fly out of the flow. In napped flow the water on the step is completely and continually flushed by the flow down the chute. Hence the flow has a vorticity of zero that is the same as that of the water flowing down the chute. In skimming flow the exchange of water between the region above the tread and the water skimming past it is much weaker as may be shown by injecting dye. In this case frictional forces (together with vortex stretching) have time to act such as to change the vorticity of this water to that required for a recirculating flow. The resulting vortex acts like a rotating cylinder and the periphery of the vortex is in contact with both the tread and riser of the step and the mainstream of the flow. The shear between the mainstream of the flow and the recirculating flow provides the energy for the rotation balancing frictional losses. This shear (and associated energy loss) slows the mainstream of the flow. Thus there is a distinct change in the dynamical properties of the water above the tread in the napped flow and skimming flow cases. In transition conditions this exchange of water is only partial and occurs as jets from specific regions above the tread as required by the vortex stretching along the step to supply the vorticity for the flow on the step. There have been several studies that have shown this behaviour both experimentally, e.g. Mottram (1993) and numerically, e.g. Chen *et al.* (2002), but it is the Discussers' belief that the Authors' work of the first study to truly identify such behaviour as occurring in association with the transition.

A similar problem with an apparently identical mechanism, but which avoids the chaotic motion described earlier that leads to localized splashes of water flying out of the flow, occurs in the flow over a single step with a deflector across the channel as shown in Fig. 2.

The chaotic behaviour of the stepped chute is suppressed because only one step is used and the mechanism described earlier requires multiple steps. This suppression makes this similar situation an excellent analogous situation for studying the full chute's behaviour.

An experiment with this geometry was performed to understand the vortex behaviour. In this experiment the rise was 150 mm and the tread length between the 75 mm (height) by 45 mm (width) deflector was 380 mm and the flow was 0.23 m^3/s over a channel width of 920 mm. The flow pulsated quite dramatically with a period of about 4 s as shown in video-footage at http://www.civenv.unimelb.edu.au/laboratories.shtml.

The behaviour is the same as that described by the Authors except that it occurs across the entire channel rather than as small but violent ejection of the splashes or jets associated with the chaotic behaviour in the Authors' experiment. Although this distributed but less violent periodic behaviour makes the mechanism associated with the flow easier to study, the Discussers still do not understand what controls the period of four seconds either using dimensional analysis or mechanics. Maybe the Authors, with there appreciation of the transition flow, may be able suggest what might generate this time scale when localized ejection of splashes is suppressed as here.

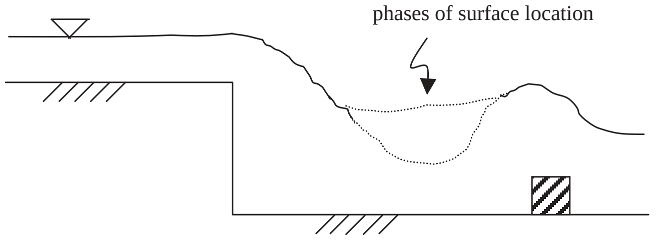

Figure 2 Sketch showing the geometry of the pulsating flow studied here.

References

1. CHEN, Q., Dai, G. and LIU, H. (2002). "Volume of Fluid Model for Turbulence Numerical Simulation of Stepped Spillway Overflow". *J. Hydraul. Engng.* 128(7), 683–688.
2. MOTTRAM, S.R. (1993). "Energy Dissipation and Aeration on Stepped Spillways". MS thesis, University of Natal, Natal, South Africa.

Reply by the Authors

The writers acknowledge the discussion. In their last comment on flow at an abrupt drop with a sill, the discussers observed a kind of oscillating jump flow. This flow pattern was studied by numerous researchers and important contributions included Ohtsu and Yasuda (1991), Mossa (1999) and Mossa *et al.* (2003). Such a flow instability is a completely different process from transition flow on stepped chutes.

The development proposed by the discussers is a welcome attempt to comprehend the complexity of stepped chute flows, but the outcome is highly arguable. In large laboratory models and prototype channels, stepped chute flows are highly turbulent. It is grossly incorrect to assume zero vorticity in any flow regime. Further the pseudo-mathematical development is based upon incorrect assumptions, namely quasi-atmospheric pressures, zero flow resistance and no streamline curvature! None of the assumptions are correct in stepped channel flows. Stepped spillways are well known for their high rate of energy dissipation and large flow resistance for all flow regimes (e.g. Chanson, 2001; Chanson *et al.*, 2002), while the discussers' sketch emphasized a strong streamline curvature at step edges.

References

1. CHANSON, H. (2001). *The Hydraulics of Stepped Chutes and Spillways*. Balkema, Lisse, The Netherlands, 418 pp.
2. CHANSON, H. and TOOMBES, L. (2004). "Hydraulics of Stepped Chutes: the Transition Flow". *J. Hydraul. Res.* 42(1), 43–54.
3. CHANSON, H., YASUDA, Y. and OHTSU, I. (2002). "Flow Resistance in Skimming Flows and its Modelling". *Can. J. Civil. Engng.* 29(6), 809–819.
4. MOSSA, M. (1999). "On the Oscillating Characteristics of Hydraulic Jumps". *J. Hydraul. Res.* 37(4), 541–558.
5. MOSSA, M., PETRILLO, A. and CHANSON, H. (2003). "Tailwater Level Effects on Flow Conditions at an Abrupt Drop". *J. Hydraul. Res.* 41(1), 39–51.
6. OHTSU, I. and YASUDA, Y. (1991). "Transition from Supercritical to Subcritical Flow at an Abrupt Drop". *J. Hydraul. Res.* 29(3), 309–328.