Developing Air Concentration and Velocity Probes for Measuring Highly-Aerated, High-Velocity Flow

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Abstract

The U.S. Bureau of Reclamation's stepped spillway overtopping protection research program required velocity and air concentration profile data be obtained during testing in a large, 15.2-m-high outdoor flume. Both velocity and air concentration profile measurements were needed to evaluate energy dissipation, bulking, and model/prototype correlation with a smaller indoor model.

Measuring highly-aerated, high-velocity (12-17 m/s) flow is not practical using available instruments. Although air concentration measurement devices exist, most are custom made by researchers. As a result, two instruments were developed and calibrated by Reclamation to gather prototype data in our overtopping facility. The instrument development, calibration, and verification will be discussed.

Introduction

The instruments were developed to measure in highly-turbulent, highly-aerated, high-velocity flow. The instruments were developed for obtaining prototype scale velocity and air concentration measurements to verify and extend laboratory data on overtopping embankment dam protection schemes.

Both instruments were developed by Reclamation to quantify energy dissipation in flow over rough surfaces on steep slopes. Tests were performed in a large, outdoor flume facility located at Colorado State University in Fort Collins, Colorado (fig. 1). The 2:1 sloping facility is 15.2-m-high by 1.52-m-wide, and is capable of passing unit discharges of 2.9 $m^3/s/m$, thus theoretical velocities, of up to 17 m/s.

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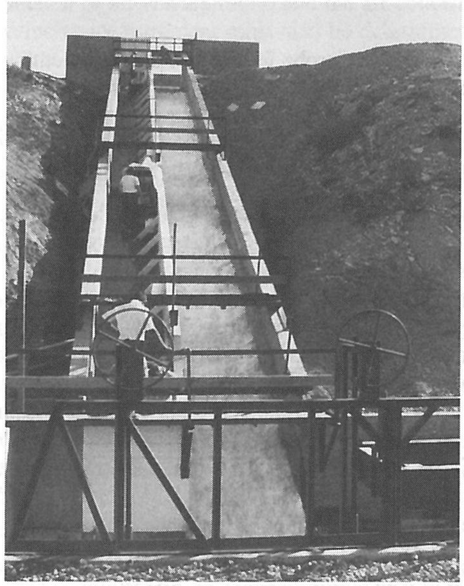


Figure 1. - Near-prototype test facility where instruments were used.

Quantifying energy dissipation requires measurement of flow velocity and air concentration profiles along the slope of the flume. No standard measuring devices were identified that could be used to measure flow velocity or air concentration for the two-phase flow and high-velocity test conditions. In addition, shallow flow depths limited the size of the instruments.

Velocity profile measurements required a very sturdy instrument capable of measuring point velocities in air-water flow. A back flushing pitot tube concept, used earlier in Reclamation's laboratory to determine velocities in slurry flow, was utilized. The components of the velocity probe will be discussed.

An air bubble detector developed by Wood, 1978, and later improved by Bachmaier, 1988, was chosen to measure air concentration. The principle for the air bubble detector is based upon the difference between the electrical resistivity of air and water. The detector electronics and physical probe assembly will be discussed.

Both probes required laboratory calibration to provide relationships to known values or baseline information and prove reliability. The calibration apparatus, procedures, and results are discussed. The instruments were tested and calibrated in Reclamation's hydraulic laboratory prior to their use on the prototype facility. Verification of the instrument's measurements will be presented.

Velocity probe

The development of a velocity probe focused on using something technically simple and stout. This plan was devised after attempting to use several "off the shelf" propeller-type meters. A pitot-static tube designed for mounting on the fuselage of an airplane was attached to the end of a 2-m-long, triangular-shaped shaft. The pitot tube and structural shaft provided good strength for the measuring device.

Flow from a constant head source is fed to both the static pressure ports and the total head port of the pitot tube. This flow provides continuous back flushing of the pitot tube during operation. Back flushing is necessary to maintain a fluid of known density (or in this case solid water) within the pitot tube and connecting tubing. The constant head supply pressure used for back flushing must be larger than the maximum expected velocity head to be measured in the flow. The back pressure is set with a pressure regulating gage. The back flushing flow rate to each port is controlled by low-flow-rate rotameters. Through laboratory testing, a back flushing flow rate of 3.79 l/hr in air was chosen. This flow rate was the minimum flow rate that could be passed and still produce a continuous flow out of the pitot tube ports in air. Back flushing flow rates of 7.57 and 11.36 l/hr also produced good results; however, the lower flow rate provided better low end sensitivity of the instrument.

