible to measure quantities such as concrete and air temperatures, reservoir water level, seepage and leakage, displacements in the dam and in its foundation, joint movements, strains and stresses in the concrete, and pressures, among others.

In this case study, the daily variation of the horizontal displacements (radial direction) measured in the highest base of the FP2 pendulum is analysed. In Fig. 3, the location of the FP2 pendulum and the relative position of the highest base are shown.

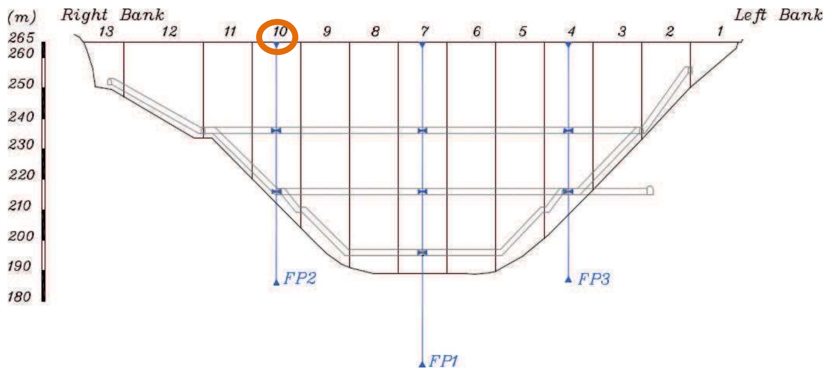

Figure 3: FP2-264(m) location.

The data analysed corresponds to a period between November 2012 and April 2015, resulting in more than 16,903 observations per variable. The time evolution of the reservoir water level, air temperature and radial displacements in the referred FP2 base are presented in Fig. 4. The samples were collected every hour. Among the different loads acting on concrete dams, it is usual to distinguish, as the most important ones for structures in normal operation, the hydrostatic pressure and the temperature variation, Fig. 4. Missing data resulted from malfunction of the data logger.

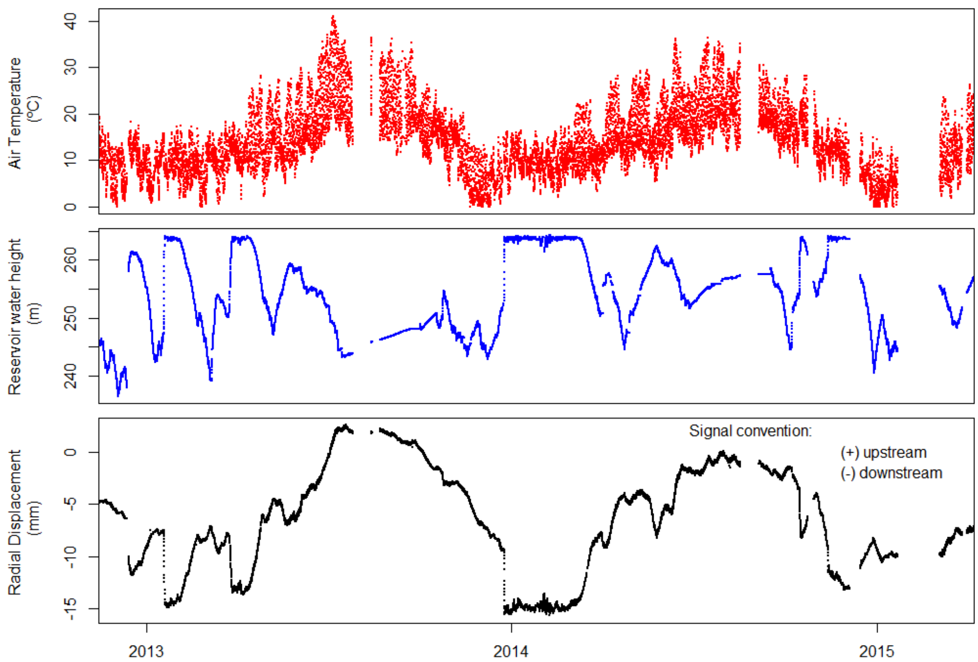

Figure 4: Radial displacements in FP2 - 264m, reservoir water level and air temperature along time.

