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Prototype measurements of pressure fluctuations in The Dalles Dam stilling basin

Mesures prototype des fluctuations de pression dans le bassin de tranquillisation du barrage de Dalles

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ABSTRACT

At The Dalles Dam on the Columbia River, fish are believed to sustain injury from exposure to turbulence and from collisions with baffle blocks and end sills in the stilling basin at high spillway discharges. Because taking velocity measurements would be exceedingly difficult in this environment, a system of pressure transducers was installed to record high-frequency pressure data for a range of spillway discharges. The sensors were mounted below two of the spillbays on the tops, faces, and sides of baffle blocks; in the gaps between baffle blocks; and on the top and face of the end sill. Statistical analyses on results from three sensors below one of the two spillways showed that mean pressure increased during head-on flow, decreased in flow separation zones, and was proportional to water depth. Power spectra indicate increased low-frequency spectral power with increased discharge, typical spectral decay rates, and the existence of spectral peaks of possible hydraulic origin. The high-frequency pressure data collected at full scale in extremely turbulent environments will contribute to efforts to improve fish passage and to develop and validate three-dimensional computational fluid dynamics models.

RÉSUMÉ

Au barrage de Dalles sur le fleuve Columbia, les poissons sont censés supporter des dommages dus à leur exposition à la turbulence et aux collisions avec les blocs latéraux et les seuils à l'extrémité du bassin de tranquillisation lors des décharges importantes. En raison de la difficulté excessive des mesures de vitesse dans cet environnement, un système de capteurs de pression a été installé afin d'enregistrer les données de pression à haute fréquence pour toute une gamme de décharges de déversoir. Les sondes ont été montées en-dessous de deux des déversoirs, sur le dessus, la face, et les côtés des blocs latéraux; dans les espaces entre les blocs latéraux; et sur le dessus et la face du seuil d'extrémité. Les analyses statistiques des résultats provenant de trois sondes situées en-dessous d'un des deux déversoirs ont montré que la pression moyenne augmentait pendant l'écoulement frontal, diminuait dans des zones de séparation d'écoulement, et était proportionnelle à la profondeur d'eau. Les spectres de puissance indiquent un accroissement de la puissance spectrale de basse fréquence avec l'augmentation du débit, des taux spectraux typiques de décroissance, et l'existence de pics spectraux probablement d'origine hydraulique. Les données de pression à haute fréquence rassemblées à grande échelle dans ces environnements extrêmement turbulents contribueront aux efforts réalisés pour améliorer le passage des poissons et pour développer et valider les modèles numériques tridimensionnels de dynamique des fluides.

Keywords: Prototype measurement, pressure fluctuation, stilling basin, pressure spectra, fish injury.

1 Introduction

The Dalles Dam is located at river kilometer 306 on the main stem Columbia River. The dam consists of a navigation lock, a 22-unit powerhouse, a 23-gate spillway, and fish passage facilities. The stilling basin at the dam contains wedge-shaped baffle blocks and an end sill to dissipate hydraulic energy. Fish are believed to sustain injury as a result of collisions with those structures and exposures to the severe turbulence in the stilling basin (Coutant and Whitney, 2000; Deng *et al.*, 2005). Data from observations, physical modeling, and computational fluid dynamics (CFD) modeling (Cook *et al.*, 2002) suggest that strong lateral entrainment flow occurs in the stilling basin at some spill patterns. This lateral flow increases the probability that retention time of fish in the stilling basin will be longer, subsequently increasing the potential for fish to collide with the structures and be exposed to severe turbulence.

Characterization of the hydraulic environment near the baffles and end sill in the stilling basin is extremely difficult due to high velocities, turbulence, and entrained air. One possible approach to acquiring information on the flow field in such an environment is to mount pressure transducers to record pressure data. These

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transducers can then provide information on the means, extremes, and variations in pressure, which can be used to estimate mean velocity and turbulence.

Numerous studies deploying pressure transducers to collect hydraulic information in turbulent environments have been conducted. Most of these focused on tidal environments and wave action (e.g. Herbers and Guza, 1994) or wall pressure beneath boundary layers in lab environments (e.g. Bull, 1996). The studies most applicable to our situation, however, were those examining pressure fluctuations associated with hydraulic jumps (e.g. Bowers and Tsai, 1969; Toso and Bowers, 1988; Armenio *et al.*, 2000) or submerged obstacles (e.g. Lauchle and Kargus, 2000). Bowers and Tsai (1969) scaled pressure data from model studies of stilling basins to prototype values. They showed that the pressures fluctuated 40% above and below the mean pressure and that most of the energy in the power spectrum of pressure data was at frequencies below 1 Hz. We found no studies, however, in which high-frequency pressure data were collected at full scale in extremely turbulent environments such as The Dalles Dam stilling basin.

