PAP-647

AIR CONCENTRATION MEASUREMENTS IN HIGHLY-TURBULENT FLOW ON A STEEPLY-SLOPING CHUTE

August 1994

by

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Presented at the ASCE 1994 Symposium on Hydraulic Measurements and Experimentation, Buffalo, New York

Air Concentration Measurements in Highly-Turbulent Flow on a Steeply-Sloping Chute

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Abstract

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

A probe was developed to measure air concentration in a free-surface, highly-aerated flow. The probe acts as an air bubble detector and is based upon the difference in electrical resistivity between air and water. The basic components of the air bubble detector and its operation are discussed. A sample of the measured air concentration profiles is given with basic comparisons made to published data on aerated flow. The success of the measurements with this instrument means its use could improve the ability to measure the volume of air in an air/water mixture, for a known water flow, in numerous situations.

Introduction

Reclamation has completed investigations of a tapered, overlapping block system installed on the downstream face of an embankment dam to prevent damage during overtopping. The final phase of testing consisted of conducting large scale tests of the tapered block overtopping protection to confirm the stability of the blocks, to investigate energy dissipation, aeration, bulking of the flow, and to confirm model/prototype scaling relationships.

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Quantifying energy dissipation required measuring flow velocity and air concentration profiles along the flume slope. Since standard measuring devices have not been developed for use in the highly-aerated, high-velocity flow conditions encountered, instruments were developed. This paper presents the results from the use of the developed air concentration measurement device.

Overtopping Facility

An overtopping facility was constructed at Colorado State University (CSU) where tapered concrete blocks and other protection measures could be tested at near-prototype scale. The 2:1 sloping facility is 15.2-m high by 1.52-m wide, and is capable of passing unit discharges up to 2.9 $m^3/s/m$ (fig. 1).

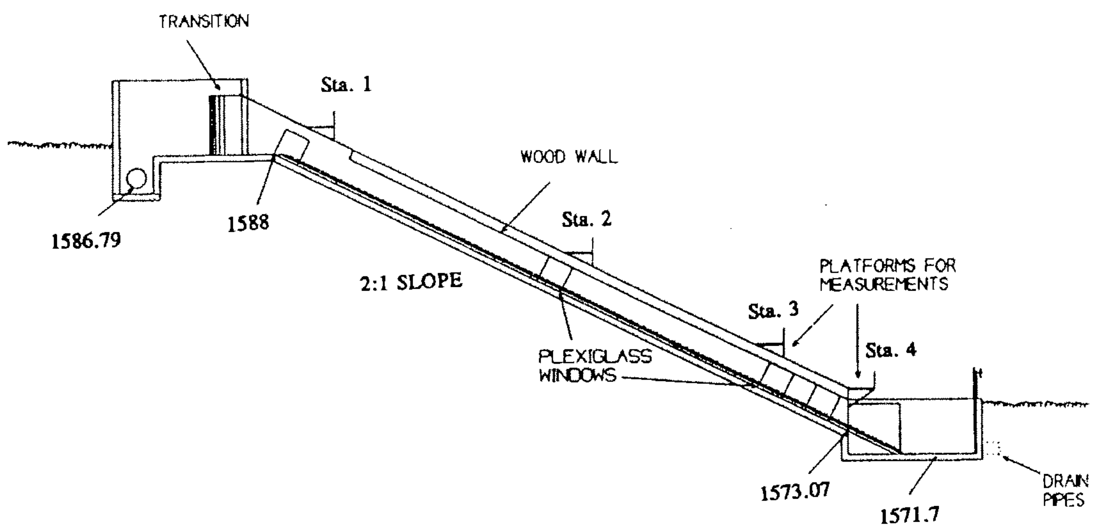

Figure 1. - Facility where air concentration and velocity measurements were taken.

The first series of tests in the overtopping facility proved the stability of the block system (Slovensky, 1993). The next portion of the study determined the energy dissipated by flow over the uniformly rough surface created by the tapered block system. Velocities were measured and corrected with the results of the air concentration measurements to determine final design criteria for the overtopping block protective system.

Flow Conditions Over the Blocks

The overlapping tapered block system produces a uniformly rough surface formed by 63-mm-high step offsets. This extremely rough surface, compared to typical spillway surfaces, causes different flow conditions under the different discharges tested. At the lowest flow tested, 0.31 $m^3/s/m$, water cascades over the blocks, breaking up and entraining air immediately after going over the crest. The air entrainment occurs rapidly and no solid water is observed beyond the second block, about one meter downstream from the crest.

As the discharge and the water depth increases, the cascading flow is replaced by skimming flow. A solid layer of water is observed near the embankment crest and the flow skims over the blocks moving the inception point of air entrainment down the slope. The step roughness creates a separation zone and eddy at the downstream face of each block and an impingement zone on the top of the blocks. These flow conditions create turbulence which quickly extends throughout the flow depth with distance down the slope. Under the highest flow rates tested, entrained air penetrates the full flow depth about one-third to one-half (12-15 m) the distance down the slope (fig. 2). As may be seen from the typical flow condition shown in figure 2, it was difficult to measure velocities and air concentrations in this highly-aerated, high-velocity (12-17 m/s) flow.

Figure 2. - Aerated flow conditions experienced by the flow over the tapered blocks.

