MODEL-PROTOTYPE COMPARISON OF THE PRESSURE FLUCTUATIONS IN THE BOUNDARY LAYER OF A HIGH-HEAD TUNNEL SPILLWAY

K. Warren Frizell

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ABSTRACT

Model and prototype measurements of pressure fluctuations in the left spillway tunnel of Glen Canyon Dam were performed. The 41-ft-diameter, free flowing tunnel was modeled at a 1:42.83 scale at the U. S. Bureau of Reclamation hydraulic laboratory in 1983 when spillway aerators were being designed. Pressure fluctuations were measured at several locations on the tunnel invert throughout the spillway's vertical bend. In 1984, a prototype test was performed to verify the aerator design. At that time, pressure fluctuations were recorded at the same locations as the model measurements. Analysis of the fluctuations for peak values and dominant frequencies was performed. While static pressures followed Froude scaling from model to prototype, the dynamic pressure did not. Spectral analysis identified reasons for the scaling problems which exist.

INTRODUCTION

Pressure fluctuations can be a very important feature in the design and performance of hydraulic structures. Damage due to pressure fluctuations has been serious at a number of structures (1, 4). However, many scaling difficulties arise when predicting prototype values from model data (2, 5). In general, there are three important types of flows which cause pressure fluctuations in hydraulic structures: (1) hydraulic jumps, (2) free falling jets, and (3) bounded and free shear layer flows. As one might expect, due to the different natures of the forcing flows, the resulting pressure fluctuations have some very different characteristics. Most flows have some shear layer induced fluctuations; however, in the case of both a hydraulic jump and an impinging jet, these pressure fluctuations become secondary.

The pressure fluctuations attributed to hydraulic jumps and impinging jets are typically due to the large scale structures characteristic of each of these flows. In a large model, one would expect to scale the eddies and thus the resulting pressure fluctuations. However, pressure fluctuations generated in shear layer flows are much more dependent on the fine scale turbulence. The smaller eddies generated in a model carry much less energy due to viscous dissipation. Air entrainment and air bubble size also become important. These reasons cause pressure fluctuations in shear layers to scale poorly.

*Hydraulic Research Engineer, Hydraulics Branch, U. S. Bureau of Reclamation, D-1532, PO Box 25007, Denver, Colorado 80225.

While generally thought not to be damaging, in high velocity flows the pressure fluctuations in the boundary layer can become important. In a localized sense, cavitation inception first occurs due to fluctuating pressures near the boundary.

The measurement of pressure fluctuations in both the model and prototype has become easier due to developments in transducer technology and analysis equipment. Comparisons, however, are still lacking. The study presented here deals with the measurement of pressure fluctuations in the left spillway tunnel of Glen Canyon Dam. Pressure fluctuations in the turbulent boundary layer in the vertical bend of the spillway tunnel were measured in both the prototype and a 1:42.83 scale hydraulic model.

TESTING

Measurements of the dynamic pressure fluctuations were made using a high frequency response, flush mounted, piezoelectric pressure transducer. Data were collected with a computerized data acquisition system, recording both frequency spectrums and digital time series of pressure data. In the prototype tests, five transducers were installed slightly off bottom center of the 41-ft-diameter spillway tunnel at Glen Canyon Dam. Instrumentation boxes had been embedded in the tunnel lining starting roughly halfway down the vertical bend and continuing into the near horizontal portion of the tunnel. Due to the extreme environment in which the transducers were placed, only three remained operational throughout the tests. These transducers were located at stations 24+20, 25+00, and 26+20, see figure 1. Five discharges were tested: 6,500 ft^3/s, 10,000 ft^3/s, 20,000 ft^3/s, 35,000 ft^3/s, and 50,000 ft^3/s. Data were taken for each of the flow rates on all transducers. Digital pressure measurements were collected at a rate of 500 Hz, allowing for a frequency analysis via FFT (Fast Fourier Transform) up to 250 Hz. Frequency spectrums were measured with a spectrum analyzer, providing energy spectrums in several different frequency ranges (up to 25 kHz).

Model testing was done before and after the prototype tests were completed. A 1:42.83 Froude based scale model had been used in the design of the aeration slots which had been installed in the prototype. The prototype test conditions were duplicated in the model, including transducer location, flow rates, radial gate positions, and reservoir elevations. Digital pressure data were acquired 6.54 times faster in order to attempt scaling frequency information. The model spectrum analyzer data were not taken at scaled frequencies, allowing direct or scaled comparisons.

