Enlarged Cotter Dam Diversion Gate Design – The Challenge and the Test

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This paper highlights the importance of hydraulic diversion control structures during construction of large dams and the value of allocating sufficient resources during project planning and implementation.

The design of the diversion gate for construction of the Enlarged Cotter Dam presented various challenges, including operation for up to 38m head for discharge into a 3m diameter conduit and the need to serve as an upstream concrete form during eventual diversion closure.

The short duration of operation allowed acceptance of increased level of operational risk and a higher level of design uncertainty. The design used generally accepted gate design methods, but no hydraulic modelling. The hydrodynamic forces were estimated using published data. After installation, a 1 in 100 AEP flood event resulted in the gate being subjected to 90% of its design head while operating in conditions close to the maximum design down-pull force. Attempts to raise the gate succeeded only after increasing the hydraulic pressure above the design value.

Keywords: *Guard gate design, outlet works, dam, construction.*

Introduction

During construction of the Enlarged Cotter Dam near Canberra in Australia, the second stage river diversion consisted of a 3m diameter, 200m long dogleg conduit with a closure gate located at the bend in line with the upstream face of the dam. The purpose of the closure gate was to allow the diversion conduit to be sealed once construction of the RCC dam wall had progressed sufficiently. It would then be replaced by the third stage diversion via the permanent outlet tower.

Due to late design changes while construction was in progress, the size, layout and design criteria for the diversion works was only determined about 12 weeks before the gate had to be placed into operation.

The Challenge

Part One: Initial Design

Target: Complete the design and manufacturing drawings for the diversion closure gate within 4 weeks. This would allow 2 weeks for tendering and contract award and a further 6 weeks for construction of the gate and built-in parts. As with all construction projects, tight budget constraints were in place. The design had to be uncomplicated to reduce manufacturing time and cost and all materials used were to be available ex stock from suppliers. Installation of the built-in parts and completed gate had to be achieved in two days.

The major design criteria for the gate were:

- Close a clear opening of 2.5 m wide x 2.8 m high;
- Be able to close into full flow;
- Design head of 7.5 m;
- Would only be used once;
- To be installed using a mobile crane;
- Double acting seals required (upstream water pressure and downstream concrete pressure during sealing of the conduit).

These criteria were addressed by designing a fixed wheel, vertical lift gate. Only four wheels were required due to the relatively low wheel loads. The wheels were positioned to carry equal loads. The wheels would utilise self-lubricating elastomer bushes. This simplification would be possible as at the relatively low design head the gate weight would overcome the seal and wheel friction loads.

The main horizontal beams were also distributed to carry equal load and consisted of flat bar welded to the upstream skinplate to produce a T-section profile. A double bulb seal used for the top and sides allowed the gate to seal from upstream and downstream. The gate nose was designed at an angle of 30 degrees to the horizontal, resulting in a favourable hydrodynamic profile for once off closure into flow.

The down-pull forces acting on the gate during closure were estimated using the method developed by Naudascher as described in Erbisti's "*Design of Hydraulic Gates*". This theoretical estimate for the hydrodynamic forces acting on the gate was considered acceptable due to the temporary nature of the gate, the relatively low design head and the expectation that it would only be used once.

The guide rails, main rails and sealing faces were designed to be assembled as a unit during manufacture. This would assure the necessary tolerances would be achieved for trouble free installation. The gate would be installed by mobile crane positioned on top of the partially constructed RCC dam wall. A length of chain would be used to connect the crane hook to the gate and could be sacrificed if the water level was above the gate during installation.

With the design 90% complete, further delays in the construction programme became apparent. Changes to some of the design criteria had to be made, resulting in a major re-design of the gate.

