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Optical measurements in dam spillways during major flood events: a down-to-earth review of pros and cons

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ABSTRACT

In overflow spillways, the chute flow is a high-speed, highly-turbulent motion with Reynolds numbers typically ranging from 10^6 to over 10^8. In these high-Reynolds-number free-surface flows, the upstream section is non-aerated and a strong air-water mix develops downstream of the onset region of air entrapment. On a steep spillway chute, the onset of free-surface aeration is typically observed when the outer edge of the boundary layer starts to interact with the free-surface. On flat chutes, in contrast, the inception region presents a rippled surface driven by free-surface instabilities, tending to become a choppy water surface when self-aeration takes place. Currently, our knowledge in the operation of large dam spillways, including these hydrodynamic instabilities, is adversely impacted by a major knowledge gap linked to an absence of detailed field observations, including accurate quantitative measurements. In this study, a review of observations of and measurements during the operations of large dam spillways is developed. Observations were undertaken during the 2010-2011, 2013, 2015, 2017, 2021 and 2022 floods at several large dams in southern Queensland, Australia. The experiences provided insights into the spillway operations. The presentation is complemented by some discussion on the intricacy the field measurement techniques at two large dam spillways, including optical velocity measurements of high-Reynolds-number spillway hydrodynamics.

INTRODUCTION

In spillway chutes, the flow is rapidly accelerated at the crest and initially un-aerated. Some free-surface aeration, i.e. 'white waters', takes place once the onset conditions of self-aeration are fulfilled (Falvey 1980, Chanson 1993). In free-surface chute spillways, the bottom friction induces the growth of a turbulent boundary layer (Rao and Kobus 1974). On steep chutes, the onset of self-aeration occurs when the boundary layer's outer edge begins interacting with the free-surface (Michels and Lovely 1953, Wood 1985). The interactions are very dynamic transient processes in prototype chutes (Chanson 2013,2022). Photographs of the onset processes of self-aeration and of self-aerated flows are shown in Figure 1 for several prototype spillways during recent major floods.

Field observations in dam spillways are extremely rare during large flood events. A few detailed prototype studies were conducted during controlled releases at Dniepr Powerplant (Grinchuk et al. 1977) and at Aviemore Dam (Cain and Wood 1981a,b). These works took place at low- to medium-discharges. While important data sets, they might not be representative of very-large flood events. Recently, optical techniques were developed and applied to field measurements in rivers during large floods and inland tsunamis (Fujita and Komura 1994, Fritz et al. 2006, Muste et al. 2008). While optical techniques were successfully tested and used in laboratory (Bung and Valero 2016, Zhang and Chanson 2018, Pozos-Estrada et al. 2022), their successful application to large spillways remains extremely limited.

Very recently, an optical technique was applied successfully to two large dam spillways during major floods (Chanson 2022, Chanson and Apelt 2022). The expertise gained in these two studies are developed, as well as the experience gained from several field deployment during 2010-2011, 2013, 2015, 2017, 2021 and 2022 floods in Australia. The aim of this contribution is to expand on the intricacy of prototype spillway operation observations and non-intrusive field measurement techniques, including potential applications and limitations.

Figure 1. Large dam spillway operations in Queensland (Australia). (A) Hinze Dam Stage 3 on 5 March 2022 (Q = 85.5 m^3/s). (B) Chinchilla MEL weir on 15 Dec. 2021 (Q = 144 m^3/s). (C) Paradise Dam on 5 March 2013 (Q = 2,500 m^3/s). (D) Gold Greek Dam on 26 Feb. 2022 (Q = 38 m^3/s).

STUDY SITES AND FIELD EXPERIMENTATION

Located in South-East Queensland, Australia, the Hinze Dam was first completed in 1976, and since upgraded twice. The Hinze Dam Stage 3 spillway was designed with a compound ogee crest followed by a stepped chute, ending in a stilling basin (Fig. 1A). The compound ogee crest includes a low level section leading to a 1V:0.8H slope (θ = 51.3°) with 1.5 m high concrete steps. Photographic and cinematographic records were collected from the bridge above the ogee crest and the viewing platform facing the stepped spillway (Chanson 2021). The spillway discharge was calculated based upon the measured reservoir elevations for the USBR ogee crest design (USBR 1987).