2 Experimental equipment and procedure

Each pair of pressure transducers used in this study consisted of a Model 1502 (static) and a Model 106B (dynamic) pressure sensor by PCB Piezotronics, Inc. The Model 1502 and 106B unit were accurate to within 0.035 and 0.058 m of water, respectively. The pressure transducers were installed in the stilling basin downstream of Spillbay 4 and Spillbay 9 (Fig. 1). The transducer pairs were located on the front faces, the tops, and the sides of the baffle blocks; on the front and top of the end sill; and in the channels between the baffles. They were mounted in prefabricated housings with the cables bundled, covered, and run under an angle iron held down with flanges bolted into the concrete.

Pressure data were collected at ambient flow conditions (static scenario) with zero spillway discharge, discharge centered around Spillbay 4 (scenario 1), discharge centered around Spillbay 9 (scenario 2), symmetric discharge spanning the side of the stilling basin (scenario 3), and asymmetric discharge on the side of the stilling basin, as recommended by National Marine Fisheries Service (2000) (scenario 4). Each flow scenario began with a 15 min flow stabilization period, followed by data recording for 5 min at 2,500 Hz in Spillbay 4 and 6000 Hz in Spillbay 9.

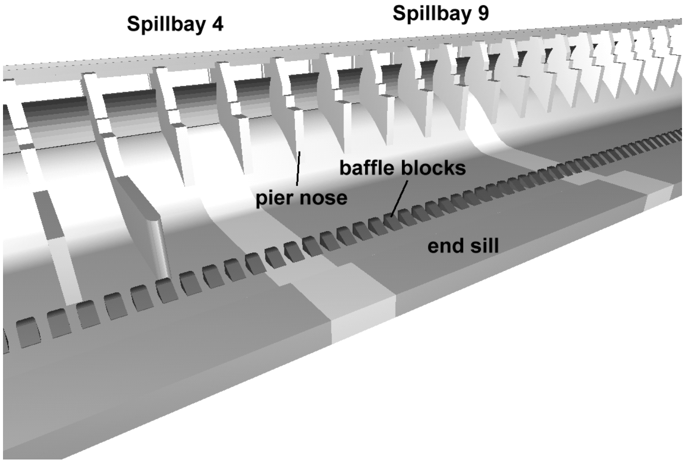

Figure 1 Overview of The Dalles Dam spillways looking upstream.

3 Data analysis

A data analysis and visualization software package (DADiSP) was used to process all data. The normalized data for each channel from each scenario were divided into 20 equal bins. A power spectrum was generated for each bin, and the power spectra for all the bins were then averaged to create the final power spectrum for each scenario. Skewness and excess kurtosis (defined as kurtosis minus 3) also were computed for each sensor at each scenario to verify the normality (symmetry and shape) of the dataset distribution (Zar, 1999).

Spectral decay was examined as well. Using the classical Kolmogorov (1941) theory (Frisch, 1995), Monin and Yaglom (1975) theoretically derived the general form of the pressure spectrum as $p(k) = \phi(k\eta)\bar{\varepsilon}^{3/4}k^{-7/3}$ where ϕ is a non-dimensional function, where k is the spatial wave number, and η is the Kolmogorov scale. The wave number k is defined as $k = 2\pi/\lambda$, where λ is the wavelength. As suggested by Taylor's frozen field hypothesis, k is related to frequency f by $k = 2\pi f/U_c$, where U_c is the average streamwise velocity. For a given measurement, U_c is treated as a constant. Therefore, $P(k) \propto k^{-5/3}$ is equivalent to $P(k) \propto f^{-7/3}$. Many investigations (e.g. Hill and Thoroddsen, 1997) have been conducted on the scaling of the pressure spectrum in turbulent flow, although there still is no general agreement. In addition, some studies using a direct numerical simulation (DNS) technique (e.g. Gotoh and Rogallo, 1999) showed that a $P(k) \propto k^{-5/3}$ better represents the scaling of pressure spectra than the classical $k^{-7/3}$.

4 Experimental results

The extreme turbulence in the stilling basin damaged many of the transducers as testing commenced. Below Spillbay 4, three transducers were able to collect usable data for all scenarios. The data collected by the four sensors below Spillbay 9 appeared to contain excessive noise. Therefore, only the data from Spillbay 4 are presented in this paper.