The structural response of, for instance, the displacement in any point of the dam, is strongly related to the corresponding variation in the water level in the reservoir. The observations presented in Fig. 4 will be used for the computation of the models presented in this work. Signs (+) indicate displacements towards upstream and signs (−) towards downstream.

In this case study, the HST model with the best performance for the upstream–downstream crest displacement of the FP2 pendulum $y^{HST, FP2}$ was obtained as the sum of the hydrostatic pressure term $\beta_4 \times h^4$ (where h is the reservoir water level height and can vary between 0 and 71 m) and the temperature terms $\beta_5 \times sin(d) + \beta_6 \times cos(d)$ to represent the effect of the annual thermal variation of the temperature. The time effect did not seem to have a significant importance in the period examined by this study. The regression coefficients of the quantitative models obtained are $\beta_4 = -3.8188 \times 10^{-7}$, $\beta_5 = -3.0163$ and $\beta_6 = -4.5356$, with $k=-0.5940$; being the HST model represented trough the Eq. (7).

$$Y^{HST, FP1} = \beta_4 \times h^4 + \beta_5 \times sin(d) + \beta_6 \times cos(d) + k \tag{6}$$

As referred before, the residuals were obtained through the difference between the observed horizontal displacement and the corresponding predicted value obtained throught the HST model. These values contain all information that cannot be explained by the model, Fig. 5.

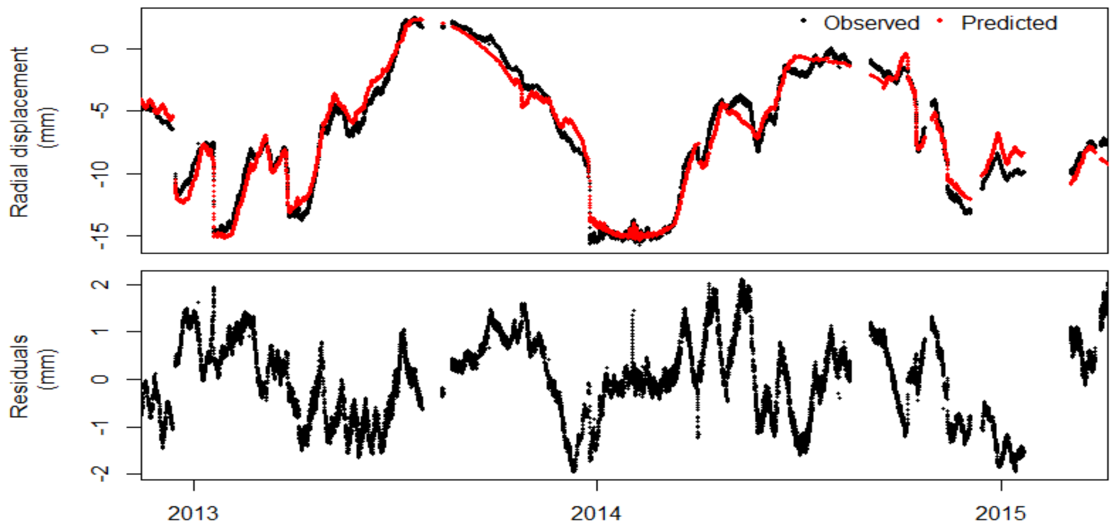

Figure 5: Radial displacements in FP2 - 264m: observed values, predicted values and residuals over time.

4 METHODOLOGY

A procedure to explain the structural response (the daily variation of horizontal displacements in this case study) resulting from the daily temperature variations based on wavelet transforms is presented herein. The aim is to extract the information contained in the residuals[1] obtained from the traditional quantitative models where the thermal effect is usually represented by an annual thermal wave, not considering the effect of the thermal wave with a daily variation.

The proposed procedure is based on the study of the hourly observed values collected by the automated monitoring system and on the analysis of the residuals. A wavelet analysis is

[1] Residuals are the difference between the observed values and the predicted values obtained by models. Besides anomalous phenomena, the residuals contain information related to errors (measurements and model) and other unknown effects.

performed on the residuals in order to assess if there is a pattern on the dam behaviour that can be explained by the temperature daily variation.