A differential pressure cell measures the pressure difference between the static and total head ports. The voltage output from the differential pressure cell is sent to an HP3457A integrating voltmeter to determine the average voltage. Using the cell calibration the voltage is converted to pressure head.

The back flushing flow rate is set in air and a baseline reading, or zero offset, is measured from the differential pressure cell. The baseline reading is used to shift the measured data to a common zero velocity that is independent of the back flushing flow rate. This zero reading in air eliminates differences between initial settings of the back flushing flows through the rotameters. Figure 2 shows a schematic of the velocity probe components. After recording the pressure zero, the pitot tube is ready to measure velocity in flowing water.

The velocity from the measured pressure of the pitot tube is determined by:

$$V=\sqrt{\frac{2\,(p_t-p_s)}{\rho}}$$

where: V = velocity (m/s), p_t = total pressure head (Pa), p_s = static pressure head (Pa), and ρ = fluid density (kg/m^3).

This equation shows that pitot tube velocity measurement is dependent on fluid density. In the air entrained flow of the tests, the density of the two-phase fluid varies through the flow depth with air concentration. Therefore, the pitot tube must be calibrated as a function of air concentration and the air concentration of the flow at the point of the velocity measurement must also be determined.

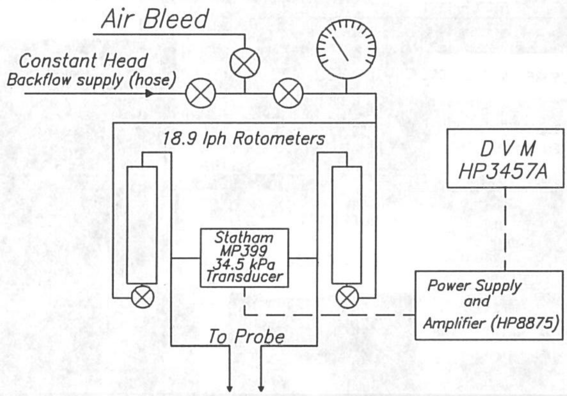


Figure 2. - Schematic of the components used for the velocity probe.

<u>Velocity probe calibration</u>

The velocity probe was calibrated for air concentrations of 0 to about 70 percent by volume. The same calibration setup was used for both the velocity probe and the air concentration probe (Bachmaier, 1988). The calibration apparatus consists of an inverted "U" shaped water pipe system with the water and air volumes entering the system measured with rotameters (fig. 3). Water is supplied to the pipe system on the up leg and an air line with pressure regulator and rotameter is connected to the water pipe on the down leg of the system.

For the velocity probe calibration, a 10-cm-long tip of smaller diameter pipe is attached to the end of the piping system to provide backpressure and obtain a relatively smooth uniform jet of air/water mixture leaving the pipe. Pressure in the tip is monitored using a piezometer tap located two tip diameters upstream of the end. The pressure in the tip is needed to determine the tip cross-sectional area occupied by air as opposed to water. It is desirable to have near atmospheric pressure in the tip to prevent rapid volumetric changes in air concentration at the tip exit. The pitot tube is placed within one tip diameter of the end and centered within the free jet. Water velocity impinging on the total pressure port of the pitot tube is assumed to be equal to the water velocity internal to the calibration apparatus tip. Water velocity is determined as the water discharge divided by the area of the tip minus the area of the entrained air. Air and water discharges are adjusted to achieve a wide range of air/water concentrations and velocities impinging on the pitot tube.

