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Modelling spillway and weir operation during major overflows. On optical measurements in prototypes: pros and cons

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ABSTRACT

At weirs and dams, the spillway flow is a high-velocity turbulent motion operating at very-large Reynolds numbers and physical measurements are challenging. In these high-speed free-surface flows, the upstream flow is not aerated and some air entrainment takes place downstream of the inception of free-surface aeration. The state-of-the-art knowledge in large dam spillway hydrodynamics currently reaches a major knowledge gap because of a lack of detailed quantitative field measurements in both the non-aerated and air-water flow regions. In this contribution, a review of prototype observations and measurements is presented based upon optical data sets conducted between 2010 and 2022 during floods at several large dam spillways in eastern Australia, with a focus on the key requirements for successful optical velocity measurements in high-velocity (prototype) spillway flows. The experience and expertise gained in these studies provide new insights into the operation of large dam spillways and their modelling. The intricacy of field measurement techniques is discussed using the experience at dam spillways during large floods, encompassing optical velocity measurements of spillway hydrodynamics at two structures. Overall, the paper presents current challenges on the modelling of large dam spillway flows.

1. Introduction

In dam spillways, the water is rapidly accelerated at the upstream end where the flow is non-aerated. Some self-aeration occurs when the inception conditions for air entrainment are satisfied [1–3]. In a free-surface spillway, the no-slip condition along the bottom invert facilitates the development of a turbulent boundary layer [4,5]. On a flat spillway chute, the onset region of self-aeration exhibits a rougher surface induced by free-surface instabilities, generating a choppy air-water interface and self-aeration [6]. On a steep spillway channel, the inception of free-surface-aeration takes place when the boundary layer growth reaches the free-surface [7,8]. The turbulence-free-surface interactions are dynamic and transient in prototype spillways ([9,10], [11]). Some photographic examples of self-aeration inception and of air-water flows on prototype dam spillways are shown in Fig. 1. In Fig. 1, most illustrations are high-shutter speed photographs and the shutter speed is listed in the figure caption.

Prototype observations of dam spillway operations are rare especially during large floods, and quantitative data are very scarce. A few seminal studies were undertaken under controlled releases with low-to medium-discharges, e.g. at Dniepr Powerplant, Ukraine [12]. at Aviemore Dam, New Zealand [10], at Grande Dixence, Switzerland (Volkart and Rutchmann 1984) [13]. Although the data sets are significant, they were obtained for flow conditions corresponding to Reynolds numbers Re about 10^6 to 3×10^6 that might not be representative of large flood events. In the last few decades, some optical techniques were applied to remote field observations in large rivers in floods [14,15] as well as inland tsunamis [16]. Optical techniques were used in laboratory spillway models [17,18], but the successful implementation to large dam spillways during major floods has not been always successful.

In the last few years, a remote optical flow methodology was applied to prototype observations at two large spillways during major flood overflows [11,19]. The experience and expertise derived from the two studies are discussed and complemented by further experience gained from several field deployments between 2010 and 2022 during major floods. This contribution aims to expand on the difficulties and intricacy of prototype observations of large dam spillways using optical non-intrusive remote techniques, including potential applications and limitations, as well as key requirements for successful optical velocity measurements in high-velocity spillway flows. Finally, current challenges and future outlook on large dams' spillway flows are discussed.

