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Application of numerical modelling to spillways in Australia

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ABSTRACT: Recent revision to design flood estimates of a number of Australian dams have required their spillways to be upgraded to cope with increased discharge rates. Their hydraulic performance was investigated by numerical modelling instead of using scaled physical model. For most projects, where possible, a rigorous validation exercise using published or physical test results was performed to ensure its correctness and reliability before embarking on further parametric study. The various analysis capabilities allowing better understanding of the flow behaviour taken from eight spillway upgrade projects will be described in the paper. The benefits and limitations were also highlighted. Some future research and development needs have been suggested. With prudent engineering guidance, it is anticipated this emerging technology may become a standard design tool for analysing spillway flow in the future.

1 INTRODUCTION

Recent revision to design flood estimates of a number of Australian dams have required their spillways to be upgraded to cope with increased discharge rates. In coping with the increased discharges, the existing spillways may face potential problems such as the generation of excessive negative pressure over the spillway crest, erosion of unprotected cut banks, overtopping of chute walls, and flow impact on crest bridges and gates. Furthermore, the discharge coefficient and rating curve will usually need to be re-evaluated for greater operating heads.

Traditionally, scaled physical hydraulic models have been constructed in laboratories to study these behaviours. However, these models can be expensive, time-consuming and there are many difficulties associated with scaling effects. Most models built are only kept for a limited time.

Nowadays, with the use of high-performance computers and more efficient computational fluid dynamics (CFD) software, it is feasible to investigate the hydraulic performance of full scale spillways. It should be noted that this technology has been well established in the aerospace, automotive and maritime industries worldwide.

This paper describes how the application of this numerical modelling technique has benefited a number of dam upgrade projects in Australia. As this type of spillway analysis technique was used for the first time in this country, the need to carry out validation was essential. A rigorous staged validation process was conducted for the Warragamba Dam drum gate upgrade project. In all the subsequent spillway upgrade projects, comparisons were made between computed and measured values, using the results of physical modeling carried out during the original design of the dam, where available, to raise the confidence level of the analysis technique.

Use of numerical modelling has led to the development of innovative devices to mitigate the impact of flows on gate structures and concept designs to reduce excessive negative pressure over a spillway crest. Significant cost savings were achieved for these upgrade projects. The benefits as well as the limitations of numerical modelling of spillway flow will be highlighted in the paper. Some future research and development needs will also be suggested.

2 A BRIEF OVERVIEW OF NUMERICAL MODELLING FOR HYDRAULIC APPLICATION

A literature search of numerical modelling of spillways in overseas application has revealed that it began as an investigative tool at research institutions (Kjellesvig 1996, Savage & Johnson 2001), and it was gradually being accepted by the hydraulic/dam engineering community (Higgs, 1997, Yang & Johansson 1998, Cederstrom et al. 2000, Teklemariam et al. 2002, Gessler 2005). In terms of CFD technology in civil engineering applications, not necessarily confined to hydraulic engineering, a keyword search for "CFD" in the American Society of Civil Engineers (ASCE) database revealed the number of publications related to this technology increased rapidly as shown in Table 1. It appears this has a strong correlation with the increase in computing efficiency over this period of time.

In Australia, computational or numerical modelling of hydraulic performance has also been carried out at research level. For example, Brady (2003) investigated free surface flow for sewer overflow, and Barton (2003) studied numerical modelling of fishways. In terms of its application to dam spillways, this type of modelling was not mentioned in the recent Australian National Committee on Large Dams (ANCOLD) publication on the history of dam technology from 1850 to 1999 by Cole (2000). There has been no published information on numerical analysis of spillways in Australia until recently (Ho et al. 2003, 2004, 2005).

