Self-Aerated Flows on Chutes and Spillways[a]

Discussion by H. O. Anwar[2]

The author in his interesting paper has attempted to review the mechanisms of self-aerated flows on chutes and spillways. He has accepted: (1) the concept of the inception point, where the turbulent boundary layer, starting to grow almost from the crest, reaches the free surface; and (2) the surface air entrainment occurs downstream from the inception point, when the vertical component of the turbulent velocity exceeds the surface tension pressure. These processes are difficult to envisage. From a series of field experiments carried out by the writer it was found that the turbulent boundary layer on a spillway grew much quicker than anticipated by the author (namely, the inception point, irrespective of the flow thickness) and that it occurred at a distance approximately 1.40 m downstream from the crest, in comparison with 2.35 m calculated from (10) suggested by Wood et al. (1983). Downstream from this point there appeared surface deformation, which, in turn, curved inwardly in the mean flow direction, entrapping air, very similar to the data depicted in Fig. 1 (see also Fig. 2). Fig. (12) was produced by viewing through a rotating prism (Anwar 1965). This leads to the conclusion that the flow became turbulent, not only due to the shear stress of the rigid boundaries, as assumed by the author, but also due to gravity waves, produced by roughness and irregularities at the boundaries, where the global Froude number, based on the mean velocity and the water depth, is larger than unity. The perturbation velocities produced by these waves extended throughout the water depth, enhancing the onset of turbulence. Furthermore, surface deformations (see Figs. 12 and 13) were produced by the gravity waves and also by impingement on the free surface of the upward movements of the turbulent eddies. Interestingly, it was found that by removing the roughness elements from the weir surface, these surface deformations formed further downstream and in some cases disappeared altogether, and the free surface became glossy. The global Froude number at a section upstream from section A-A (see Fig. 12) was approximately unity; it increased to 1.12 at section B-B. The length of the surface deformation at section C-C and beyond, irrespective of the flow discharge over the weir, was on the order of 10 mm; the surface velocity, using the rotating prism, was $U_s = 1.60$ m/s. The air concentration C below the surface was 0.40, and reduced to $C = 0.05$ at middepth, indicating that a great volume of the entrapped air escaped to the atmosphere (see Fig. 13).

The author suggested that by analogy with the aerated flows on spillways,

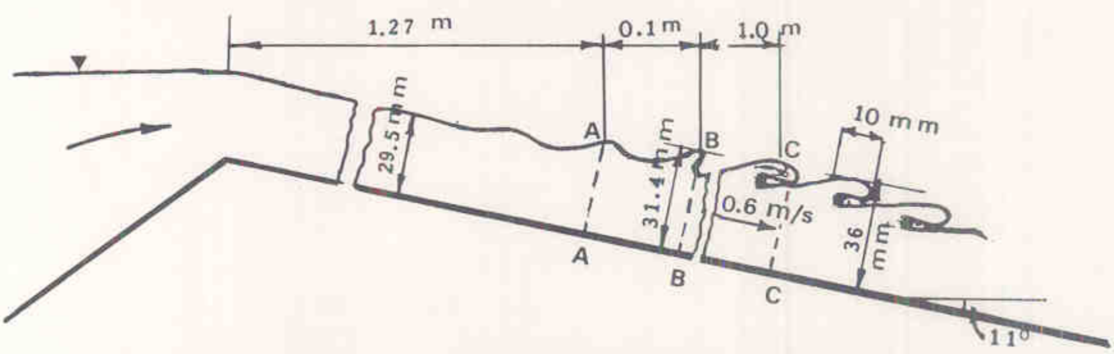

FIG. 12. Surface Deformations of Flow Over Weir

[a]February, 1993, Vol. 119, No. 2, by H. Chanson (Paper 2874).

[2]Hydr. Consultant, 3 Curtyn Close, Abingdon, Oxfordshire OX14 1SE, England.