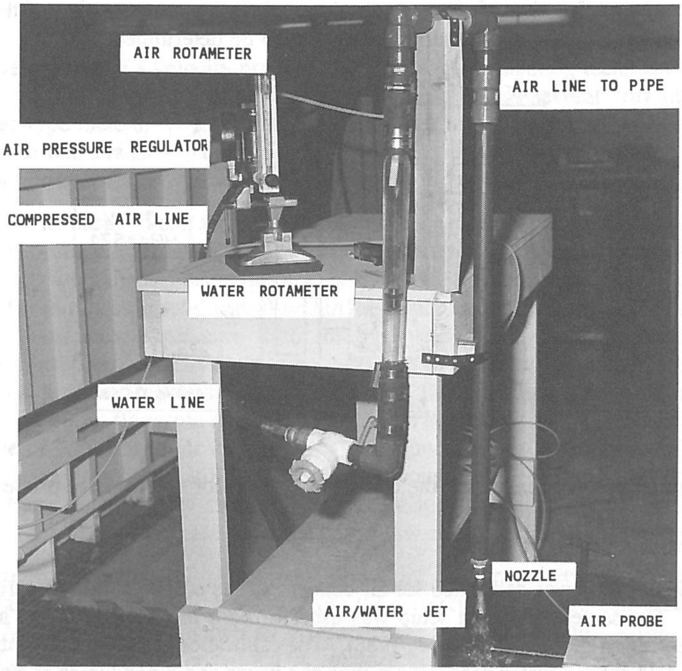


Figure 3. - Test apparatus used to calibrate both the velocity and air concentration instruments.

The calibration produced a family of curves of pressure differential versus velocity for each percent air concentration tested (fig. 4). Good agreement with the theoretically predicted coefficients for air/water density was achieved for 0 and 40 percent air; however, with the higher air concentrations of 58 and 68 percent, the coefficients from the calibrations are significantly higher. The reason for this discrepancy is not known at this time. As may be seen, the data scatter is limited and it was also repeatable. These curves were used with the air concentration data from the large scale flume to correct the measured velocity profiles for the influence of varying density throughout the flow depth. This primary calibration was checked in water (0 percent air concentration) against velocities measured using a laser doppler velocimeter.

Air concentration measurements

An air concentration probe, which acts as an air bubble detector, was based upon previous instrumentation reported by Ian Wood of the University of Canterbury, Christchurch, New Zealand, in 1988. The air concentration measurement is based

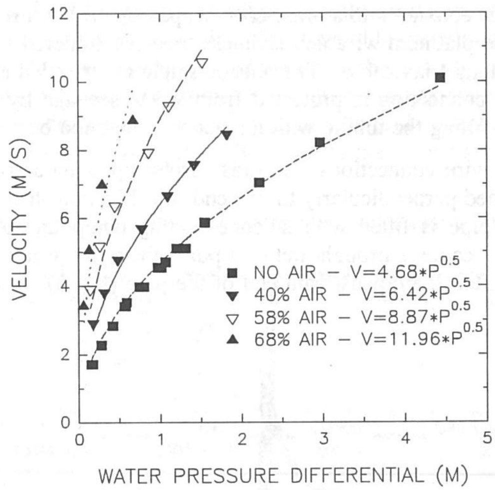


Figure 4. - Calibration curves for the velocity probe.

on the difference in electrical resistivity between air and water. The air probe consists of two concentric conductors encased in a protective support. The tip of an insulated platinum wire is encased in a stainless steel sleeve. The probe polarity is periodically reversed to prevent plating, gassing, and degradation of the probe conductors due to electrolytic action. An air bubble passing across the probe tip interrupts the current flowing between the two conductors. This current is amplified and conditioned to produce a step output. Integrating the resulting signal over time gives the probability of encountering air in the air/water mixture.

The air concentration probe discussion will be separated into the three components that comprise the instrument: the physical probe, the electronics, and the output or data collection equipment. Finally, the calibration results will be presented.

<u>Air probe</u>

The function of the air probe is to provide the conductor or air bubble sensor. The concentric conductors are a 0.2-mm platinum wire set in a 1.59-mm-outside-diameter stainless steel tube 50.8-mm long with waterproof epoxy. The probe sensor and the wire leads are then encased in a sturdy, streamlined support to prevent damage under the high-velocity testing conditions and to carry the wires out to the electronics. The critical part of the probe construction is preventing water from reaching and shorting out the conductors.

The probe sensor is epoxied into a brass cone-shaped tip with a threaded base. The two leads from the platinum wire and stainless tube are soldered to the center and inside shield of a long triax cable. The outside shield is grounded at the electronics end. Every wire connection is protected from water seepage by placing each in shrink tubing and filling the tubing with a silicone compound before shrinking.