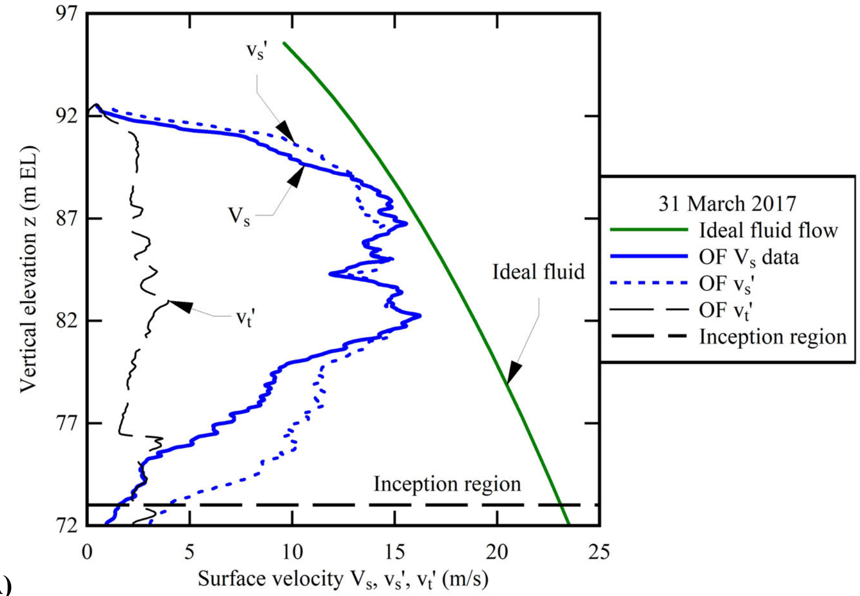
The Chinchilla minimum energy loss (MEL) weir is located on the Condamine River, which is part of the Murray-Darling basin (Australia) (Fig. 1B). Completed in 1973 to provide irrigation water, the Chinchilla weir is a 14 m high earthfill embankment with a 410 m long dam crest including the abutments (Turnbull and McKay 1974). The overflow spillway consists of a broad crest, 3.05 m long, and 213.4 m wide, followed by a smooth converging chute with a 1V:5H slope ($\theta = 11.3°$). The downstream width of the chute is 81.2 m. No dissipation structure was built. The overflow section is concrete-lined, with a series of drains to reduce seepage pressure. The overflow discharge was deduced based upon the measured reservoir elevations for the broad-crest design.

The photographic and video observations were undertaken with dSLR cameras (Pentax™ K-01, Pentax™ K-7, Pentax™ K-3) equipped with prime lenses which produced images with negligible degree of barrel distortion, a digital camera Casio™ Exilim EX-10, a digital camera Sony™ RC100VA and an iPhone XI. The movies were typically recorded with frame rates between 25 fps and 60 fps. More details on the camera sensor resolution and lens characteristics were discussed in Chanson (2021).

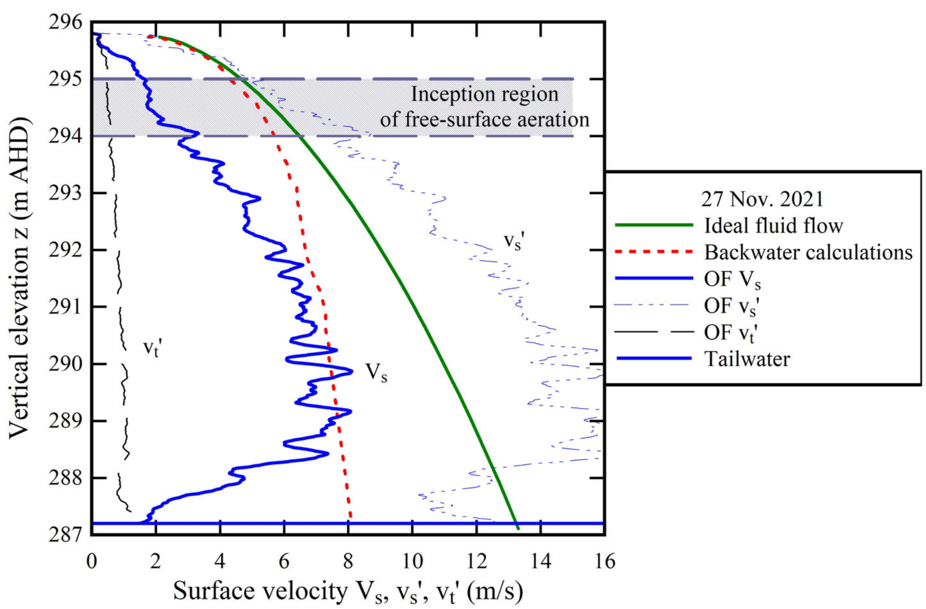
The analyses of flow patterns were conducted using both high-shutter speed photographs and movies. The pseudo-randomness of occurrence of flow features, the optical quality and lighting conditions, e.g. under heavy rainfall, and the broad range of free-surface details prevented the usage of any automated pattern recognition. The tracking and measurements of the air-water surface features were conducted manually to guarantee both reliability and high degree of quality control.