Identical pressure transducers were used in the model and prototype, the only difference being in the mounting. In the prototype, the tunnel radius allowed flush mounting of the 0.218-in-diameter diaphragm; however, in the model the tunnel radius was too small to consider a flush mount so a manufacturer's recommended chamber mounting was used. A chamber of 0.0625-in diameter and 0.25-in length lead directly to the transducer diaphragm.

DATA ACQUISITION SYSTEM

Similar data acquisition systems were used in the model and prototype tests. The basic system consisted of:

- Desktop calculator with dual disk drives
- Multichannel scanner
- High-speed digital voltmeter
- Spectrum analyzer
- Analog antialiasing filters

The desktop calculator acted as the system controller by running a program used to control the channels which were read, the number of readings, the acquisition rate, and storing of the digital pressure data and spectrums from the spectrum analyzer. The pressure transducers were powered by a constant current source and operated in a current loop configuration. The coupler controller which powered the transducers also provided a voltage output linearly proportional to pressure. In the prototype, long test leads were required to power and receive information from the transducers. A low capacitance cable was used to keep losses to a minimum. Computation of the frequency response of the system with all elements considered, indicated plenty of dynamic range to cover our interests. In the model, the transducers were operated in a similar manner, the main difference being much shorter cable lengths.

Prior to testing, the transducers were calibrated with a dynamic pressure calibrator. The calibrator applied a constant pressure to the transducer over a wide range of frequencies, comparing the output to that of a standard transducer. In addition, the transducer's time constants were measured. The manufacturer's calibrations were found to be satisfactory, and with time constants on the order of 1 second, the sensing of fluctuations about the static pressure level was assured.

RESULTS AND DISCUSSION

The model and prototype results were analyzed in similar manners to allow for comparison. First thoughts were to check if the amplitudes of the pressure fluctuations would scale independently of frequency. The maximum, minimum, and rms (root mean square) values of each time record were tabulated. The model data were scaled to prototype values using Froude scaling laws, see table 1. Conformity in general is poor. The model data do not vary much for changes in discharge. The arithmetic means of the model data tend toward zero whereas in the prototype, we get some variation in the mean above a zero level. The lack of conformance in amplitude alone lead to the inclusion of frequency in the scaling process. Firstly, energy spectrums acquired by the spectrum analyzer were compared directly, see figure 2 for a sample. The basic shapes were similar in the low frequency range (<30 Hz). This is expected based on results of previous researchers. However, much above 100 Hz, the prototype spectrum shows much higher levels. This translates to much higher energy in the small eddy sizes. Another major difference was in a sharp frequency peak present in the model spectrums, figure 3. These peaks were first attributed to the chamber leading to the transducer diaphragm. However, after an analysis of the chambers resonant frequency it was deemed not to be the case. One hypothesis is that air bubbles in the flow are being excited to their resonant frequencies due to the turbulence. The noise peaks are characteristic of zero mode (volumetric) resonant frequencies of air bubble sizes present in the flow. Additional frequency analysis was performed on the digital time series of pressures using FFT techniques. Power spectrums were computed and total power integrated from these for a frequency span of 0-250 Hz, figure 4. As a relative comparison of total energy in a specified frequency span, the prototype levels are three orders of magnitude higher than scaled model results.

Researchers have shown variation in frequency spectrums due to differences in the active pressure sensing area [3]. This could be another consideration in the relatively poor comparison of model and prototype spectra.

CONCLUSIONS

The scaling of pressure fluctuations from Froude-based models is still somewhat of an art. The data presented here showed almost no conformance at all. One might expect that larger models might begin to simulate boundary induced pressure fluctuations more closely since they seem to be tied closely to the fine scale turbulence. As mentioned previously, the pressure fluctuations attributed to large scale eddies, i.e., hydraulic jump and free falling jets, do scale better for all ranges of model sizes. Future work needs to be performed to systematically define the scaling limitations of pressure fluctuations in bounded shear flows.

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CONVERSIONS

1 ft = .3048 m, 1 in = 25.4 mm, 1 $\frac{ft^3}{S}$ = .00283 $\frac{m^3}{S}$

Table 1. - Comparison of P_{rms}, P_{max}, P_{min} for measurements at Sta. 26+20. Model data has been scaled by Froude scaling. Fluctuations are about the static pressure level.