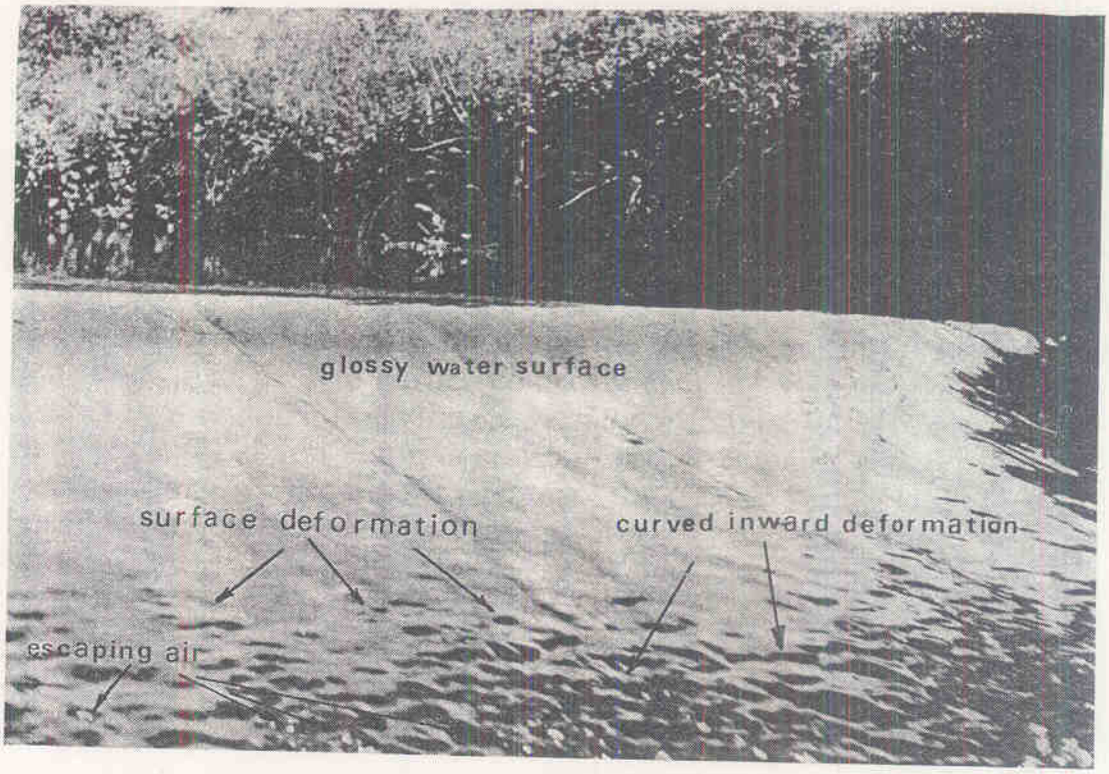

FIG. 13. Development of Flow Over Weir

the suspended sediments in a turbulent boundary layer reduces the skin friction and the von Kármán constant. By contrast, results of extensive laboratory measurements undertaken by Lyn (1988, 1991) revealed that the suspended sediment, not affecting the von Kármán constant, increased the skin friction. Similar results were obtained from a series of field measurements, disclosing that the coefficient of skin friction was close to those measured in clear-water flow over gravel beds (Anwar, in press, 1993).

ACKNOWLEDGMENTS

The writer expresses his thanks to A. F. Whillock and R. May of Hydraulics Research, Wallingford, England, for their help in measurements.

APPENDIX. REFERENCES

Anwar, H. O. (1965). "Flow in a free vortex." *Water Power*, (Apr.), 1–11.
Lyn, D. A. (1988). "A similarity approach to turbulent sediment-laden flows in open channels." *J. Fluid Mech.*, Vol. 193, 1–26.
Lyn, D. A. (1991). "Resistance in flat-bed sediment-laden flows." *J. Hydr. Engrg.*, ASCE, 17(1), 94–114.
Wood, I. R., Ackers, P., and Loveless, J. (1983). "General method for critical point on spillways." *J. Hydr. Engrg.*, ASCE, 109(2), 308–312.

Closure by H. Chanson[3]

The writer thanks the discusser for his interesting comments and information. The writer wishes to clarify three points: free-surface instabilities,

[3]Lect., Hydr. and Fluid Mech., Dept. of Civ. Engrg., Univ. of Queensland, Brisbane QLD 4072, Australia.