The mean pressure for each sensor was comparable to the water depth of the submerged sensor during the static scenario (Table 1). The mean pressure increased on the end-sill face and decreased on top of the baffle block and end-sill top when subjected to direct flow. A hydraulic jump occurred just downstream of the end sill at high discharges.

Pressure measurements and their power spectra (Fig. 2) illustrate the time series of pressure data and the signal strength with respect to frequency for the component waveforms of the data. The raw pressure data show an increase on the end-sill face and a decrease on the end-sill top and the baffle block top that occurred at high flows (Fig. 2(a) 2(c) and 2(e)). On the end-sill top, the

Table 1 Mean pressure measurements (μ) and standard deviation (σ) in meters of water at Spillbay 4

Location	Depth (m)	Static $\mu(\sigma)$	Scenario 1 $\mu(\sigma)$	Scenario 2 $\mu(\sigma)$	Scenario 3 $\mu(\sigma)$	Scenario 4 $\mu(\sigma)$
End-sill top	3.505	3.225 (0.040)	2.838 (0.320)	2.822 (0.067)	3.365 (0.155)	3.051 (0.308)
End-sill face	5.334	4.679 (0.037)	5.718 (0.293)	4.276 (0.055)	5.133 (0.192)	5.685 (0.357)
Baffle top	5.243	4.718 (0.040)	3.685 (0.573)	4.276 (0.058)	4.642 (0.460)	2.914 (0.378)

