Dynamic testing of a concrete arch dam

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ABSTRACT: Dynamic testing can offer insight into the behaviour of dams and the calibration of dam structural models. A major drawback has been the need to measure excitation forces during testing in order to extract modal parameters (natural frequencies, damping ratios, modal mass, etc) from measurements. The development of the so called output only techniques (operational modal analysis) for extracting modal parameters has expanded the applications of dynamic testing. Output only techniques do not require the input force to be measured in order to extract modal parameters. Operational modal analysis lends itself well to testing of large structures such as dams. This paper reports on dynamic testing of a concrete arch dam. The results of dynamic tests will be used to establish baseline measurements for long term dynamic monitoring of the dam. Also the application of wavelet analysis in long-term monitoring is demonstrated.

1 INTRODUCTION

This paper reports ambient vibration testing of Roode Elsberg dam. The goal of the testing program was to obtain the as built dynamic characteristics (natural frequencies & damping ratios) of the dam to be used as baseline measurements for long term monitoring of the dam. The measurements would also be used to calibrate the finite element model of the dam. The need for a long term monitoring system forms part of the Department of Water Affairs’ program of dam surveillance and monitoring. At present the monitoring system on the dam consists of Maihak clinometers, stress cells, temperature sensors, pendulum clinometers and crack gauges. Monitoring of the dynamic characteristics will provide in depth understanding of the structural behaviour of the dam including the interaction between the dam and the bedrock and the interaction between dam building blocks.

2 AMBIENT VIBRATION TESTING OF DAMS

Early ambient vibration testing of dams was reported by Ellis et al (1982) and Brownjohn et al (1986). Their findings highlighted the challenges of identifying natural frequencies of large stiff structures from ambient vibration testing. Kemp et al (1996), Loh and Wu (1996), Darbre et al (2000) reported successful periodic ambient vibration testing of Ruskin, Fei-Tsui and Mauvoisin dams respectively. Darbre (2002) monitored Mauvoisin dam for a period of about 180 days. These studies indicate that there have been significant improvements in ambient vibration testing of dams from early trials in the 1980s. The improvements can be attributed to developments in instrumentation and signal processing algorithms.

Although there have been successful applications of ambient vibration testing to dynamic testing of dams challenges still exist. Nonlinear behaviour of concrete dams coupled with low
level excitation results in a non-stationary system which makes it difficult to identify dynamic characteristics using techniques which assume that a dam is a stationery system. Here the potential of wavelet analysis for analysis of ambient vibration signals is proposed. Wavelet analysis is now well established for time-frequency analysis Daubechies (1992), Strang and Nguyen (1996). The main advantage of wavelet analysis over windowed Fourier analysis is that whereas the Fourier coefficients at different frequencies depend on the full length of the selected window, wavelet coefficients are a function of scale. Scale is related to frequency by:

\[ F_a = \frac{F_c}{a \Delta t} \]  

where \( F_a \) = the pseudo-frequency at scale \( a \) (Hz), \( F_c \) = centre frequency of a wavelet (Hz), \( \Delta t \) = sampling period (seconds).

The time-windowed analysis provided by wavelet analysis enables detection of abrupt changes and transients which is not easily achievable in Fourier analysis. This property makes wavelet analysis well suited for ambient vibration testing monitoring of dams where nonlinear effects and varying environmental loads are present.

3 ROODE ELSBERG DAM

Roode Elsberg Dam (Figure 1) is located on the Sanddrift River about 9 km west of De Doorns and 30 km from Worcester. The dam is the lower of two storage dams constructed on the Sanddrift River (Figure 2). The two dams supply irrigation water to the surrounding vineyards.

The Roode Elsberg Dam is a double curvature concrete arch dam with a centrally located spillway. The dam has a gross capacity of 8.21 million m\(^3\). The height to lowest foundation point is 72 m and the length of the crest is 274 m. The dam consists of two galleries with the lower gallery at foundation level. Figure 3 show a typical cross-section through the dam.