Several movies were taken from downstream and analysed using an optical flow (OF) technique, with the camera fixed on a sturdy professional-grade tripod. The optical flow (OF) is a set of tools, detecting the flow motion between consecutive frames, based upon the brightness constancy assumption (Horn and Schunck 1981). While the OF was originally developed for computer vision, the OF technique may be applied to fluid flows (Liu and Shen 2008, Bung and Valero 2016, Zhang and Chanson 2018). In the current study, a Farnebäck OF technique was applied for the calculations of the instantaneous surface velocity field (Farnebäck 2003). The approach followed the earlier work of Arosquipa Nina et al. (2022) who derived the surface velocity field on a large-size stepped spillway model at the University of Queensland. The Farnebäck OF technique is robust and simple, with a relatively small number of OF parameters. The OF was applied to the video movies. Detailed post-construction plans (Irrigation and Water Supply Commission 1972, Seqwater 2011) provided the required ground reference points, using landmarks and cross-sectional transects. The positioning of the ground reference points in the spillway and in the image was precisely done. Standard uncertainties of 10 mm and 2-5 pixels were assumed for the ground reference point co-ordinates and image co-ordinates respectively.

In absence of independent validation measurement data sets, the OF surface velocity was systematically compared to (a) the ideal fluid flow velocity, derived from the Bernoulli equation neglecting drag in the developing non-aerated flow region, and (b) the application of the backwater region in the fully-developed aerated flow region. Typical comparisons are presented in Figure 2, with the streamwise surface velocity component V_s shown as function of the vertical elevation z. In the same figure, the standard deviation of the longitudinal and transverse surface velocities, i.e. v_s' and v_t' respectively, are shown as well. Figure 2A presents a comparison between the time-averaged OF surface velocity V_s and the ideal fluid flow velocity at Hinze Dam Stage 3 spillway. The result showed a reasonable agreement between elevations 81 m EL and 91 m EL. Above, the invert and free-surface curvature induced optical artifacts. Below, the strong spray and splashing in the stilling basin generated some "fog", i.e. a dense cloud of fine particles, which affected adversely the optical imagery. Figure 2B shows a comparison between the time-averaged OF surface velocity, the ideal fluid flow velocity and the backwater calculations for the converging chute of Chinchilla weir. A good agreement was noted between the OF results and backwater calculations in the fully-developed aerated region. In the non-aerated flow region, the glassy water surface yielded meaningless optical data. At the downstream end of the chute, some optical artifacts were caused by the splashing and spray above the hydraulic jump, causing some underestimation of the surface velocity. These examples (Fig. 2) were typical of field observations recorded during the 2013, 2015, 2017, 2021 and 2022 flood events at these two sites (Chanson 2022, Chanson and Apelt 2022).



(A)



(B)

Figure 2. OF surface velocity: comparison with theoretical estimates. (A) Comparison between optical flow (OF) surface velocity data and ideal fluid flow velocity at Hinze Dam Stage 3 on 31 March 2017 (Q = 334 m^3/s). (B) Comparison between optical flow (OF) surface velocity data and backwater calculations at Chinchilla MEL weir on 27 November 2022 (Q = 121 m^3/s).

DISCUSSION: CHALLENGING OPTICAL CONDITIONS AND METROLOGY

With prototype flow movies, the OF data quality was diversely affected by several issues, and the optical artefacts were very different from previous laboratory observations (Zhang and Chanson 2018, Arosquipa Nina et al. 2022). In all prototype data sets, the pictures encompassed the upstream non-aerated developing flow region, the inception region, and the fully-developed self-aerated flow downstream of the inception region of free-surface aeration, and sometimes the stilling basin.