Q (ft^3/s)	P_{rms} (ft of water)	P_{max} (ft of water)	P_{min} (ft of water)	
6,500	5.675	51.86	-63.21	Model
	6.91	28.01	-25.10	Prototype
10,000	2.375	54.52	-59.27	Model
	26.55	62.65	-6.03	Prototype
20,000	2.035	53.24	-57.31	Model
	42.2	91.13	-22.72	Prototype
35,000	3.79	55.64	-63.22	Model
	28.62	126.98	-67.36	Prototype
50,000	4.95	55.33	-65.23	Model
	12.86	55.09	-34.56	Prototype

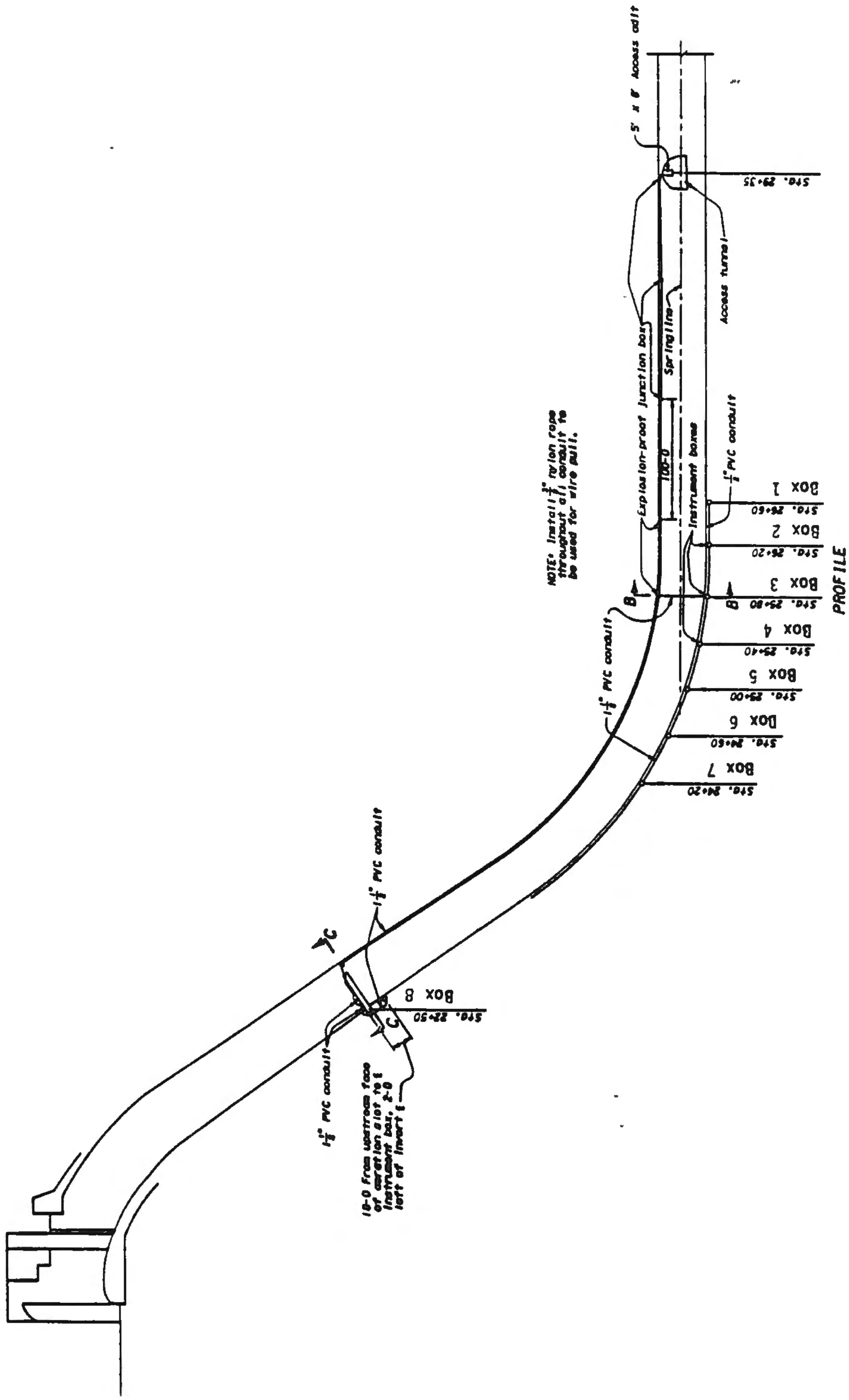

Figure 1. - Glen Canyon left spillway tunnel, location of instrument boxes.