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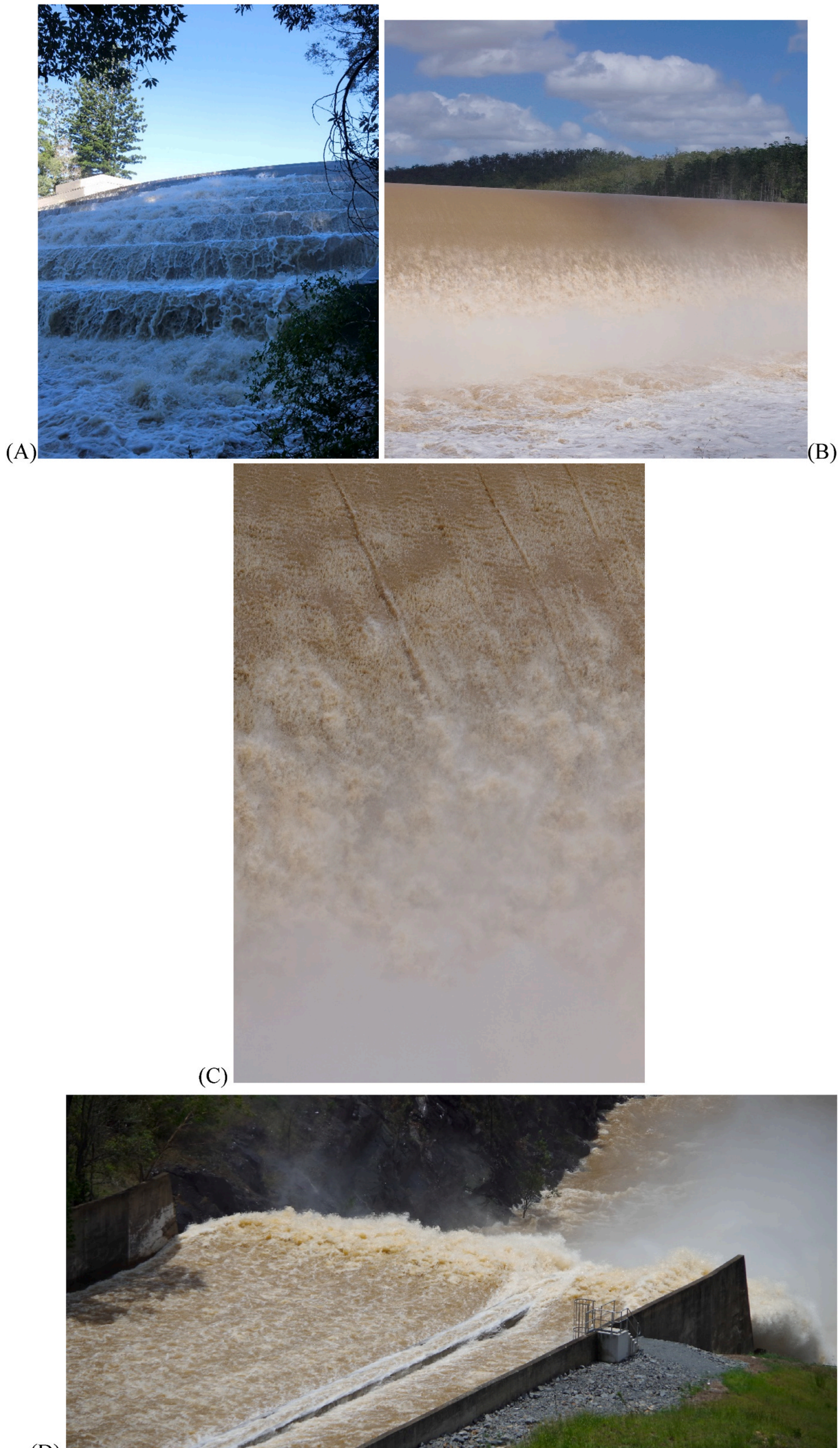

Fig. 1. Photographs of turbulent air-water flows in large dam spillways - (A) Gold Creek Dam spillway on May 2, 2017 after 162 mm of rainfall in the catchment; (B) Paradise Dam spillway on March 5, 2013 (shutter speed: 1/1600 s); (C) Details of the inception region of free-surface aeration at Paradise Dam on March 5, 2013 (shutter speed: 1/1600 s); (S) Hinze Dam spillway smooth chute and flip bucket on January 29, 2013 (shutter speed: 1/4000 s).

2. Dam spillway and field observations

2.1. Presentation

The optical observations were primarily performed at two large dam spillways located in eastern Australia, the Hinze Dam and the Chinchilla weir (Fig. 2). The Hinze Dam was first completed in 1976 and upgraded later, and is located on the Nerang River. The Hinze Dam Stage 3 is equipped with a spillway consisting of a compound ogee crest controlling the discharge over a stepped chute, followed by a stilling basin and a smooth-invert chute further downstream leading to a flip bucket (Fig. 3A & 1D). The spillway crest includes a low level channel leading to a 51.3° stepped chute with 1.5 m high concrete steps. Photographs and video movies were recorded from two sturdy observation sites: i.e., a concrete platform facing the spillway chute and a reinforced concrete bridge overlooking the spillway crest [20]. The overflow discharge was computed based upon the measured reservoir elevations for the spillway crest design [21].

The Chinchilla weir is located on the Condamine River, within the Murray-Darling basin. The structure was completed in 1973 for irrigation water. The Chinchilla weir is a 14 m high earthfill embankment with a 410 m long dam crest including the abutments [22]. It is a minimum energy loss (MEL) weir design. The spillway is equipped with a 3.05 m long 213.4 m wide broad crest leading to a converging smooth-invert chute with a 11.3° slope (Fig. 3B). The spillway chute is concrete-lined, with a series of drains to reduce seepage pressure. At its downstream end, the chute is 81.2 m wide and no energy dissipator structure was built.

2.2. Field investigations

Photographic and cinematographic observations were conducted with Pentax™ dSLR cameras and professional-grade prime lenses, generating images with negligible barrel distortion. Further optical records were performed with a digital camera Sony™ RC100VA, a digital camera Casio™ Exilim EX-10, and an Apple ™ iPhone XI. The video movies were recorded at frame rates ranging from 25 fps to 60 fps, although a few high-speed movies (120 fps & 240 fps) were taken for mostly qualitative observations.