![Figure 1: Roode Elsberg Dam.](image)

4 PHOTOGRAPHS AND FIGURES

The following were the objectives of the field tests:

i) Assess the capabilities of ambient vibration testing of concrete dams;

ii) Obtain dynamics characteristics of the dam to be used as baseline measurements for long term monitoring of the dam.
Ambient vibration measurements were taken on the dam’s crest and in the two galleries. Two measurements were taken per block on the crest while measurements were taken at approximately 10m intervals in the galleries. No measurements were taken on the spillway owing to lack of access. All measurements were taken the radial direction.
Testing was carried out over a period of two days, 11\textsuperscript{th} and 12\textsuperscript{th} December 2008. Measurements on the crest and the lower gallery were done on the first day of tests and measurements in the middle gallery were carried out on the second day. The 11\textsuperscript{th} of December 2008 was windy and hot while the 12\textsuperscript{th} of December 2008 was warm, with very little wind. In both cases the dam was 100% full.

4.1 Instrumentation and sampling

Four roving force balance accelerometers with a resolution down to 1\(\mu\)g and intrinsic noise of 7 \(\mu\)g (0-10Hz) and 70 \(\mu\)g (10-500Hz), with one reference accelerometer were used. The accelerometers were have a nominal sensitivity of 6V/g. Data acquisition was via the National Instruments 8 channel dynamic signal analyser (NI PCI 4472B). All 8 inputs are simultaneously sampled with a 24bit resolution at 1000Hz with each point sampled for 1-5min. Power supply was provided by a portable generator.

4.2 Listing and numbering

Figure 4 shows a typical time history measured on the dam crest. Output only frequency response functions were obtained using MEScope software ® (Figure 5). The frequency response spectrum suggests that there the first mode occurs at about 3.09 Hz. The first five natural frequencies and damping ratios estimated from the measurements are given in Table 1. Modes shapes were obtained by interpolating on measurements. Figure 6 shows the mode shapes corresponding to 3.09 Hz and 4.39 Hz respectively.
Table 1: Natural frequencies

<table>
<thead>
<tr>
<th>Frequency (Hz)</th>
<th>3.09</th>
<th>4.39</th>
<th>5.64</th>
<th>6.49</th>
<th>7.23</th>
</tr>
</thead>
<tbody>
<tr>
<td>Damping (%)</td>
<td>1.41</td>
<td>0.15</td>
<td>1.00</td>
<td>0.38</td>
<td>0.10</td>
</tr>
</tbody>
</table>

Figure 6: Mode shapes

Figure 7: Scalogram of time history.
The continuous wavelet transform was applied on a segment of time history data (8192 samples) using db8 wavelet. Analysis focused on scales corresponding to the frequency range 0.667Hz – 1.30Hz. The centre frequency of the db8 wavelet is 0.666667Hz and thus the relevant scale range is 667 to 500 respectively (using equation 1). Figure 7 shows the wavelet scalogram of the transformed data. The scalogram clearly shows energy concentration on scales 933, 857, 730, 567 corresponding to pseudo-frequencies of approximately 0.71Hz, 0.78Hz, 0.91Hz and 1.18Hz respectively indicating possibility of modes of vibration at these frequencies. The wavelet transform is thus able to show the possibility of natural frequencies which would have been missed by the traditional methods.

5 CONCLUSIONS

Dominant natural frequencies of Roode Elsberg dam were obtained using ambient vibration testing. Application of wavelet analysis revealed that there are possible modes of vibration at natural frequencies lower than those determined by output only frequency response techniques. Thus integrating wavelet analysis in longterm vibration based monitoring of dams.

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REFERENCES


Brownjohn, J.M.W., Severn, R.T., Taylor, C.A., (1986), Ambient vibration survey of Contra Dam, University of Bristol, pp 31

Daubechies, I. 1992. Ten lectures on wavelets, SIAM.