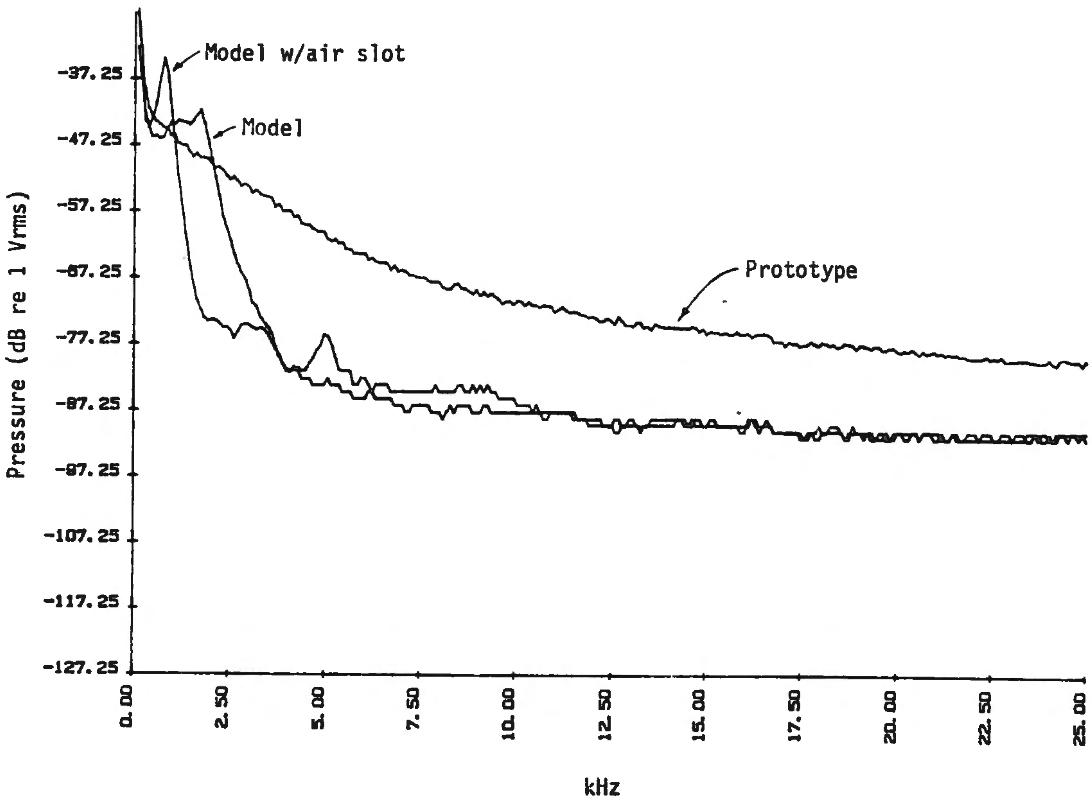

Figure 2. - Direct comparison of spectra measured with spectrum analyzer. Sta. 24+20, amplitudes of model data scaled up. Q = 10,000 ft^3/s.