The spillway flow patterns were analysed based upon a combination of high-shutter speed dSLR photographs and video movies. The use of automated pattern recognition was not meaningful because of the pseudo-randomness of highly-turbulent flow features, the optical and lighting conditions, e.g. during intense rainfall (Fig. 4A), as well as the wide range of relevant free-surface details and the relatively slow movie frame rate. The air-water surface features were basically tracked and measured manually to ensure both reliability and high quality control. Fig. 4A illustrates a typical example of differences in lighting conditions, between two photographs of the same spillway taken with the same camera, same lens and same shutter speed from the same location, but under two very different natural lighting conditions, i.e. strong rainfall (Fig. 4A1) and sunny weather (Fig. 4A2).

A number of video movies were recorded from downstream looking at the free-surface of the spillway flow. They were subsequently analysed using an optical flow (OF) technique. The camera was fixed in all cases. More details on the camera location and specifications are discussed later (section 3). Simply, the optical flow (OF) is a series of tools to detect the flow motion between consecutive frames. It is based upon the assumption of brightness constancy [23]. Although the original development and application was for computer vision, the OF technique was successfully implemented in fluid flows [24], including high-velocity free-surface flows [17,18]. In dam spillways, the Farnebäck technique was applied to derive instantaneous surface velocity field [25]. The methodology followed closely the approach of Arosquipa et Nina al. (2022) [26] for the surface velocity field in a large-size stepped spillway model. The Farnebäck technique was selected because it is a relatively simple and robust OF technique which uses a relatively small number of calibration parameters. The OF technique was applied to the video observations of the large dam spillway operations. The ground reference points were obtained from detailed

Fig. 2. Map of Australia with locations of large dam spillways discussed in this article.

Fig. 3. Spillway operations at Hinze Dam and Chinchilla MEL weir - (A) Hinze Dam spillway operation on January 29, 2013; (B) Chinchilla MEL weir spillway on December 15, 2021.

post-construction plans, providing the necessary landmarks and cross-sectional transects with relevant precision and accuracy. Typical standard uncertainties for the ground reference point co-ordinates and image co-ordinates were 10 mm and 2–5 pixels respectively.

No independent validation measurement data set was available. In turn, the OF surface velocity data were compared to theoretical values, that is, (1) the ideal fluid flow velocity, derived from the Bernoulli equation neglecting drag in the developing non-aerated flow region, and (2) the application of the backwater equation in the fully-developed air-water flow region. A few comparisons are shown in Fig. 5, with the streamwise surface velocity component V_s as a function of the vertical elevation z. In the same graph, the streamwise surface turbulence v_s'/V_s, and surface turbulence intensity v_t'/v_s' are also presented, where v_s' and v_t' are respectively the standard deviation of the longitudinal and transverse surface velocity components. In Fig. 5A, the comparison between the time-averaged OF surface velocity V_s and the ideal fluid flow velocity at Hinze Dam spillway showed a reasonable agreement. in the upstream non-aerated flow region. In the inception region and in the air-water flow region, the OF outputs were adversely affected by the optical imagery, including spray, splashing and intense free-surface aeration. In Fig. 5B–a comparison between the time-averaged OF surface velocity, the ideal fluid flow velocity and the backwater calculations is presented for the converging chute of Chinchilla weir. A good agreement was noted between the OF results and backwater calculations in the air-water region downstream of the inception region. In the non-aerated flow region, meaningless optical data were caused by the surface glare. The examples, shown in Fig. 5, are typical of a series of field observations recorded between 2013 and 2022 at these two dam spillways [11,19].

3. Challenges in prototypes: optical conditions and metrology

3.1. Presentation

In prototype spillways, the OF data quality may be diversely impacted by several practical considerations, and the present experience indicated very different optical artifacts from previous laboratory observations, including Zhang and Chanson [18], Shi et al. (2020)[27] and Arosquipa Nina et al. [28]. With the movies recorded at both prototype sites, the frames included the upstream non-aerated flow, the inception region of free-surface aeration, and the air-water flow region downstream, with sometimes the downstream energy dissipation structure.

At the Hinze Dam, the air-water flow was very bright and near-plain white: the OF surface velocities were systematically inaccurate. The errors were caused by a combination of extreme brightness and lack of brightness intensity gradient, as well as the relatively low movie frame rates. In practice, the bright white colour of the air-water flow induced a saturation of the camera sensor and it was near-impossible to adjust its brightness in the field conditions. At the Chinchilla MEL weir, the natural light conditions created a "glassy" and shiny appearance of the upstream spillway flow (Fig. 3B), preventing any meaningful OF data in the non-aerated flow region. In contrast, some good data sets were obtained in the air-water flow region. This situation was the result of a combination of the grainy/coarse water surface texture and its beige colour, which indicated a flow mixture of sediments, water and air: i.e., a three-phase mixture.