3 AN OVERVIEW OF THE NUMERICAL MODELLING TECHNIQUE

There are a number of textbooks that explain in detail the theory and numerical implementation of CFD technology, for example, Abbott & Basco (1989), Wilcox (1993), Versteeg & Malalasekera (1995). For hydraulics application, the governing equations describing the behaviour of the incompressible water are the conservation of mass (continuity equation) and momentum (Navier-Stokes equation). These partial differential equations, inherently non-linear, are discretised both in space and time and they can be solved using a variety of numerical schemes. Due to the complexity of turbulent behaviour, it can be simplified and approximated using an averaged approach (i.e. Reynolds-averaged Navier-Stokes or RANS). For practical purposes, the RNG (Re-Normalised Group) k-ε turbulent energy dissipation model has been rather successful and is currently an industry-standard model for hydraulic turbulence. It is important to note that just like any other numerical modelling, the need for validation against prototype performance is essential.

Table 1. Literature search on the ASCE publication database for "CFD" till the end of 2005.

Period	All document types	Conference papers	Journal papers	Main topic covered in journal papers
1980–1989	0	0	0	N/A
1990–1994	3	3	0	N/A
1995–1999	13	9	3	Simulation of fire and smoke in the built-environment
2000–2004	47	28	14	Mostly hydraulics related
2005	10	6	3	All hydraulics related

4 APPLICATION IN AUSTRALIAN SPILLWAY UPGRADE PROJECTS

To date, the spillway upgrade projects which utilised numerical modelling to investigate hydraulic performance are shown in Table 2. It can be seen that a variety of existing and proposed spillway types were analysed. A general methodology is summarised in a flowchart as shown in Figure 1. Note that this will vary with the purposes of analysis and project requirements. The complexity of the problem can vary from a simple 2D model (Fig. 2) to a complex full 3D model (Fig. 3).

As mentioned previously, validation of the numerical technique is important and therefore it formed one of the analysis tasks in most of the spillway upgrade projects. The use of CFD analysis to study the suction effect on the drum gate at the spillway crest as part of the Warragamba Dam up grade was subjected to an extensive validation to ensure the numerical modelling was correct. The validation process was carried out in a multi-staged approach. The validation of the standard ogee spillway profile using the US Army Corp of Engineers Waterways Experimental Station (USACE-WES, 1952) design guides was carried out both two- and three-dimensionally to determine the suitability of the code. The influence of the piers was correctly captured by the 3D analysis. Then the actual spillway geometry in question was analysed and the results compared with those obtained by physical testing. A reasonable agreement was achieved for practical purposes. More details are reported by Ho et al. (2003).

The CFD code, *FLOW-3D*®, developed by Flow Science, Inc., was selected primarily for its ability to accurately model free surface flow, which is essential for modelling open-channel flow behaviour. It utilizes a true volume of fluid (truVOF™) method for computing free surface motion (Hirt & Nichols, 1981) and

Table 2. Summary of spillway project using numerical modelling.

									Analysis output, scenario & flow behaviour								
Dam, location	Spillway type	Chute	Numbers of bays	Gate type	Standard Ogee or Elliptical crest	Bridge piers	CFD geometry model	Validation against physical model test	Re-evaluate discharge	Orifice flow	Overtopping or submerged flow	Pressure distribution	Impact on gates	Impact on pier/bridge structures	Erosion impact	Shockwave simulation	Hydraulic jump
Warragamba, NSW	Gated	Short	5	Radial & drum	Neither	✓	Local 3D utilising symmetry	✓	✓	×	Overtop failed radial gate	✓	✓	–	–	–	–
Hume, NSW/VIC	Gated	Short	29	Vertical-lift	Neither	✓	Local 2D & 3D utilising symmetry	✓	✓	✓	Overtop parapet wall & crest bridge	✓	–	✓	–	–	–
Buffalo, VIC	Gated	Short	3	Vertical-lift	Ogee	✓	Half 3D model	USACE/ HDC	✓	×	×	✓	–	–	–	–	–
Wivenhoe – existing spillway, QLD	Gated	Short	5	Radial	Ogee	✓	Full 3D & half 3D models	✓	✓	✓	Overtop crest bridge & raised gates	✓	✓	✓	–	–	✓
Wivenhoe – auxiliary spillway, QLD	Fuse plug embankments	Short	3	N/A	Elliptical	✓	Full 3D model	–	✓	–	–	✓	–	✓	–	–	–
Goulburn Weir, VIC	Gated	Short	9	Radial	Neither	✓	Half 3D model	✓	–	✓	Submerged	✓	✓	✓	–	–	–
Blowering, NSW	Uncontrolled	Long	1	None	Ogee	×	Full 3D model	✓	✓	–	Overtop spillway chute walls	✓	–	–	✓	✓	–
Tullaroop, VIC	Uncontrolled	Long	1	None	Ogee	✓	Full 3D model	✓	✓	–	–	✓	–	✓	✓	✓	–
Tallowa – proposed upgrade, NSW	Gated	Short	21	Radial	Ogee	✓	Local 3D utilising symmetry	–	✓	×	Submerged for some cases	✓	✓	✓	–	–	Drowned