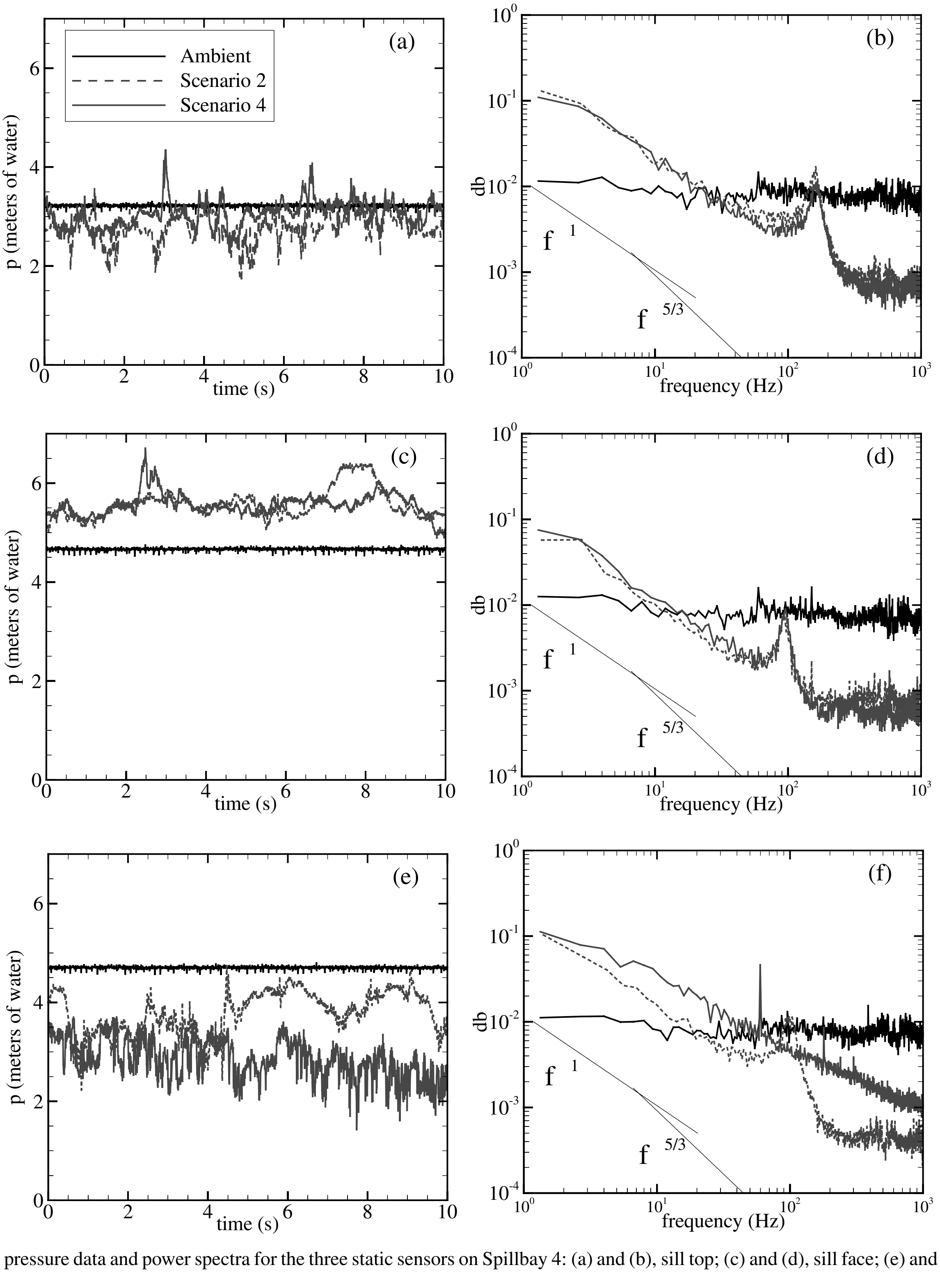

Figure 2 Raw pressure data and power spectra for the three static sensors on Spillbay 4: (a) and (b), sill top; (c) and (d), sill face; (e) and (f), baffle top.

end-sill face, and the baffle block top, the low-frequency spectral energy increased and the high-frequency spectral energy decreased during head-on flow. Some low-frequency spectral peaks existed below 10 Hz, which may have resulted from waves or large-scale turbulent flow. Higher-frequency peaks also existed in each of the power spectra. The corresponding frequencies were 102, 94, and 162 Hz at baffle blocks, end-sill face, and end-sill top, respectively. Because they were not due to electrical noise or other obvious sources, they most likely were related to small-scale vortex shedding off the triangular static sensor housing.

The skewness of the end-sill top and baffle top was negative, indicating that data were skewed slightly to the left of the mean and lower-pressure measurements (Table 2). However, the pressure data at the end-sill face were positively skewed, indicating a slight skew to high pressures. The positive excess kurtosis values indicated a high concentration around the mean and in the tails far from the mean as compared to a normal distribution (Zar, 1999). These values suggest that low-frequency, extreme-pressure events may have occurred more often on the end-sill face than on the top of the end sill and baffle.

5 Discussion and conclusions

The mean pressures were proportional to water depth; the incident flow velocity, variability, and spectral power increased with oncoming flow; the mean pressure decreased in flow separation zones on top of structures; and a hydraulic jump occurred at the end sill. Toso and Bowers (1988) and Bowers and Tsai (1969) found that the total pressure fluctuations are on the order of 80 to 100% of the incident velocity head in a hydraulic jump. They also stated that the pressure fluctuations can be on the order of 10 to 20 times the RMS of the pressure. Using these relationships and substituting the pressure standard deviation (σ_p) for the RMS, we estimated the incident velocity to the end sill as

$$0.8\frac{v^2}{2g} = 10.\sigma_{\mathrm{p}} \Rightarrow v = \sqrt{\frac{2g10\sigma_{\mathrm{p}}}{0.8}} = 8.47\,\mathrm{m/s}$$

which agrees well with the estimates derived from computational fluid dynamics model results (Cook *et al.*, 2002).

Pressure data collected at the end-sill face were skewed toward higher pressures, while those of the end-sill top and baffle top were slightly skewed to lower pressures. All measurements had positive excess kurtosis values, indicating peak distribution instead of the standard normal distribution. In addition, the measurements at the end-sill face had the largest excess kurtosis values. Therefore, the end-sill region may have experienced more low-frequency, severe-pressure events than the end-sill top and baffle top.

Table 2 Higher-order statistics of pressure measurements at Spillbay 4 for Scenario 1

Location	Depth (m)	μ(m)	σ(m)	Skewness	Excess kurtosis
End-sill top	3.505	2.838	0.320	−0.27	1.60
End-sill face	5.334	5.718	0.293	0.72	2.19
Baffle top	5.243	3.685	0.573	−0.51	1.93

The power spectra in this study had a typical decay rate of f^{-1} for low frequencies; they appeared to be more similar to the $f^{-5/3}$ law than to the $f^{-7/3}$ in the higher-frequency range. This characteristic is comparable to the pressure spectra of a plunging jet with jet core impact measured by Bollaert and Schleiss (2003). Power spectra also indicated increased low-frequency spectral power during heavy flows and the existence of spectral peaks of possible hydraulic origin. In addition, the high spectral energy in the low-frequency range indicated that large-scale motions contributed most to the production of turbulent kinetic energy, which is consistent with the findings by Carlson (2001) that dominant large-scale, unsteady vortices exist in the flows of some regions of hydropower plants. Carlson also found that these vortices could have important biological effects, as they have the potential to disorient passing fish and result in increased injury or indirect mortality rates due to predation. Furthermore, these complex flow structures could create zones of high instantaneous shear stress and turbulence, thus contributing more directly to fish injuries.

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