The current application of technique may be adversely affected by several types of possible errors. Some might be caused by the lighting conditions, the movie recording settings, the image processing and the post-processing. Altogether, the field experiences at large dam spillways highlighted a number of challenging considerations associated with the implementation of to prototype spillway flows. These have rarely been discussed in the literature to date. The frame size is typically relatively large, and many scales of the turbulent flow motion may be smaller than the interrogation area size on which the OF calculations are performed. These medium-to small-size turbulent scales are not resolved in turn by the OF analysis. Ideally, the upper bound analysis frequency is the ratio of two times the surface velocity to the physical pixel size. A related problem is experienced in large-scale image velocimetry in fluvial hydraulics [15,29,30]. One solution could be the usage of much higher camera sensor resolutions. Some careful considerations must also be thought in terms of the temporal scales, for data sets recorded at relatively low frame rates, as this was the case at the Hinze Dam and Chinchilla weir. Further, the relatively important distance between camera and spillway flow, as well as some possible oblique angle between camera axis and water surface, may cause some optical and

(A1)  (A2)

(A) Effect of natural lighting conditions on dSLR photography with a Pentax™ K-3 camera equipped with Pentax™ FA31mm f1.8 Limited lens, and 1/8,000 s shutter speed - (A1) Hinze Dam spillway on 23 March 2021 under intense rain (daily rainfall > 100 mm); (A2) Hinze Dam spillway on 24 March 2021 under sunny conditions and blue sky

(B) Physical access during natural disasters: submerged access road to Chinchilla MEL weir on 5 January 2011, with water level gauge on the right.

Fig. 4. Field observations of large dam spillway operations and associated challenges

geometrical distortions. The former may be minimised with the use of professional-grade prime lens with small distortion. The latter may be removed by the application of geometrical transformation [29], although the additional computational post-processing may add potential errors and require large computational resources.

3.2. Optical challenges

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

(C1)   (C2)

(C) Optical measurement setup at prototype spillways: (C1) Chinchilla MEL weir on 15 December 2021; (C2) Hinze Dam on 3 March 2022

(D) 

(D) Long prime lenses used for optical observations by the first author: From left to right: Pentax™ M400 mm (1.24 kg), Pentax™ FA300mm (0.935 kg), Voigtlander™ 120 mm (0.69 kg); note the absence of lens hood, although the field observations were typically undertaken with lens hood

Fig. 4. (*continued*).

- Both physical and optical access are essential.
  - One cannot emphasise enough the difficulties to access hydraulic structures during major flood events. At the Chinchilla weir, the access road was overtopped by over 1 m at the peak of the Nov–Dec 2021 flood, preventing any field observation for the largest discharge [19]. Fig. 4B illustrates the submerged access road during a previous flood event. The first author experienced a similar issue when attempting to reach the Paradise Dam (Australia) during the January 2013 flood.
  - Similarly, any optical observations rely upon optical access and line of sight. A suitable optical access of the spillway chute is rare and sometimes unpractical during a major spill, because of impracticalities, atmospheric conditions or safety.
- The recent field measurement experience and OF datasets may be discussed in comparison to top view movies recorded during recent laboratory experiments in a large-size stepped spillway model [28].
  - The laboratory data were meaningless in the non-aerated flow region and only validated in the air-water flow region. In contrast, the OF data at the Hinze Dam spillway provided physically