4.1 Theoretical concepts - Wavelets transform

Wavelet analysis can be used to identify dominant periodicities in time series that contain nonstationary power at many different frequencies [10].

By decomposing the fluctuations of time series into a series of local wavelets (expressed as local wavelet power spectra), both the frequency (periodicity) and the timing of the fluctuations can be analysed. As a result, wavelets transforms decompose a signal into a set of "frequency bands" (referred to as scales) by projecting the signal onto an element of a set of basis functions called wavelets.

Assume that one has a time series, x_n, with equal time spacing δ_t and $n = 0 \dots N - 1$. Also assume that one has a wavelet function, $\psi_0(\eta)$, that depends on a nondimensional "time" parameter η. To be "admissible" as a wavelet, this function must have zero mean and be localized in both time and frequency space [11].

Wavelets in a basis are all similar to each other, varying only by dilatation and translation [12]. There are different wavelet functions, such as: Haar wavelet, Meyer wavelet, Morlet wavelet, Daubechies wavelet, among others. In this work, the Morlet wavelet was used because it provides a good balance between time and frequency localization [13]. The Morlet wavelet consists of a plane wave modulated by a Gaussian, Eq. (5).

$$\Psi_0(\eta) = \pi^{-1/4}\, e^{i\omega_0\eta}\, e^{(-\eta^2)/2t} \quad (5)$$

where ω_0 is the nondimensional frequency, here taken to be 6 to satisfy the admissibility condition [14]. The continuous wavelet transform on a time series x (t) can be written as

$$W_x(\tau, s) = \int_{-\infty}^{+\infty} x(t)\psi_{t,s}^{*}(t)dt \quad (6)$$

where * represents the complex conjugate. Thus, the wavelet transform decomposes a time series x(t) in terms of certain basis functions (wavelets), $\Psi_{\tau,s}(t)$ analogously to the use of sines and cosines in Fourier analysis. The term wavelet means small wave. "Small" because it has a finite duration and "wave" because it presents an oscillatory behaviour. These basis functions are derived from the so-called mother wavelet $\Psi(t)$ defined as

$$\psi_{t,s}(t) = \frac{1}{\sqrt{s}}\psi\left(\frac{t-\tau}{s}\right) \quad (6)$$

where τ determines the moment in time, and s the scale.

4.2 Application and results

The time series of the residuals shown in Fig. 5 contain several data gaps. To perform the wavelet analysis of the residuals, these gaps were filled by linear interpolation in order to obtain the bigger picture of the behavioral pattern of the residuals, shown in Fig. 6. However, as larger gaps could not be filled by interpolation without affecting the results, wavelet power spectra for two subsets of the time series, with trend removed and with a sufficient number of consecutive data points, were calculated separately, and are shown in Fig. 7.

From Fig. 6, a well define wave with period equal to 24 h can be observed, but only in the warm seasons, and not during the cold ones. The blue bands correspond to the time periods with lag of data filled by linear interpolation.