NSW = New South Wales
VIC = Victoria
QLD = Queensland

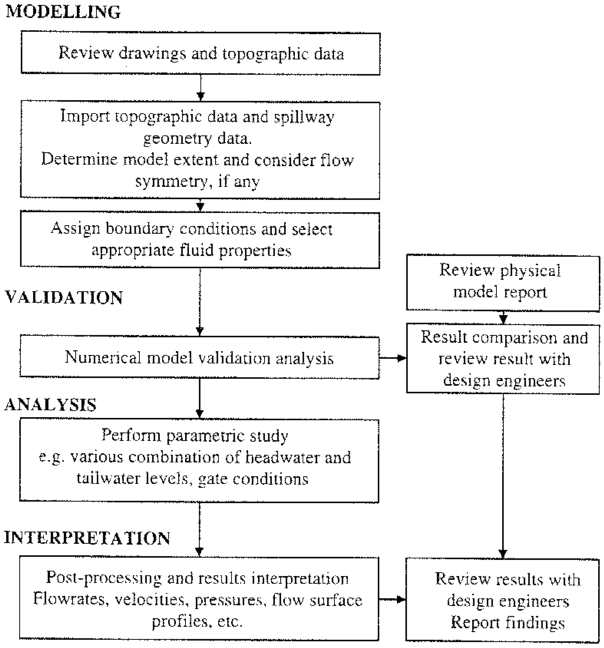

Figure 1. Flowchart showing a general methodology.

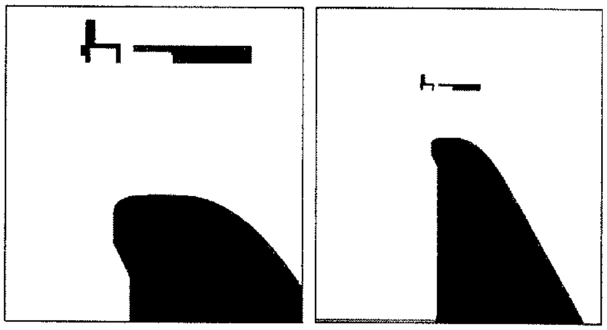

Figure 2. 2D geometry model of the Hume Dam spillway. Zoomed-in details of parapet wall, drop gate gap and crest bridge shown on the right.

the fractional area/volume obstacle representation (FAVOR™) technique to model complex geometric regions (Hirt & Sicilian, 1985). The true VOF method tracks the sharp interface accurately and does not compute the dynamics in the void or air regions. The single fluid approach allows faster run time.

The code's ability to model wall roughness (Souders & Hirt, 2002), air entrainment (Hirt, 2003) and cavitation was also important. Other considerations in the code selection process were the ease of use (e.g. obstacle and multi-block grid creation) and cost. It should be noted that a similar validation exercise on a standard ogee crest spillway was conducted by Savage & Johnson (2001) using the same code, which provides further confidence in the analysis technique.