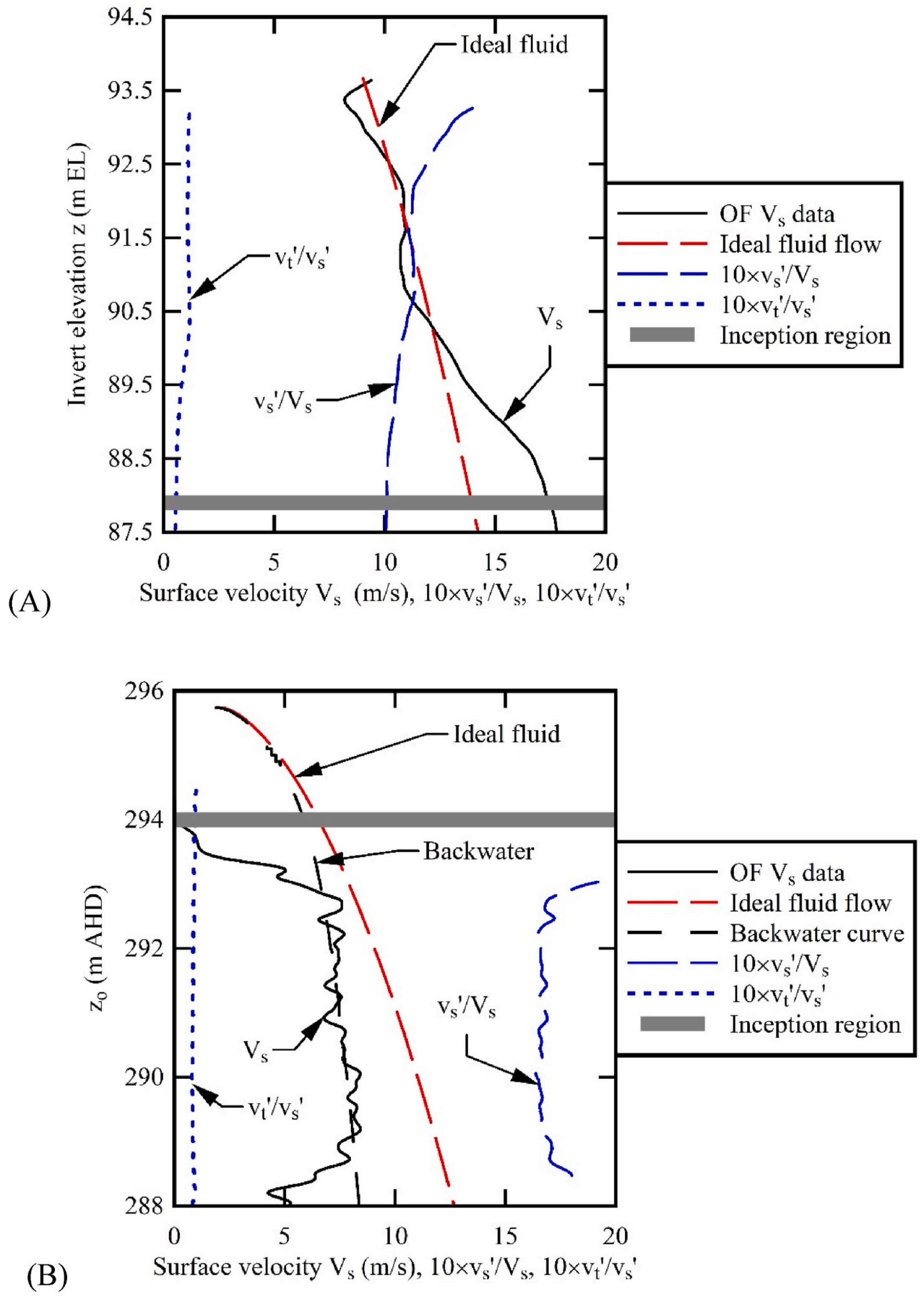

Fig. 5. Optical Flow (OF) time-averaged surface velocity V_s, streamwise surface turbulence v_s'/V_s, and surface turbulence intensity v_t'/v_s' - Comparison with theoretical estimates. (A) Hinze Dam stepped spillway on March 24, 2021 (see also Fig. 4B); (B) Chinchilla MEL weir on December 15, 2021 (see also Fig. 3B).

meaningful surface velocities in the non-aerated flow region. The different outcome might be linked to the large presence of suspended sediments in the prototype, the faster movie frame rate in laboratory, and the different light conditions.

- The OF data at the Chinchilla MEL weir yielded physically meaningful velocities at the surface of the air-water flow region, although the water surface texture differed substantially with the laboratory flow conditions.

- In a number of occasions, the OF data outputs were physically meaningless. Several explanations may be proposed, encompassing a poor optical access, some hardware limitation, incl. spatial and temporal resolution, accuracy of ground reference points, some lighting conditions, weather and atmospheric conditions ….
- The current OF experience in large dam spillways hinted that both faster frame rate and large camera sensor size are required to achieve some meaningful temporal resolution in very-bright air-water flow regions. A few suggestions may be developed.
  - The OF technique tracks the changes in brightness intensity linked to reflectance difference associated with the passage of air-water surface features. The time step between successive movie frames has to be smaller than the relevant time scales of the interfacial features of the "white waters", typically within 1 ms–50 ms. At low movie frame rates, in addition, the large changes in luminance between successive frames violate the fundamental assumption of brightness constancy. Both arguments would suggest a minimum frame rate of 1000 fps to 5000 fps to enhance the temporal resolution.
  - A larger camera sensor would increase the spatial resolution, e.g. a 12K sensor or larger.

- Possibly, different OF parameters could be selected to suppress the noise and high frequency bias, but the calibration and validation of such OF parameters are most problematic with prototype spillway data sets, in absence of independent validation data sets.
- For completeness, the combination of faster frame rates and larger sensor size would generate large movie files, with the associated implications in terms of storage during field deployment and subsequent post-processing time and data analyses.