At the Hinze Dam Stage 3 spillway, the self-aerated flow region was white and very bright: the OF systematically yielded inaccurate surface velocity data there, because of the combination of extreme brightness and limited video movie frame rate. Practically, the adjustment of the brightness of the self-aerated waters was near-impossible in the field conditions, and the bright white colour induced a saturation of the camera sensor. At the Chinchilla weir, the glassy surface of the upstream flow region prevented any meaningful OF results in the developing flow region. On the other hand, good results were achieved in the fully-developed self-aerated flow region. This was linked to a combination of the grainy/coarse water surface and the beige colour of the surface. The latter was an indication of a three phase overflow, i.e. sediment + water + air.

The current OF technique application may be affected by several possible types of errors. These might be linked to the lighting conditions, movie recording, image processing and post-processing. Overall, the present field experience showed a number of challenging issues with the application of OF to prototype spillway flows, which have rarely been discussed in the literature. First, given the relatively large size of the pixel area, many scales of spillway flow motion may be smaller than the size of the interrogation area on which the OF analysis were performed: these scales are thus not resolved. An ideal upper bound analysis frequency would be twice the surface velocity divided by the physical pixel size. A similar problem is known in large-scale image velocimetry in rivers (Fujita et al. 1998, Aberle et al. 2017) and one solution would be a much higher camera sensor resolution. Further, careful considerations must be given to some temporal scale issues, when the data are recorded at relatively low frame rates like herein. The large distance between the camera lens and flow, and sometimes the slight oblique angle between the lens axis and the free-surface, may introduce lens and geometrical distortions. The former may be avoided by using prime lens with small distortion, and the latter may be removed using some geometrical transformation (Fujita et al. 1998), albeit with additional computational post-processing and potential errors.

In the specific context of the application of OF technique to high-velocity prototype spillway flows during major floods, the present experience highlighted several challenges:

● The present field measurement experience may be compared to the past laboratory experience of Arosquipa Nina et al. (2022) with top view movies.

At the Hinze Dam Stage 3, the OF data provided reasonably meaningful surface velocities in the non-aerated flow region upstream of the inception of free-surface aeration. This contradicted the laboratory results, and might be linked to the darker water colour in the field.

At the Chinchilla weir, the OF data delivered meaningful surface velocities in the self-aerated flow region, in line with the laboratory experience of Arosquipa Nina et al. (2022).

● The OF data were physically meaningless in a number of situations. Several reasons may be put forward, including the optical access, the limited temporal resolution and movie frame rate, the coarse spatial resolution, the lighting conditions, the weather conditions.

● The OF experience suggested that both a faster movie frame rate and a larger video camera sensor would be required to achieve some meaningful temporal resolution in very-bright "white water" regions, as seen at Hinze Dam Stage 3. A few suggestions for future work could be mentioned.

Since the OF technique tracks the changes in brightness due to reflectance difference associated with passages of air-water surface features, the time step between successive frames must be smaller than the time scales of these interfacial features, i.e. 1 ms to 50 ms. At low frame rates, furthermore, the large changes in luminance between successive frames violate the fundamental assumption of brightness constancy. Both arguments would suggest a minimum frame rate of 2,000 fps to 5,000 fps at least.

A larger video camera sensor would be warranted, e.g. 12K or more. It is also conceivable that different OF parameters could be chosen to suppress the noise and high frequency bias, although the calibration and validation of these OF parameters are problematic in field data sets.

For completeness, the usage of higher frame rates and larger sensor size (e.g. 12K) would yield larger movie file sizes, with the implications in terms of storage during a field deployment and post-processing times.

● The quality of the OF data was closely linked to the suitability of the optical access, the quality of the observation point and the stability of the camera.

Ideally the camera should be placed perpendicular to the chute. At both Hinze Dam Stage 3 and Chinchilla weir, this was not always possible because of flood levels and physical access issues, as well as local atmospheric conditions, i.e. mist and wind.

The OF data quality was linked to the seeding of the water free-surface. At Hinze Dam Stage 3, reasonable results were achieved in the non-aerated flow region with the presence of sediment-laden brown coloured waters. But the development of very long air-water streaks seemed to induce some errors, as on 31 March 2017. Generally, no issue was observed in the self-aerated flow region at Chinchilla weir.