Based on the analyses performed to date, the following sections highlight some of the interesting findings taken from the numerical modelling experience.

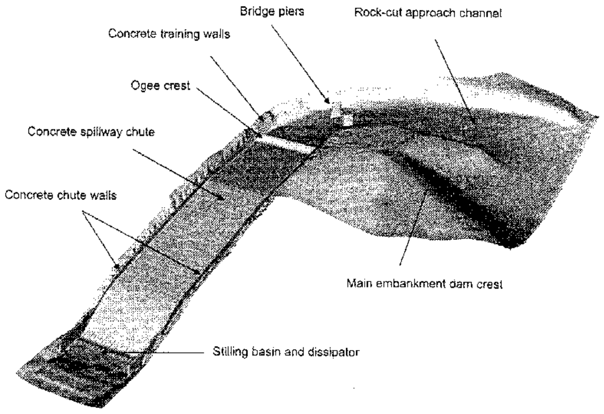

Figure 3. Full 3D geometry model of the Tullaroop Dam Spillway.

It should be noted that only the steady-state flow condition was of interest for these projects. For most models, the upstream and downstream boundary conditions were fixed at the appropriate head levels. After a period of time, the analysis reached a dynamic "steady-state" when the flow rate and other flow behaviour could be obtained and observed.

4.1 *Validation against physical models*

In many of the projects, where possible, at least one flood level was analysed so that the computed results could be compared against old physical model test results (see Table 3). Typically, the discharge rate, pressure distribution and flow surface profile were used for comparison purposes. In some cases, velocity profiles were also available for comparison.

In general, the flow rate computed by the numerical model can be up to 5% greater than physical model results for head levels equal to and greater than the design head of the spillway. Typically, the over-estimation is around 3%. Similar over-estimation has also been reported by Gessler (2005). Yang & Johansson (1998) also reported a similar trend of over prediction even though different CFD code and a two-phase flow model (i.e. water and air) were used.

Some fluctuation in pressure distribution along a crest section may occur due to limiting grid resolution and the way the results are extracted. In general, the averaged trend gives a reasonable agreement. It should be noted that there will also be accuracy resolution issues with physical measurement. Similar to the pressure distribution, the flow surface can fluctuate depending on the grid density. However, the averaged trend gives a reasonable agreement.

4.2 *Spillway discharge*

One important output of most investigations is to determine the discharge efficiency of the existing spillway

Table 3. Validation summary.

Upgrade projects	Physical model scale (year of test)	USACE/WES	Flow rate	Pressure distribution	Free surface profile	Velocity profile
Warragamba Dam*	1:100 (1991)	✓	✓	✓	✓	✓
Warragamba Dam**	1:100 (1991)	–	✓	✓	✓	–
Hume Dam	1:50 (1962)	–	✓	✓	✓	–
Buffalo Dam	Not used	✓	✓	✓	✓	–
Wivenhoe Dam	1:80 (1979)	–	✓	✓	✓	✓
Goulburn Weir	Not used	–	✓	✓	–	–
Blowering Dam	1:80 (1971)	–	✓	✓	✓	–
Tullaroop Dam	1:30 (1958)	–	✓	✓	✓	✓
Tallowa Dam	Not used	–	–	–	–	–

* Drum gate bay
** Radial gate bay

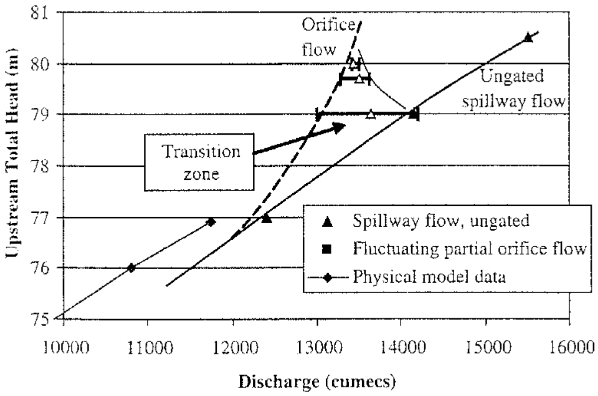

Figure 4. Rating curve showing the transitional flow region between free discharge and full orifice flow.