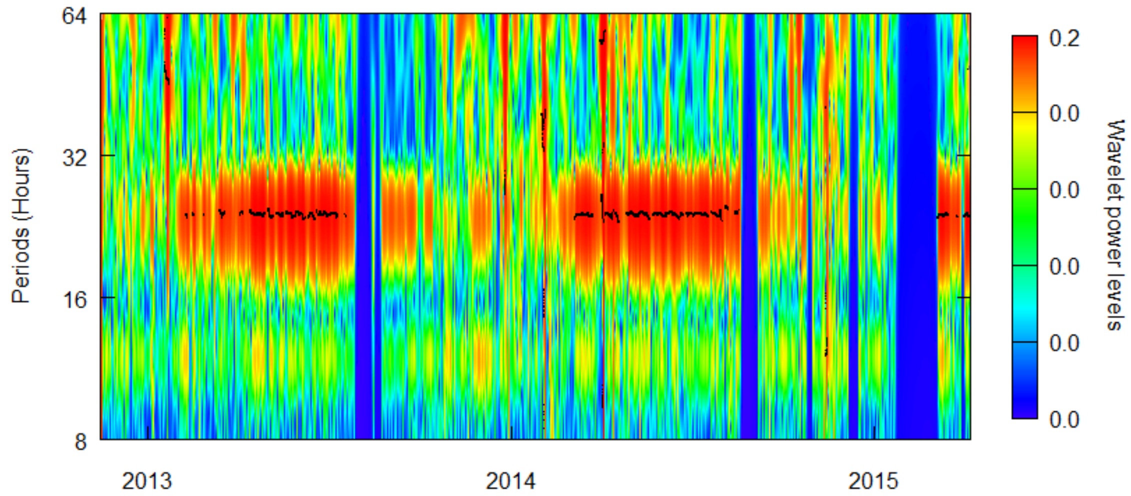

Figure 6: Wavelet power spectrum of the residuals.

From a preliminary analysis of the data shown in Fig. 5, it appears that the residuals from the horizontal displacement model do not have any unconsidered effect. They seem to comprise only random and noisy behaviour. However, when two zooms, from 2013-11-09 to 2013-11-15 (Fig.7a) and from 2014-06-24 to 2014-06-30 (Fig.7b), of the residual distribution are considered, a daily variation is observed in the second but not in the first. The results of the wavelet transform of the time periods considered in Fig.7a and in Fig.7b are consistent with this pattern, being possible to carry out the reconstruction of the time series, using the wavelet decomposition, for the warm seasons but not for the cold ones, as shown in Fig. 7b. A possible explanation for this phenomenon, not usually seen in monitoring activities of concrete dams is related to the fact that the contraction joints are more closed during the warm seasons, allowing a strong structural continuity effect, resulting that the effect of the thermal daily variation has greater influence on the structural dam behaviour. Once the Varosa dam is a structure with great thermal inertia, small effect of this daily variation is expected.

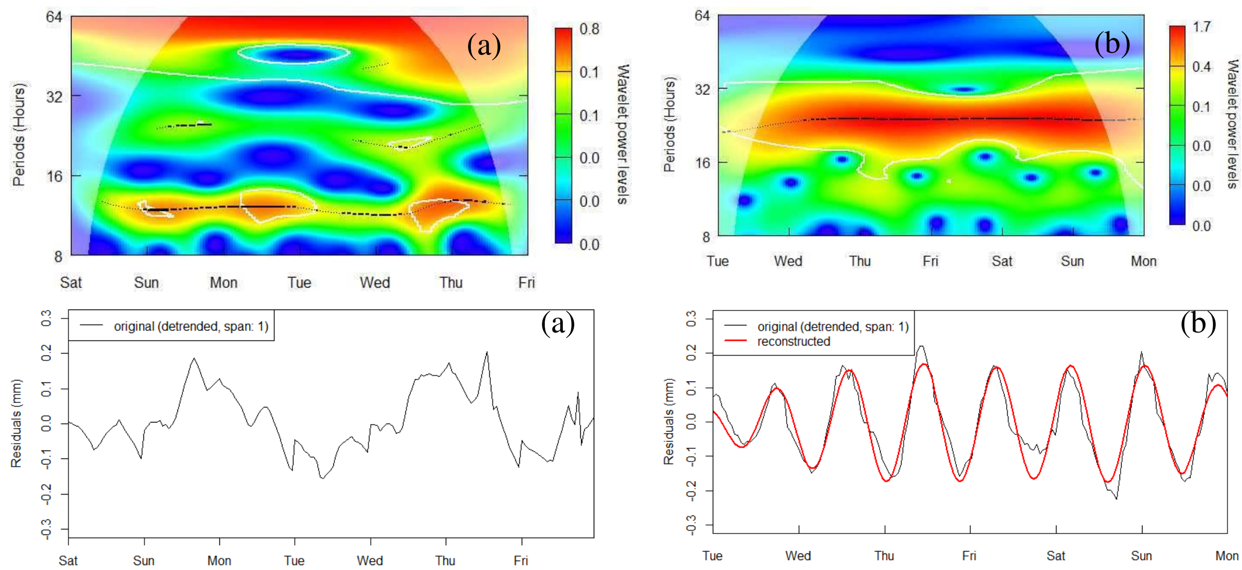

Figure 7: Wavelet power spectrum of the residuals for the time series (a) comprised between 2013-11-09 and 2013-11-15, and (b) comprised between 2014-06-24 and 2014-06-30.