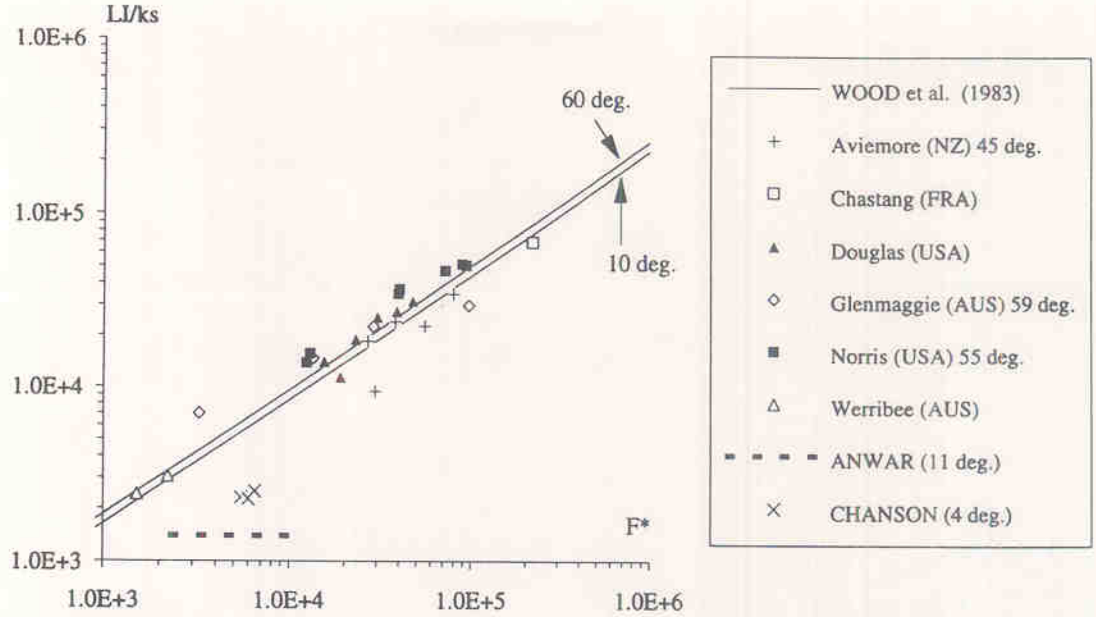

FIG. 14. Location of Point of Inception L_I/k_s: Comparison between Prototype Data (Aviemore, Chastang, Douglas, Glenmaggie, Norris, Werribee), Discusser's Data (Anwar) and Writer's Data (Chanson)

calculations of the inception point of air entrainment, and analogy between self-aerated flows and sediment-laden flows.

First, the paper did not address the effects of free-surface instabilities (e.g. roll waves) on the location of the point of inception. The writer agrees with the discusser that free-surface instabilities and roll waves might induce free-surface aeration upstream of the position where the outer edge of the boundary layer reaches the free-surface.

For small discharges, it is known that the free surface becomes unstable and is characterized by the formation of a series of roll waves [e.g. Cornish (1910) and Keulegan and Patterson (1940)]. Several criteria were developed to characterize the instability of uniform free-surface flows (Chow 1959; Rouse 1965). For turbulent flows, Rouse (1965) predicted instabilities for $\mathsf{F} > 1.3$ to $1.7\sqrt{\cos\alpha}$, where F is the Froude number. For laminar sheet flow, Chen (1993) showed that roll waves develop for $\mathsf{F} > 0.527\sqrt{\cos\alpha}$.

For the experiments of the discusser (Fig. 13 of the discussion), the writer estimates that the Froude number exceeds probably these critical values and roll waves are likely to develop. The development of free-surface instabilities and roll waves enhances the turbulence near the free surface, and higher level of turbulence might induce self-aeration if (1) and (2) are satisfied. Air entrainment might appear upstream of the location where the outer edge of the bottom boundary layer reaches the free-surface if the free-surface instabilities are large enough.

Second, the discusser compared his results with the calculations of Wood et al. (1983). The writer wants to emphasize that the formula of Wood et al. (1983) was fitted from Keller and Rastogi's (1975, 1977) calculations and that they were verified with model and prototype data obtained with steep slopes (i.e. $\alpha > 40°$) (Fig. 14).

The writer performed new experiments in a flat channel ($\alpha = 4°$). The flume was made of planed wooden boards ($k_s = 1$ mm) and is 0.5 m wide. Velocity distributions were measured at various locations along the flume using a Pitot tube. The position of the inception point of air entrainment coincided with the location where the outer edge (δ_{99}) of the boundary layer reaches the free surface. The Froude numbers at the point of inception ranged from 7.5 up to 10.5. The experimental results are shown in Fig. 14 as well as the data of the discusser. Both set of data obtained with flat slopes (4° and 11°, respectively) indicate that the empirical correlation of Wood et al. (1983) is not accurate for flat chutes. The writer believes that further experimental investigations are required to provide accurate predictions of the inception point on flat spillways.

Third, the analogy between self-aerated flows and suspended sediment flows was extended recently by the writer (Chanson 1994). In sediment-laden flows, and despite earlier controversies, the velocity distribution in the inner flow region follows the classical logarithmic profile (Coleman 1981; Lyn 1988) and the von Kármán constant is 0.4. But suspended sediment is observed either to increase or to decrease the friction factor. Historical cases of drag reduction include observations of suspended silt flood flows in the Nile (Buckley 1923), Indus (Lacey 1923) and Mississippi (McMath 1883) rivers. A recent study (Chanson and Qiao 1994) suggested that drag reduction in suspended sediment flows is observed only: (1) For starved bed flows or rising flood flows (i.e. with no sediment deposition); and (2) with microparticles ($\varnothing < 0.1$ mm).