under revised flood levels that may be several times the original design flood level. The situation can be complicated by the presence of crest structures such as bridges and gates. In these cases, as the upstream flood level increases, the discharging water can undergo several stages of flow behaviour starting from a free discharge, then a transitional flow, followed by orifice flow and eventual overtopping of the crest structure. This sequence of flow behaviour was encountered in the Hume and Wivenhoe existing spillways.

A typical rating curve is shown in Figure 4 for the Wivenhoe Dam existing spillway. The computed result for the original design flood is in good agreement (~5% over-prediction) with the physical test data. For the free spillway flow without the influence of the gates, the data appears to follow the power relationship for higher head levels.

4.2.1 *Transitional flow*

By observing the transient flow of water in the 3D model for a certain head level within the transition zone, the water impacted on the under side of the skin plate of the raised gates from time to time. A complex 3D partial orifice flow would occur and this also varied across the spillway from bay to bay. This explains the range of discharge computed for a particular head level within this zone.

4.2.2 *Full orifice flow*

When the head level is high enough, oscillations in the discharge rate cease as the flow settles into a complete orifice flow where the full width of the skin plate is impacted upon across all bays.

Depending on the raised gate and crest bridge configuration, overtopping may eventually occur when the upstream head level is sufficiently high. In this event, further deviation of discharge curve would result.

4.3 *Spillway integrity*

The concrete spillway's integrity can be assessed in terms of cavitation number or index and the overall stability under high flood discharges.

4.3.1 *Cavitation*

When excessive negative pressure occurs, there is a potential for cavitation to take place which can cause significant damage to the concrete surface of the spillway. This can occur not only at the spillway crest, but also at floor slabs further downstream along the spillway chute. Based on the computed pressure and flow velocity distributions, the numerical model is able to predict whether cavitation damage will potentially occur not just in the crest region, but right through the spillway structure including the downstream structures such as the chute floor slabs, flip bucket, apron and plunge pool.

When the cavitation model is enabled or with adequate aeration in the analysis, flow separation can be predicted to take place from the numerical model. The vapour pressure will depend on the water temperature and the elevation of the spillway site relative to the mean sea level.

4.3.2 *Overall stability*

The pressure distribution on the surface of the spillway can be computed. Together with the self-weight of the structure and any underlying uplift pressure, the factor of safety (FOS) against overturning and sliding failure modes can be calculated. Should the FOS become unacceptable under increased flood levels, mitigation solutions such as installation of post-tension anchors can be considered. For example, the revised head for the Buffalo Dam spillway is almost three times the original design head (Newman & Foster, 2005). Although the spillway is a standard ogee profile, the pressure distribution cannot be extrapolated directly from the USACE design guides. The numerical model was able to provide this missing information.

4.4 *Structural integrity*

The numerical model was able to determine if the discharging water under the revised flood levels would impinge on existing gate and bridge structures. One project examined the potential for flows to impact on the arms of raised radial gates. The loads determined by the CFD analysis were applied to a finite element (FE) model of the gate to check for structural integrity and to decide if mitigation measures were necessary.

It is generally reasonable to assume the steel gates are relatively stiff. Therefore the use of non-deforming obstacles or baffles to represent the gate would be valid. Although it is possible to analyse a fully coupled fluid-structural interaction using combined CFD and FE analyses, the extra computing resources required will be significantly increased and it is probably not justifiable for these projects.