- The quality of the optical data outputs is closely linked to the optical access, the quality of the observation point and the stability of the camera.
  - In ideal conditions, the camera should face the spillway chute and be aimed perpendicular to the water surface. At both Hinze Dam and Chinchilla MEL weir, such an ideal location was not always feasible for a combination of factors, including the flood levels and physical access, the weather conditions, i.e. sun, wind, rain, and the local atmospheric conditions, i.e. mist and wind. For example, at the Hinze Dam spillway, the downstream observation platform was sometimes subjected to a strong cloud of mist and fine spray generated at the spillway toe and above the stilling basin. The fine droplets would rapidly obscure the front glass of the camera lens, even with a protective lens hood.
  - With the OF technique, the data quality is closely linked to the seeding of the water surface. At the Hinze Dam spillway, the presence of brown colour sediment-laden waters yielded reasonable data in the upstream non-aerated flow region. On March 31, 2017, however, the presence of very long air-water streaks induced a few errors. At the Chinchilla MEL weir, no issue was reported in the air-water flow region.
  - A basic requirement is a very stable camera positioning, i.e. using a sturdy professional-grade tripod placed in a solid floor. The camera and tripod should not be affected by any form of vibrations. Fig. 4C illustrates a few setups used by the first author.
  - The movie images were adversely impacted by light reflections and glare, including optical artifacts caused by free-surface instabilities. These could cause large fluctuations of the surface velocities.
- The optical conditions can change drastically between flood events, between successive days during the same flood event, and sometimes within 1 h on the same day. These changes in natural light conditions cannot be controlled although they impact substantially the image quality and OF output quality.
- As for any statistical analysis of turbulent flows, the number of images per movies should be ideally over 5000 frames [31]. Longer movie recording are desirable, although not always feasible. During recording, the camera must remain immobile and fixed for the entire duration of the recording. Noteworthy, the natural lighting conditions should "ideally" remain constant for the entire duration of recording but this is not always possible. Similarly, the camera system must be remain protected from wind effects, mist and spray. This was not always possible at the Hinze Dam because of the spillway configuration.
- Between 2010 and 2022, the first author used a range of different camera systems, owing to the time span of the observations. This experience highlighted that, for given day and atmospheric conditions, the best picture quality was obtained with professional dSLR cameras equipped with high-quality professional-grade prime lenses. The best lenses were single-focal-length lenses, i.e. prime lenses. with relatively large aperture, e.g. f1.4 or f1.2, and negligible lens distortion. The cameras were best placed on a sturdy tripod with 3-way ball head. 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 (Fig. 4D). 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. With full-frame cameras, the lens' focal lengths would need to be 40 % longer, unless accepting a lesser pixel definition. Such long to super-long telephoto lenses are rare, expensive and heavy. Fig. 4D shows some examples, with the mass of each lens listed in the figure caption. In poor natural lighting conditions (e.g. intense rain), such long tele-lenses are not fast enough to achieve the required high-shutter speeds.

All in all, we must stress again that the optical data quality is very strongly correlated to the quality of the natural lighting. While some preliminary testing is possible in laboratory to improve the brightness conditions and movie quality, most field observations rarely allow any form of testing and this could be very challenging during natural disasters. Further discussions on OF applications were developed by Arosquipa Nina et al. [26] and Chanson [32].

4. Discussion

Under suitable conditions (see Section 3), the OF surface velocity data sets can provide some quantitative information into the high-velocity free-surface flow of large dam spillways. The surface velocity maps showed streaks of fast flow region and areas of slower velocities. While their respective locations varied with time, the elongated flow patterns were seen in the contour maps of time-averaged surface velocity and their standard deviation. Fig. 6A presents a typical contour map of time-averaged surface velocities. The OF data showed that the surface streamwise turbulence v_s'/V_s was larger than 100 %, as illustrated in Fig. 5A and B. The prototype observations were in agreement with interfacial turbulence data observed in large-size laboratory models of spillways [28,33]. The transverse surface velocity fluctuations v_t' were smaller than the longitudinal surface velocity fluctuations, with $v_t'/v_s' \sim 0.13$ to 0.2 at both smooth and stepped spillways (Fig. 6B). All the data sets demonstrated a very-strong anisotropy of the surface turbulence. The combination of high-level surface turbulence and turbulence anisotropy was associated with a broad range of air-water surface features encompassing scars, boils, streak lines, foam lines, divergence, and convergence. Altogether, the OF surface velocity and turbulence maps implied the three-dimensionality of prototype dam spillway flows. The outcome has direct implications for the design of stilling basins, too often developed based upon naive one-dimensional flow approximations.