A sturdy professional-grade tripod placed in a strong floor was a basic requirement. The camera system should not be affected by vibrations. Figure 3 illustrates a few setups used by the first author.

The video movie images were adversely affected by light reflections as well as glare induced by free-surface instabilities. Both would generate large fluctuations of the surface velocities.

● One must accept that the optical conditions changed drastically between events, between successive days during the same flood event, and sometimes within one hour on a given day. These changes in light conditions could impact substantially on the image quality and were not controllable.

● The number of images per video movies should be ideally over 5,000 frames, with longer movies being desirable. Importantly, the camera should be fixed and immobile during the entire recording. During the whole movie recording, the natural lighting conditions should "ideally" remain constant, and the camera system must be protected from wind effects, mist and spray. This is not always possible.

● It is acknowledged that the video movies were recorded with a range of different systems, owing to the time span of the observations (2010-2022). The experience showed that, on a given day, the best image quality was achieved with professional dSLR cameras equipped with high-quality professional-grade prime lenses. That is, single focal length lenses with relatively large aperture and negligible lens distortion. The cameras were best positioned on a sturdy tripod, and the lens would ideally be equipped with a protective hood to minimise droplet deposition on the lens' outer glass.

Most prototype observations require lenses with long focal lengths. For example, the first author obtained excellent results using focal lengths between 120 mm and 420 mm, mounted dSLR APS-C cameras, at the Hinze Dam and Chinchilla MEL weir (Chanson 2021,2022, Chanson and Apelt 2022). With full-frame cameras, the focal lengths would need to be 40% longer, unless accepting a lesser pixel definition. Altogether, these long to super-long telephoto lenses are rare, expensive and heavy, and they are not always fast enough under poor lighting conditions.

● One cannot stress again and again that the OF data quality is very strongly correlated to the quality of the lighting. While some preliminary testing is feasible in laboratory to improve the brightness, field observations rarely permit any testing and this could be very challenging. See further discussions by Chanson (2021b) and Arosquipa Nina et al. (2021), for example.