4.4.1 *Drum gate*

For the Warragamba Dam upgrade, the CFD analysis was able to determine the lifting pressure due to increased flood level on the drum gate. This gate was originally designed to be held down in the open position by the gate's submerged self-weight, for a lower design flood level. Feasibility concepts based on stability consideration were assessed and a mitigation solution, a lock-down device, was further analysed using a FE model to confirm the design requirements.

4.4.2 *Radial gate*

CFD analysis was used to determine whether the discharging water was likely to impact on the raised gate arms, and quantify any consequent drag loads. These loads were then applied to the FE model of the raised gate in order to determine if strengthening was required.

In another scenario when the gate could not be raised during the flood event, the analysis was able to predict the pressure on the gate skin plate as well as any adverse impact due to the jet of water flowing over the gate on to the crest bridge and on the spillway further downstream (Fig. 5). The pressure acting on the skin plate was then applied to a FE model to determine whether a plastic hinge could form causing the upper cantilever portion of the skin plate to fail in bending due to this overtopping discharge. A partial failure mechanism like this may be preferable to having the entire gate washed away downstream.

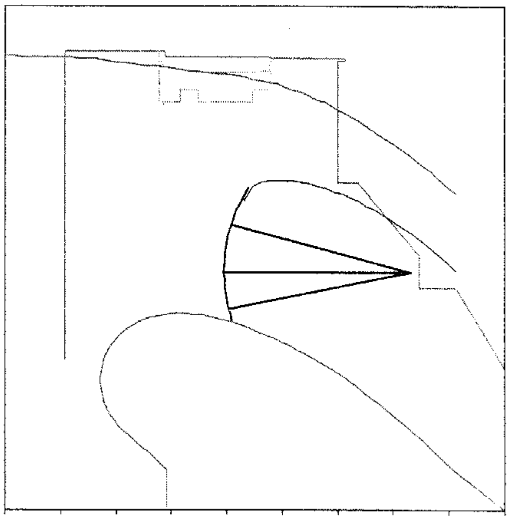

Figure 5. Flood water trajectory over a malfunctioned radial gate.

For the Wivenhoe existing spillway, it was discovered that the revised higher flood level could impact on the lower part of the skin plate of the raised radial gates. An innovative device to deflect the water away from the skin plate was designed based on the numerical model as described in Section 4.8.

In an extreme load case for the Goulburn Weir upgrade, the raised gates were completely submerged. CFD and FE analyses showed the gates were not under the most adverse condition because the head difference between upstream and downstream was not significantly large, resulting in a lower velocity flow over the drowned weir. The computed flow velocity also allowed an estimation of floating debris force impacting on the gate and bridge structures to be made.

4.4.3 *Bridge piers*

Very often there are road or service bridges on top of spillway crests. When the flood water level is high enough, the effects on the piers and even on the bridge decks will need to be investigated. The drag loads and flow velocities can be determined from the CFD model. When the bridge piers are located upstream of the spillway crest – for example, Wivenhoe auxiliary spillway and Tullaroop existing spillway – the model will need to be extended far enough to capture the pier effects.

Depending on the grid resolution around the piers, vortex shedding may or may not be captured. However,

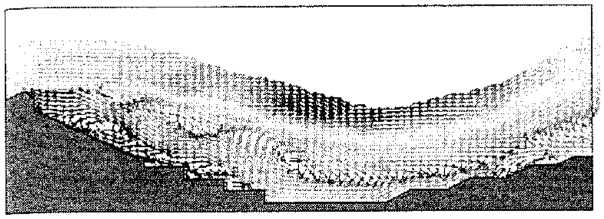

Figure 6. Velocity vectors showing re-circulation of flow in the base of the plunge pool.