After making the wire connections, the brass probe tip is mounted on a threaded 190-mm pipe welded perpendicularly to one end of a 127-mm steel rod. The entire cavity inside the pipe is filled with silicone potting compound to prevent water seepage. The coax cable is brought out to a point above the water surface through copper tubing fitted at the downstream end of the pipe (fig. 5).

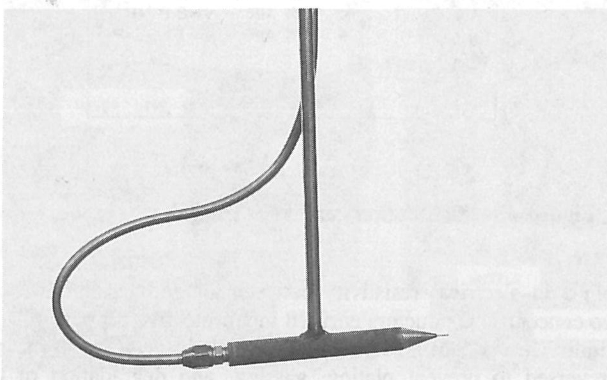


Figure 5. - Photograph of the air concentration probe assembly.

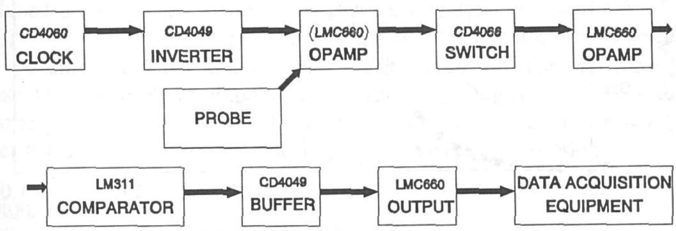
Air bubble detector electronics

The probe electronics for the original design from Wood were built initially, but gave inconsistent and unstable results. The electronics were redesigned using bipolar logic and updated devices. This eliminated the mix of transistor-transistor logic (TTL) and bipolar logic conversions between the two types of logic. The replacement integrated circuits (IC's) were all current production devices to assure continuing availability.

The air concentration probe detects the change between water and air by using the conductivity of water to change the gain of an operational amplifier (opamp). Relatively high gain is used to create an on-off signal that corresponds to the water-air environment of the probe rather than an output proportional to the actual conductivity of the water.

Measuring conductivity in water with single polarity excitation of the probe causes gassing on the probe and a corresponding drift toward higher air concentration. This problem is resolved by periodically switching the probe polarity. The opamp output is switched along with the excitation of the probe to maintain a single polarity output. A common clock signal is used to excite the probe and switch the inputs to an amplifier. The switch also reverses the inputs to maintain a single polarity output from the probe.

This block diagram describes the basic components of the system:



Probe output

Two probe outputs are provided. An analog output using a resistor capacitor filter, provides a running average between 0 and 5 volts over time. The second, is a digital on (5 volts or air) off (0 volts or water) signal that follows the air/water mixture that the probe is sensing. This output can be recorded using a computer or calculated directly using an integrating voltmeter over a fixed period of time.

Air concentration instrument calibration

The air probe electronics are always balanced in water with no air. The probe output is used as input to a Tektronics 454 oscilloscope for balancing and monitoring the quality of the signal. The same apparatus used to calibrate the velocity probe was used to calibrate the air concentration probe (fig. 3) for varying air/water volumes. The air concentration probe tip was located flush with the end of the pipe system nozzle. The probe voltage output was recorded with a Systron+Donner 1033 integrating digital voltmeter.

The air concentration is determined as a ratio of the air volume over the air volume plus the water volume measured in the pipe system. The voltage output from the probe is 0 volts when in water and 500 volts in air. The air/water mixture measured by the probe is a percent of the air voltage (500). Figure 6 shows the final calibration with air concentration versus percent air measured by the probe.