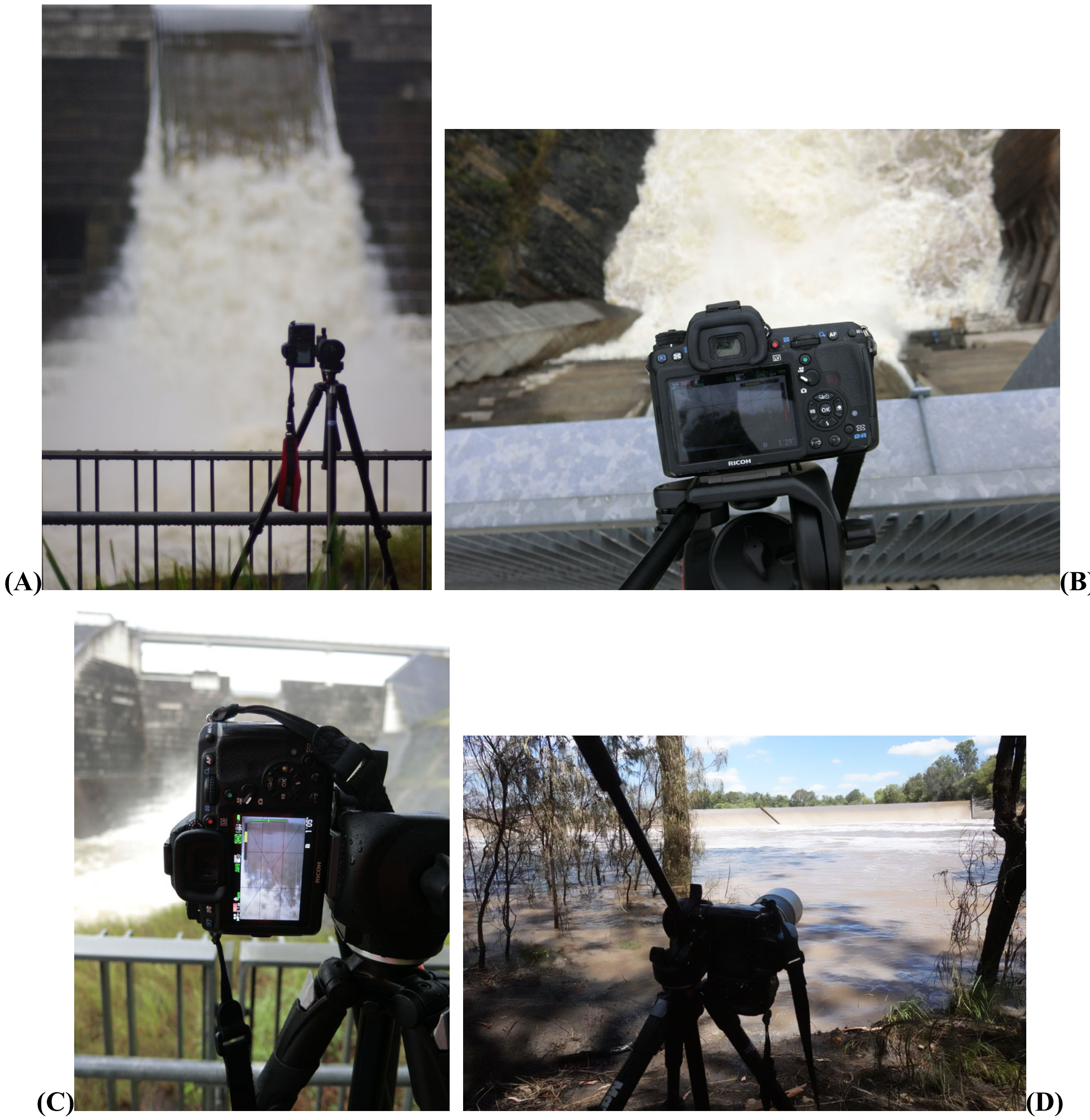


Figure 3. Optical measurement setup at prototype spillways. (A) Hinze Dam Stage 3 on 4 March 2022 ($Q = 111$ m^3/s). (B) Hinze Dam Stage 3 on 4 March 2022 ($Q = 111$ m^3/s). (C) Hinze Dam Stage 3 on 3 March 2022 ($Q = 143$ m^3/s). (D) Chinchilla MEL weir on 27 November 2022 ($Q = 121$ m^3/s).

OUTCOMES AND FUTURE OUTLOOK

At both prototype spillways and for all flood events, the OF surface velocity data delivered some key outcomes and challenging data. The time-averaged surface velocity maps showed some two-dimensional surface velocity patterns, with the presence of streaks of faster flowing waters, with slower regions and surface vortices in between. While the position of such surface streaks varied with time, their pattern tended to be well-defined, in all cases. These elongated patterns are seen in the contour maps of time-averaged surface velocity and their standard deviation (Fig. 4A). Very-high surface turbulence was recorded in both spillway flows. In the proximity of as well as upstream of the inception region, and downstream in the self-aerated flow region, the dimensionless streamwise turbulent intensity $Tu_s = v_s'/V_s$ was typically greater than unity. This is illustrated in Figures 2. The finding is consistent with interfacial turbulence data observed in large-size laboratory spillway models (Chanson and Toombes 2002, Arosquipa Nina et al. 2022). The transverse surface velocity fluctuations v_t' were significantly smaller than the streamwise fluctuations (Figs. 2 & 4B). In average across the spillway width, the transverse velocity fluctuations v_t' were about: $v_t'/v_s' \sim 0.13$ to 0.2 at both spillway chutes. The finding implied a strong anisotropy of the free surface turbulence (FST), linked to a range of air-water surface features encompassing boils, divergence, foam lines, and convergence. All in all, the OF surface velocity and turbulence maps implied a strong three-dimensionality of the prototype chute flows. The finding has direct implications for the design of stilling basin, sometimes developed based upon simplistic one-dimensional considerations. This is critical because "*the magnitude of turbulent energy that must be dissipated in hydraulic structures is enormous even in small rural and urban structures*" (Chanson 2015, p. ix).

Overall, the present observations and approach constituted a proof of concept (POC) for future field observations in high-velocity prototype chute spillways. It further paved the way for the development of a new hybrid modelling technique combining laboratory experiments and field observations (Chanson 2022b). That is, some complementary observations with spillway configurations that are geometrically scaled based upon an undistorted Froude similarity, combining optical observations in a prototype spillway with detailed imaging measurements and intrusive phase-detection probe measurements in a relatively large-size physical facility, under carefully controlled conditions.