The writer believes that the subject is still open to discussion.

APPENDIX I. REFERENCES

Buckley, A. B. (1923). "The influence of silt on the velocity of water flowing in open channels." *Minutes of the Proc. Instn Civ. Engrs., 1922–1923*, London, England, Vol. 216(part II), 183–298.

Chanson, H. (1994). "Drag reduction in open channel flow by aeration and suspended load." *J. Hydr. Res.*, 32(1).

Chanson, H., and Qiao, G. L. (1994). "Drag reduction in hydraulics flows." *Proc., 1994 IEAust. Conf. on Hydr. in Civ. Engrg.*, Brisbane, Australia.

Chen, C. L. (1993). "Unique laminar-flow stability limit based on shallow-water theory." *J. Hydr. Engrg.*, ASCE, 119(7), 816–829.

Cornish, V. (1911). *Waves of the sea and other water waves*. T. Fisher Unwin, London, England.

Keller, R. J., and Rastogi, A. K. (1975). "Prediction of flow development on spillways." *J. Hydr. Div.*, ASCE, 101(9), 1171–1184.

Keller, R. J., and Rastogi, A. K. (1977). "Design chart for predicting critical point on spillways." *J. Hydr. Div.*, ASCE, 103(12), 1417–1429.

Lacey. (1923). "The influence of silt on the velocity of water flowing in open channels—discussion." *Minutes of the Proc. Instn Civ. Engrs., 1922–1923*, London, England, 216(part II), 212–298.

McMath, R. E. (1883). "Silt movement by the Mississippi." *Van Nostrand's Engrg. Mag.*, 32–39.

Rouse, H. (1965). "Critical analysis of open-channel resistance." *J. Hydr. Div.*, ASCE, 91(4), 1–25.

APPENDIX II. NOTATION

The following symbols are used in this paper:

F = Froude number defined as $\mathsf{F} = q_w/\sqrt{gd^3}$;

F_* = Froude number defined in terms of roughness height $\mathsf{F}_* = q_w/\sqrt{g \cos \alpha k_s^3}$;

L_t = distance (m) from start of growth of boundary layer to where it reaches free surface; and

δ_{99} = thickness (m) of boundary layer defined as location where velocity equals 99% of free-stream velocity.

TURBULENCE MEASUREMENTS IN OPEN-CHANNEL FLOWS OVER ARTIFICIAL BED FORMS[a]

Discussion by Walter H. Graf,[2] Member, ASCE

The author has investigated an interesting problem, but has drawn some conclusions that in my mind are not general but are conditioned to his experiment.

Self-similarity: As can be seen from the velocity-defect profiles (Fig. 3) the flow is not self-similar, even in the outer region, commonly [White (1974), page 473] delimited by $y/H > 0.2$. In none of the three experiments is equilibrium attained. The fact that in a far outer region ($y/H > 0.8$) a self-similarity (within measuring errors and plotting techniques) seems to occur has, however, little or no physical consequence.

Since autosimilarity of flow is not achieved, any further discussion remains specific to the author's study and can in no way be extended for a general conclusion. Every type of bed form will (apparently) have a different degree of non-self-similarity; that is to say, a nonequilibrium flow situation.

Since an equilibrium in mean flow is not achieved, the self-similarity of the turbulence characteristics will not be maintained either; this is to be seen in Figs. 5 and 6.

Uniform flow: The author gives the impression of reporting on uniform flow of constant depth (page 306). It is probably more than a question of terminology to accept the flow depth as constant in flow over a bed form. In fact, flow is of the accelerating type, as is evidenced with the calculated W_o-values being lower than the values $W_o = 0.2$ for nearly uniform flow.

Reynolds stress: The choice of u_*^T is to be regretted, notably for an interpretation of the Reynolds-stress profiles. Since flow is nonuniform, the triangular shear distribution is no more valid [see Rotta (1972), page 239]. In accelerating flow—if flow is properly in equilibrium—the shear stress should have its maximum at the bed and not above the bed as seen in Fig. 6.

It would appear that the author's contribution must be regarded with care. Since the flow over bed forms is not in equilibrium, generally valid conclusions cannot be drawn.

APPENDIX. REFERENCES

Rotta, J. (1972). *Turbulente Strömungen*. Teubner, Stuttgart, Germany (in German).

White, F. (1974). *Viscous fluid flow*. McGraw-Hill, New York, N.Y.

---

[a]March, 1993, Vol. 119, No. 3, by D. A. Lyn (Paper 3791).

[2]Prof., Lab. de recherches hydrauliques, Ecole Polytechnique Fédérale de Lausanne, Switzerland.