Large dam spillways are prototype hydraulic structures, and physical experiments and numerical modelling are typically used during the engineering design to optimise the geometry as well as to ensure their safe operation [34,35]. Importantly, the modelling study must aim to deliver a reliable prediction of prototype hydraulic structure operation: "*Of particular interest are hydraulic scaling problems involved with the ultimate operation of such structures as dams […] where catastrophic failures are possible*" ([36], p. 0.1–2). This is critical because the improper operation of dam spillways can yield calamitous failure: "*the satisfactory operation of the spillway and its associated apron is vital since at the worse their failure can have catastrophic effects on property and life*" ([36], p. 0.1–2). The modelling approach must be developed based upon the fundamental principles of similitude and dimensional analysis [37–39]. Considering the operation of a dam spillway (Figs. 1 and 3), a basic dimensional analysis shows a large number of relevant parameters [39, 40]. In the model, the flow conditions must be similar to those in the full-scale hydraulic structure: i.e., a similarity of form, of motion and of forces. A true similarity does require having all dimensionless dependant parameters to be identical in physical/numerical model and prototype. This is not achievable in most geometrically-scaled models, and Professor Novak stressed the associated challenges in his 1984 keynote lecture: "*Let us remember again that our models are designed to give valuable answers to questions posed by the practicing engineer, and to do that we must be aware of the "consequences of nonsimilarity between model and prototype*

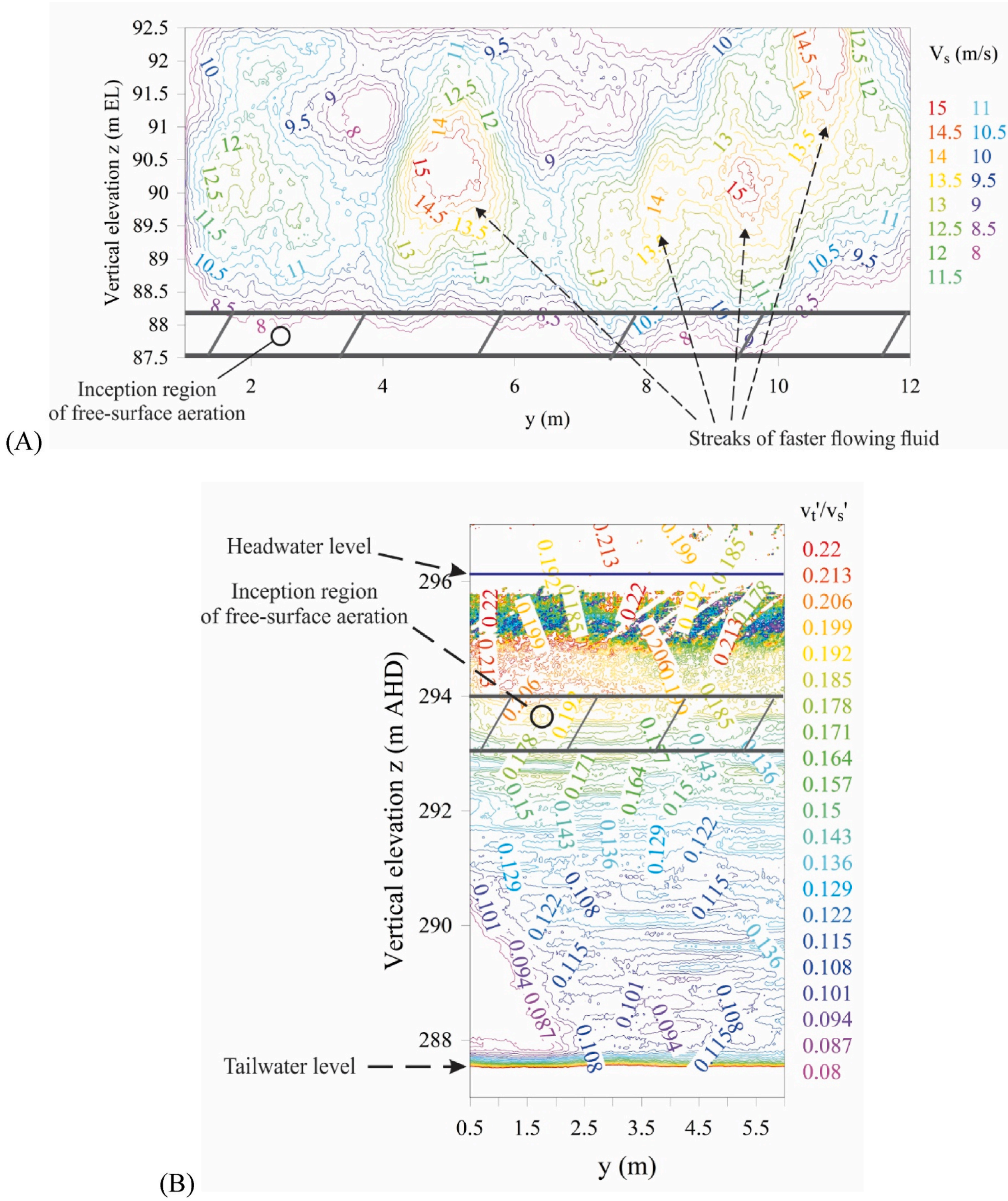

Fig. 6. Contour maps of optical surface velocity data at prototype dam spillways, with flow direction from top to bottom - (A) Time-averaged surface velocity V_s in the non-aerated flow region at Hinze Dam on March 24, 2021; (B) Turbulence intensity v_t'/v_s' at Chinchilla MEL weir on December 15, 2021.