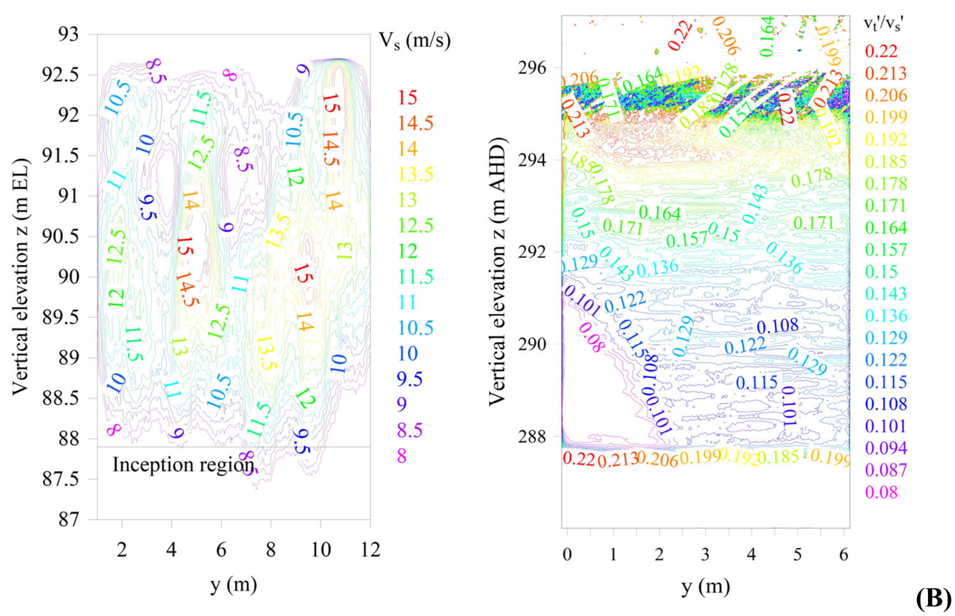


Figure 4. Optical velocity measurements at prototype spillways. (A) Contour map to time-averaged-surface velocity V_s in the on-aerated developing flow region at Hinze Dam Stage 3 on 24 March 2021 (Q = 140 m^3/s). (B) Contour map of the ratio v_t'/v_s' at Chinchilla MEL weir on 15 December 2021 (Q = 144 m^3/s).

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California Davis).

In line with recommendations of the International Committee on Publication Ethics (COPE) and the Office of the Commonwealth Ombudsman (Australia), Hubert Chanson declares a major conflict of interest with Matthias Kramer (UNSW, Canberra).

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BIOGRAPHY

Hubert Chanson is Professor of Civil Engineering at the University of Queensland, where he has been since 1990, having previously enjoyed an industrial career for six years. His main field of expertise is environmental fluid mechanics and hydraulic engineering, both in terms of theoretical fundamentals, physical and numerical modelling. He leads a group of 5-10 researchers, largely targeting flows around hydraulic structures, two-phase (gas-liquid and solid-liquid) free-surface flows, turbulence in steady and unsteady open channel flows, using computation, lab-scale experiments, field work and analysis. He has published over 1,250 peer reviewed publications including two dozen of books. He serves on the editorial boards of International Journal of Multiphase Flow, Flow Measurement and Instrumentation, and Environmental Fluid Mechanics, the latter of which he is currently a senior Editor. His Youtube channel is: {https://www.youtube.com/channel/UCm-SedWAjKdQdGWNbCwppqw}.

Dr Rui (Ray) Shi joined WSP Brisbane office as a water resource engineer since early 2021. From consulting experiences, Ray's developed sound hydrologic and hydraulic modelling skills with a focus on flood studies on major infrastructure and mine projects. Ray is experienced in use of TUFLOW, HEC-RAS, QGIS, XPRAFTS, Autodesk package, and is also interested into automation of flood modelling process, providing customised python scripts and QIGS plugins. Ray obtained his PhD in hydraulic and coastal engineering at the University of Queensland. His research involves fine-scale CFD modelling on air-water flows based on OpenFOAM, computer vision on flow turbulence, and machine learning on post-processing experimental and numerical data. His research interests extend to CFD modelling on free-surface flows, machine learning on data-driven turbulence, and integration of remote sensing and GIS system. . His ORCID number is 0000-0001-9387-9496.