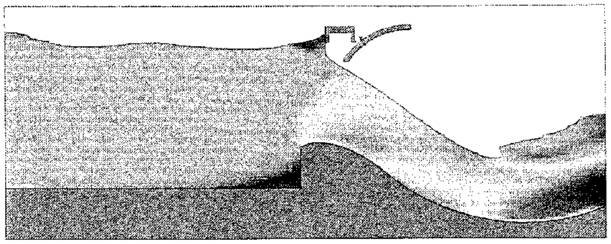

Figure 7. Section through centre of bay showing the baffle deflects water away from the underside of the gate's skin plate.

it is possible to use a sub-modelling technique to further study this effect.

Note that the influence of the stop-log slots on the flow had been included in the models where applicable.

4.4.4 *Plunge pool and stilling basin integrity*

When the model includes a sufficient extent of the downstream structure, the analysis was able to predict the occurrence of a hydraulic jump for the appropriate head and tail water condition.

The model can also reveal the flow behaviour in the plunge pool. Some flow re-circulation in the plunge pool was predicted for the Wivenhoe existing spillway (Fig. 6). Velocity and pressure profiles can be extracted for structural integrity assessment. For instance, concrete floor slabs can be lifted if they are not secured down adequately.

4.5 *Overtopping of chute walls*

The potential for overtopping of the existing spillway chute walls under the raised probable maximum flood (PMF) was investigated for the Blowering spillway. The CFD analysis was able to model the superposition of diagonal shock waves for supercritical flow in the long spillway chute downstream of the ogee crest. The ability to model this behaviour correctly was confirmed by modelling several "classical" problems with known solutions suggested by Chow (1959) and USACE (1994).

From the computed flow height the extent of chute wall raising required to contain the discharging water was determined. If the fast flowing water is allowed to overtop the chute walls, the water may potentially erode the wall's backfill and the embankment fill, thus undermining the stability of both the wall foundation and embankment dam. Details of this analysis can be found in Ho et al. (2005).

4.6 *Erosion*

Some spillways were constructed by rock excavation in the mountain side, and sometimes the rock cuts were not lined with concrete for erosion protection. Increased flood levels, combined with higher discharge velocities, may potentially cause these unprotected rock faces to erode. As part of the Tullaroop Dam safety assessment, the velocity profile adjacent to the rock face in the approach channel of the spillway was obtained from the numerical model to aid geotechnical/geological engineers to assess the erodibility of the spillway walls. Although the code has sediment transport capability to model erosion and deposition of sediment, it was not required for this project.

It is anticipated the erosion model can be used to study the progressive fill removal in a fuse plug spillway during a design flood event.

4.7 *Other flow behaviours*

In many of the models involving flow passing piers, bow waves were observed to be coming off the pier. However, their interaction was not as strong as anticipated.

When a full 3D model encompasses upstream features – for example, the Wivenhoe existing spillway model – a second control section further upstream from the spillway crest was observed from the computation.

When the tail water levels are sufficiently high submerged spillway flow will occur. This submerged flow behaviour was correctly captured for the Tallowa spillway. The results were found to follow the trend as described in the USACE's Hydraulic Design Criteria (HDC).

4.8 *Innovation*

The numerical model allows design engineers to "experiment" with innovative design to improve hydraulic performance of existing or proposed spillway structures. For example, in order to prevent the flood water from impacting the radial gate skin plate in the raised position for the Wivenhoe existing spillway, different lengths of baffle plates were tested in the model to see how the water could be deflected away from the skin plate (Fig. 7). It was found to be feasible and this option gave a cost saving of about $0.5 M when compared with the solution of locking the gate in a higher location (Gill et al. 2004).