resulting from the fact that not all pertinent dimensionless numbers are the same in model and prototype" and of the "error arising by using the model according to the main determining law and neglecting others"' ([41], p. 0.3–5). Spillway overflows are free-surface flows for which gravity effects are important, and basic dimensional considerations highlight the significance of the Froude number [42,43]. In most design applications of large dam spillways, the physical and/or numerical model is smaller than the prototype, and the Reynolds number is smaller than in the full-scale prototype flow. Thus, viscous scale effects might take place [34,39,44]. Simply, full-scale prototype data sets are necessary to validate current physical and numerical modelling, especially for very-large Reynolds number flows.

Another relevant consideration is the key differences between spillway operation during major floods and prototype spillway tests. During a major flood, the dam spillway may operate at large discharges for a number of weeks. The large flow rates may correspond to Reynolds numbers about 10^7 to 10^8, possibly more, which are typically two to four orders of magnitudes larger than physical model tests in laboratory, and often one to three orders of magnitude larger than seminal prototype tests such those at the Aviemore dam spillway (New Zeland), La Grande Dixence spillway chute (Switzerland), and Pangzhuang gate (China) [10,13,45]. A major challenge with prototype spillway tests is to achieve steady flow conditions over a long enough duration to get a meaningful data set, when these are undertaken under controlled-release conditions for short durations ([36], p. 2). The tests must start after the flow is established and a steady flow regime is achieved. This is not trivial in open channels ([31], pp. 254–255). In many hydraulic laboratory flumes, the establishment time of steady flow conditions may require several minutes, from three to 30 min depending upon the type of free-surface flows. Based upon a Froude similitude, the necessary establishment time at a prototype scale should be much larger, i.e. three to 30 min times the square root of the geometric scaling ratio, corresponding to ten to one hundred minutes in prototypes depending upon the scale [34,40]. Another challenge with short-duration prototype tests is often a lack of quality control and the inability to replicate. At both Hinze Dam and Chinchilla weir, the observations were repeated within 90–120 min during multi-week flood events, and the overflow discharges varied by less than 5 % during that period. This type of observations corresponded to a first order replication level ([46], pp. 12–13). In comparison, a recent series of controlled-release prototype outlet measurements [47] used single-discharge tests with durations of 5 min, 10 min, 25 min and 75 min, possibly insufficient to achieve steady flow regime or to replicate the testing, i.e. zeroth order level of replication ([46], p. 12).

5. Conclusion and outlook

At prototype dam spillways during major flood events, the OF surface velocity data sets may provide some unique insight into the high-velocity free-surface flow. The present work highlights some key requirements for successful optical velocity measurements in high-velocity prototype spillway flows At Hinze Dam spillway and Chinchilla MEL weir, the surface velocity maps presented a number of two-dimensional surface flow patterns implying some three-dimensionality of the flow. Some elongated flow patterns are seen in the contour maps of time-averaged surface velocity and their standard deviation. The data showed very-high surface turbulence levels in chute spillway flows, as well as a strong anisotropy of the surface turbulence. Basically, the OF velocity and turbulence maps highlighted some three-dimensional flow motion on prototype dam spillways and in turn the three-dimensional inflow conditions into the downstream stilling structure. The finding directly impacts on the modelling and design of energy dissipators, because "*the magnitude of turbulent energy that must be dissipated in hydraulic structures is enormous even in small rural and urban structures*" ([48], p. ix).

In a seminal keynote paper, an eminent engineer, Rex A. Elder, bluntly criticised "*the fallacy*" of "*costly, inefficient*" prototype tests whereby "*design factor(s) be determined by study of the prototype*" ([36], p. 2). The present discussion highlighted indeed a number of implicit limitations of (short duration) prototype tests, and in turn, strengthened the case for more field measurements during major floods. Looking forward, the present approach of remote spillway observations during large floods paves the way for future prototype observations in high-velocity chute spillways. It further shows the path for the development of new hybrid modelling methodology combining field observations and laboratory experiments [49]. This approach would combine complementary observations of spillway configurations that are geometrically scaled based upon an undistorted Froude similarity, linking optical observations in the prototype with detailed imaging measurements and intrusive phase-detection probe measurements in a relatively large-size physical facility, under controlled conditions. In the end, all the above issues suggest that further studies are still needed in the future to achieve a comprehensive and accurate modelling of prototype spillway flows.

CRediT authorship contribution statement

H. Chanson: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. **R. Shi:** Formal analysis, Resources, Software, Writing – original draft, Writing – review & editing.

Data availability

Data will be made available on request.

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