6 CONCLUSIONS

In this study, a procedure for the analysis of the daily variation of structural response was presented. It was shown how wavelet transforms can provide information that is difficult or sometimes impossible to obtain from analysis conducted in the time domain.

The main idea of the proposed procedure is to extract information that cannot be obtained by the traditional quantitative interpretation models. The presented procedure allows the earlier detection of anomalies through the analysis of the daily effects of air temperature on the dam's behaviour.

The application of wavelet transforms over the residuals from the traditional quantitative models related to structural response allows for the identification of the daily variations' waves.

The relation between the structural response and the main loads, in a concrete dam with normal behaviour, is linear. However, nonlinearities can be introduced into the structural behaviour through the influence of damage. The structural response for a damaged concrete dam can be time variant and, as a consequence, the frequency content may change over time.

The proposed procedure can be used for assessing continued performance and safety of the dam.

Future research, based on the application of the proposed procedure to dams where it is known that the daily variation of temperature has a stronger effect on the structural response, should be conducted. The improvement of information obtained is expected to be significant regarding the structural behaviour of concrete dams.

ACKNOWLEDGEMENTS

The authors acknowledge the company *EDP-Energias de Portugal* that provided the data for the procedures addressed in this paper.

REFERENCES

[1] J. Mata, A. Tavares de Castro, and J. Sá da Costa. Time-frequency analysis for concrete dam safety control: Correlation between the daily variation of structural response and air temperature. *Engineering Structures. Elsevier*, 48:8, 2013.

[2] R Development Core Team. "*R: a language and environment for statistical computing R foundation for statistical computing*". Vienna, Austria. 2008. ISBN 3-900051-07-0, <http://www.R-project.org>.

[3] Angi Roesch and Harald Schmidbauer. WaveletComp: Computational Wavelet Analysis. *R package version 1.0.*, 2014. http://www.hs-stat.com/projects/WaveletComp/WaveletComp_guided_tour.pdf

[4] RSB. Regulation for the Safety of Dams. *Decree-law number 344/2007* of October 15 (in Portuguese), 2007.

[5] Swiss Committee on Dams. Methods of analysis for the prediction and the verification of dam behaviour. In *21st Congress of the International Commission on Large Dams*, Montreal, Switzerland, 2003.

[6] G. Lombardi. Advanced data interpretation for diagnosis of concrete dams. *Technical report, International Centre for Mechanical Sciences*, Minusio, Switzerland, 2004.

[7] P. Leger and M. Leclerc. Hydrostatic, temperature, time displacement model for concrete dams. *Journal of Engineering Mechanics*, 133(**3**):267{277, 2007.

[8] F. Perner and P. Obernhuber. Analysis of arch dam deformations. *Frontiers of Architecture and Civil Engineering in China*, 4(**1**):102-108, 2010.

[9] J. Mata. Interpretation of concrete dam behaviour with artificial neural network and multiple linear regression models. *Engineering Structures. Elsevier,* 33(**3**):903-910, 2011.

[10] Daubechies. The wavelet transform time-frequency localization and signal analysis. IEEE Trans. Inform. Theory, 36, 961–1004 (1990).

[11] C. Torrence, G. Compo. A Practical Guide to Wavelet Analysis. *American Meteorological Society*, 1998.

[12] L. Barford, R. Shane Fazzio, David R. Smith. An Introduction to Wavelets. Instruments and Photonics Laboratory. HPL-92-124 (1992).

[13] A. Grinsted, J. Moore, S. Jevrejeva. Application of the cross wavelet transform and wavelet coherence to geophysical time series, Nonlin. Processes Geophys., 11, 561–566, doi:10.5194/npg-11-561-2004 (2004).

[14] M. Farge. Wavelet transforms and their applications to turbulence. Annu. Rev. Fluid Mech., 24, 395–457 (1992).