Air Concentration Instrumentation

An air concentration probe, which acts as an air bubble detector, was constructed based upon previous instrumentation presented by Cain and Wood (1981a). The air concentration measurement is based upon the difference in electrical resistivity between air and water. The air probe sensor consists of two concentric conductors, a small platinum wire encased in a stainless steel sleeve. The polarity on the sensor is periodically reversed to prevent plating or degradation of the probe tip. An air bubble (0.2 mm or greater) passing across the probe tip interrupts the current passing between the two conductors. Sampling the resulting signal over a fixed time and integrating it provides an average air concentration. Further information on the air probe design and calibration is available in another publication (Frizell, et.al, 1994).

Experimental Results and Observations

Air concentration and velocity data were collected at five different unit discharges ranging from 0.31 to 2.9 $m^3/s/m$. Data were collected on the centerline of the chute at distances of 0.7 m (STA 1), 14.8 m (STA 2), 23.8 m (STA 3), and 26.8 m (STA 4), measured down the slope from the crest (fig. 1). Air concentrations were measured at STAS 2 and 3 for all discharges and at STA 4 for discharges of 2.6 and 2.9 $m^3/s/m$.

Observations of the flow conditions and results from the velocity profiles and depth measurements indicate that uniform fully-aerated flow is attained at some point on the slope for all flow rates. Figure 3 shows air concentration profiles for a unit discharge of 2.6 $m^3/s/m$, a typical result. The air concentration profiles indicate that the flow is still developing at STA 2, where STAS 3 and 4 are in the fully aerated flow region as shown by the similar profiles. The average air concentration computed by integrating the profiles is 0.30 at STA 2 and 0.34 at STAS 3 and 4.

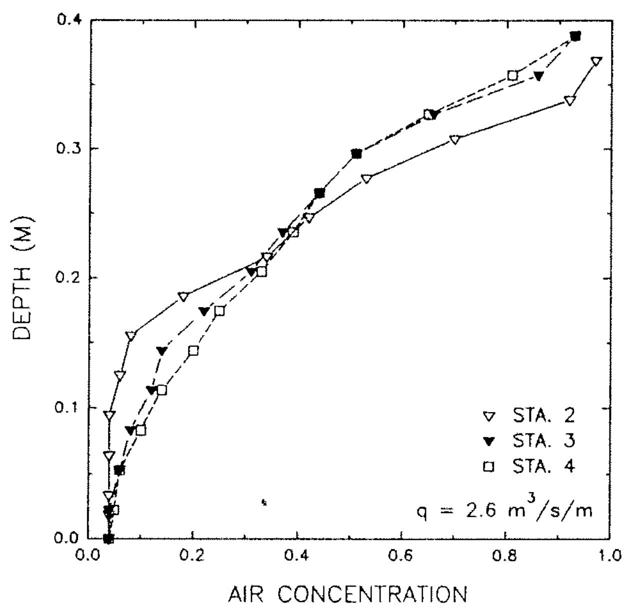

Figure 3. - Air concentration profiles down the 2:1 slope for q= 2.6 $m^3/s/m$.

Summary and Conclusions

Flow at low discharges over the uniformly rough surface produced by the step offsets (63-mm high) of the blocks produces a cascading flow regime that quickly entrains air. The average air concentrations in cascading flows exceed those commonly presented in literature. As the discharge increases, the effects of the roughness are reduced and the air entrained flow begins to skim over the edges of the blocks. In the uniform flow region, the air concentration profiles and average air concentrations become similar over both smooth and rough surfaces. This was seen by comparing the measured air concentration profiles from the rough surface in the flume with the profiles for various slopes with smooth surfaces reported from the classical work by Straub and Anderson (Wood, 1983). The average air concentration for fully developed flow on a 2:1 (H:V) sloped, rough channel (0.34) compares well to data presented for a similarly sloped smooth surface spillway (0.35) (Wood, 1983). These similarities are interesting because of the difference in surface roughness between smooth spillways and the extremely rough surface of the tapered block system.

Continuity was checked at each measurement station down the slope to verify the data. Continuity was checked by comparing the discharge computed using the water velocity profiles, corrected by the air/water density, with the known discharges into the flume. The computed discharges were, on the average, within 8 percent of the known discharges confirming the excellent performance of the instruments.

The air probe is again planned for use in 1994 to measure air entrained during flow over large riprap (0.152-0.457 m) in the same facility.

<u>References</u>

Cain, P., and Wood, I. R., "Instrumentation for Aerated Flow on Spillways," Journal of the Hydraulics Division, ASCE, 107(11), pp. 1407-1424, 1981a.

Cain, P., and Wood, I. R., "Measurement of Self-Aerated Flow on a Spillway," Journal of the Hydraulics Division, ASCE, 107(11), pp. 1424-1444, 1981b.

Frizell, K. H., Ehler, D. G., Mefford, B. W., "Developing Air Concentration and Velocity Probes for Measuring Highly-Aerated, High-Velocity Flow," Proceedings Hydraulic Engineering Conference, ASCE, Buffalo, NY, 1994.

Slovensky, G. G., "Near-Prototype Testing of Wedge-Block Overtopping Protection," Thesis presented to Department of Civil Engineering, Colorado State University, Fort Collins, CO, 1993.

Wood, I. R., "Uniform Region of Self-Aerated Flow," Journal of Hydraulic Engineering, ASCE, 109(3), pp. 447-461, 1983.