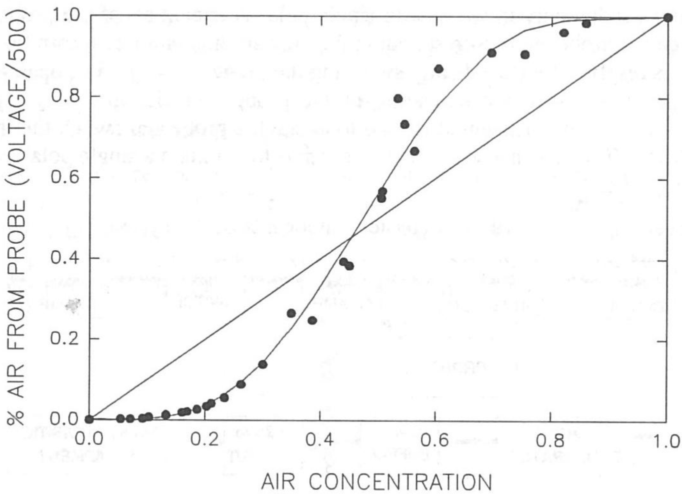


Figure 6. - Calibration curve for the air concentration probe.

When the probe is entirely in water then the probe reads zero. When the probe is entirely in air the probe reads one. If the probe were entirely linear, then this curve would show 50 percent air from the air probe when the measured air and water volumes were identical. When comparing this calibration curve to a linear relationship this curve shows an underprediction of air concentration at small air volumes and an overprediction of air concentration at high air volumes. This calibration, in spite of not being linear, was consistent and repeatable and was used to determine the air concentration in the near-prototype facility. The detector electronics and/or the calibration system could perhaps be improved to linearize the results.

Field operation and problem solving

The field test program began with the air concentration probe fully operational and confidence in the laboratory calibration. As usual with field applications, several problems arose. The primary problems were water leaking into the probe causing it to always indicate water, and the low water conductivity at the field site compared to the laboratory. The difference in water conductivity prevented balancing of the probe at the field site. To solve the problem of water intrusion into the probe it was rebuilt and sealed as discussed. The gain (feedback resistance) for the probe was increased threefold to provide sufficient gain for the detector in the low conductivity water. The higher gain, however, caused a non-symmetric output and oscillation of one of the opamps. The TL074 opamp originally used was replaced with a National LMC660 opamp. The LMC660 still showed a tendency to self oscillate on one polarity of the probe. Therefore, capacitors were installed to eliminate the noise (oscillation), but the non-symmetrical output still existed. Therefore, at high gains, only one polarity of the antiplating period could be used and data were taken only on one side of the antiplating period. These data were used in the final analysis of the project, and work is continuing to attempt to stabilize the electronics.

The LMC660 was replaced with a National LF444CN. This eliminated the noise, but produced an objectional offset. This device was again replaced, this time with a PMI OP470. The OP470 reduced the offset by 10. The noise problem has been reduced considerably, but the output is still not symmetric between the two polarities. One cycle of the output and a longer antiplating period will be used until the symmetry problem is resolved for low conductivity water. Work will continue to correct the symmetry problem and improve the ease of operation.

Conclusions

Both instruments performed very well. Continuity was checked to verify the data gathered using the instruments at various locations down the slope. To check continuity, the profiles obtained on the flume centerline were assumed to be representative of the entire flume cross section. The depth at 90 percent air concentration was assumed to be the water surface. The computed discharges, using the average water velocity times the depth times the flume width, were compared with the known water discharges to the flume. The computed discharges were, on the average, within 8 percent of the known discharges. The largest differences were at the low flow rates where the flows tumbled down the slope. Given the highly turbulent nature of the flow and the assumption that the flow was uniform across the flume width, this is excellent agreement. This simple calculation verified the excellent performance of the developed instruments.

Both instruments will be used in the same facility during the summer of 1994 to measure velocity and air concentration in flow over riprap.

Appendix

Bachmaier, Guido, "Setup, Calibration and Use of a Measuring Probe for Determination of the Air Concentration in a Spillway," Translated from German Ph.D Thesis for the Institute for Hydromechanics of Karlsruhe University, Karlsurhe, Germany, March 1988.

Cain, Paul and Ian Wood, "Measurements within Self-aerated Flow on a Large Spillway," Research Report 78-18, Ph. D Thesis, Department of Civil Engineering, University of Canterbury, Christchurch, New Zealand, April 1978.