Another example is the concept study to reduce the excessive suction on the drum gate for the Warragamba

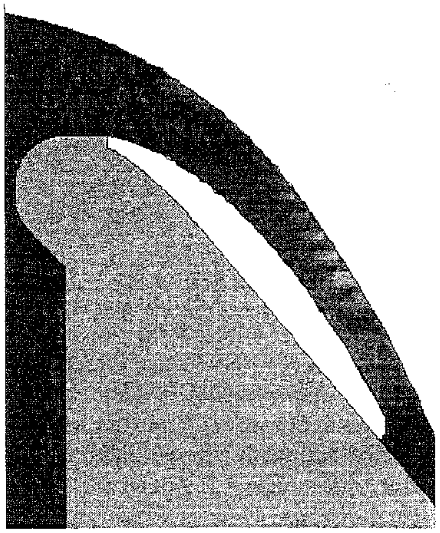

Figure 8. Re-profiled drum gate alleviated excessive suction in the crest region but the resulting flow trajectory deemed not acceptable.

Dam upgrade. A number of options such as re-profiling the drum gate (Fig. 8), re-shaping the spillway crest, installing a flow separator of different shapes and sizes were investigated using the CFD model. Although some of the concepts may provide the desired outcome for the gate, engineering practicability is also an important governing criterion.

5 BENEFITS

The numerical model enables engineers to gain a profound understanding of the flow behaviour in the spillway. Obviously, this will depend on the amount of details represented in the model.

Different "what-if" scenarios can be performed and depending on the speed of the central processing unit of the computer, the results will be obtained in a reasonable timeframe which is not unreasonable from the overall project duration perspective.

In terms of cost saving, it has been reported that the cost of numerical modelling is about 20 to 25% of the cost of conducting a physical model testing for the Wivenhoe Dam upgrade project (Chandler et al. 2003).

6 LIMITATIONS AND FUTURE DEVELOPMENT

Based on the numerical modelling experience of spillways, and from the practitioner's point of view, we have identified some limitations and suggested future research and development needs.

Small scale or local behaviour such as formation of eddies may not be captured in a large global model. Refinement of the model typically leads to increased run time. A sub-modelling approach may offer one solution but the response will highly dependent on the initial boundary conditions. Also, the time-averaged RANS turbulent model will not accurately capture the small scale behaviour. Therefore it is important to establish the scope of analysis and what information to capture prior to setting up the model.

When modelling a low flood level discharge, the volume of water involved is relatively small and the grid resolution along the spillway must be fine enough to capture the accurate flow behaviour. This will incur a longer run time. One work around is to make the grid finer in a progressive manner by utilising the "restart" feature of the code which allows the variables to be mapped from a coarse grid to a fine grid.

Further benchmark tests against established data or design guides (USACE-WES, 1952) will provide addition confidence of the analysis technique when applying to different situations or types of problems, for example, an elliptical crest spillway.

Measurement of full scale performance will provide data to validate against predictions made from the modelling – whether using a scaled physical or numerical model. However, capturing this data can be problematic because of the associated cost and limited frequency of flood occurrence. It should be noted that there will be a level of accuracy related to any kind of measurement. This must be taken into account whenever result comparison is performed.

There are some capabilities of the analysis that have not been fully tested to date. For example, modelling the water trajectory from a ski jump or flip bucket, and erosion simulation at the impact zone. It is anticipated future validation against physical test data will be required.

Further investigation may include how wave action and the direction of the upstream approach flow will affect the spillway discharge characteristics. Also, how air entrainment can be accurately modelled.

It is inevitable that information technology will continue to improve in the future. Fast computers and parallelized CFD codes will become more accessible to engineers. The role of physical modelling will need to be reappraised. Although physical models will still provide valuable information, it is anticipated that numerical models may be routinely used during the initial phase of design or feasibility study. When the preferred solution is selected, the physical model may serve to confirm design expectation. This computer-aided rapid prototyping approach is already a common practice in the automotive and aerospace industries.

7 CONCLUSIONS

The use of numerical modelling of eight spillway upgrade projects in Australia demonstrated that it is a viable technology. The benefits gained from these experiences have been highlighted. Some current limitations have been identified and future research and development suggested. It must be emphasized that this technology must be treated like any other numerical design tool or design calculation – it is not a substitute for competent engineering experience and sound judgment.

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