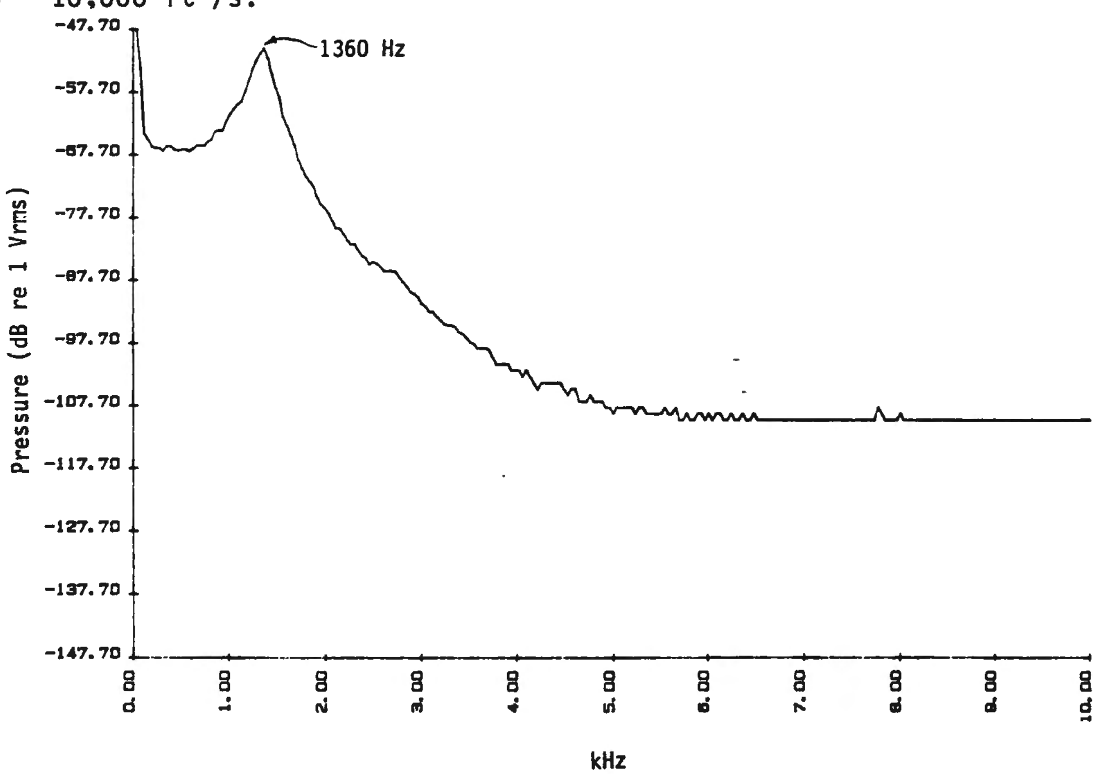

Figure 3. - Model spectra with peak at a frequency characteristic of bubble oscillation noise in the flow.

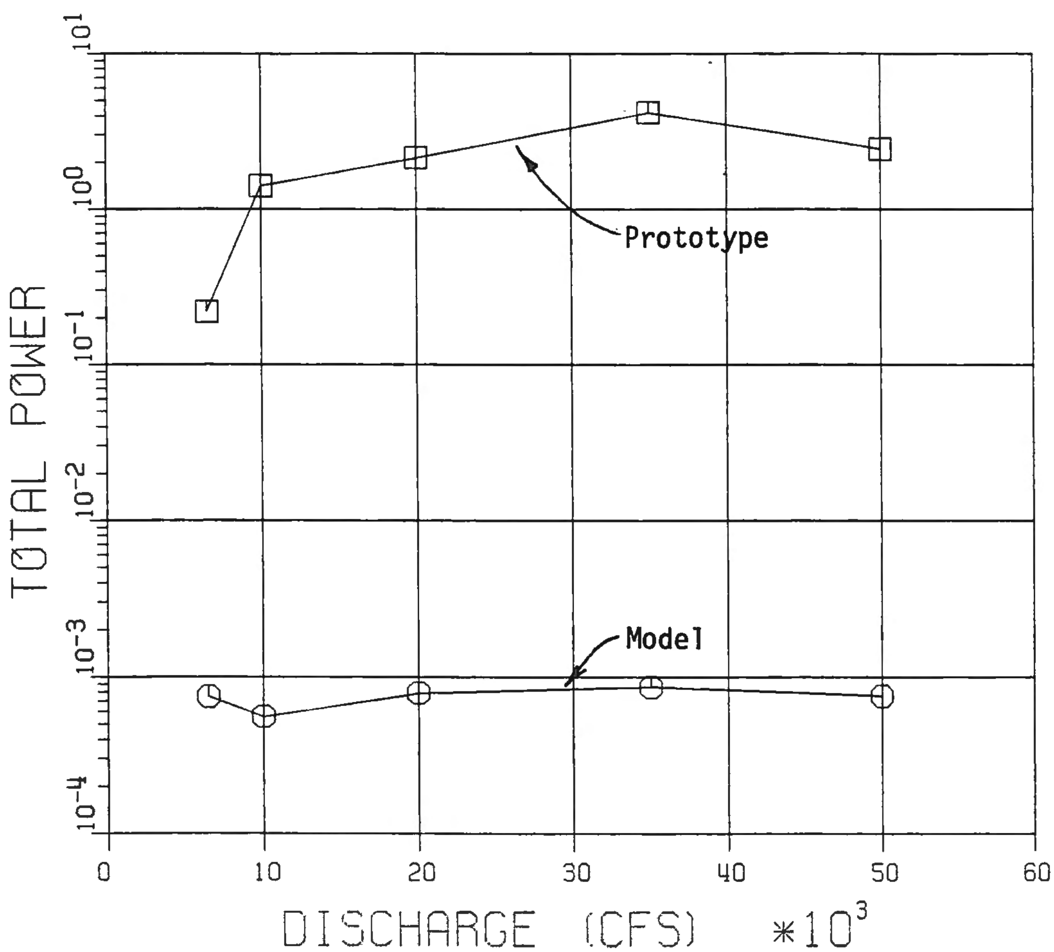

Figure 4. - Comparison of total power for prototype and scaled model (amplitude and frequency) for - 250 Hz band width. Sta. 26+20.