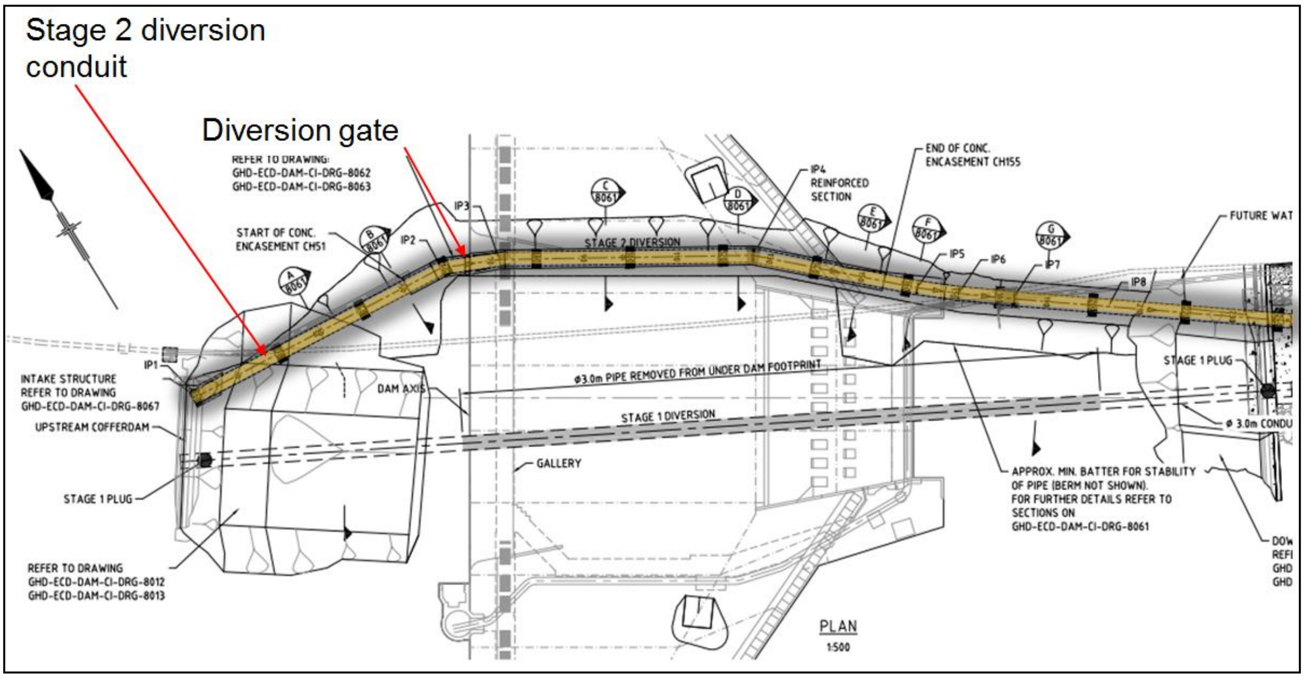

Figure 1: Plan view of diversion conduit.

Part Two: Redesign

The diversion conduit downstream of the gate consisted of a 3m diameter corrugated iron pipe designed for a maximum flow rate of 25 m^3/s. Due to the anticipated construction delays the diversion would now have to remain operational into the flood season. Large floods could result in high upstream water levels and could potentially increase the flow through an uncontrolled diversion above the design rate. The diversion gate was therefore now required to maintain the design flow during flood events to prevent damage to the conduit.

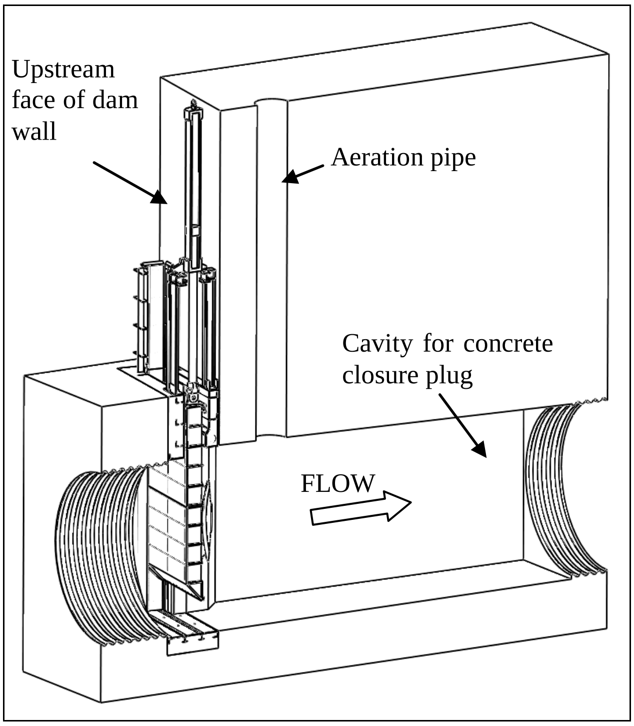

Figure 2: Sectional view of gate in conduit.

The revised design criteria now were as follows:

- Close a clear opening of 2.7 m wide x 3.2 m high;
- Design head of 38 m;
- Be able to close into full flow;
- Control the discharge through the diversion conduit;
- Provide double acting seals (upstream water pressure and downstream concrete pressure);
- Easy to manufacture, using no long-lead materials
- Installation weight to be as low as possible;
- Installation time of 2 days.

The revised design retained the basic structure of the original gate design with its constructed horizontal beams, angled gate nose and double bulb top and side seals. The higher head however necessitated a number of changes to the original design.

Four wheels were no longer sufficient to cope with the increased loading and were increased to eight. This allowed the gate to be split into two sections for manufacture and installation, each with four wheels. With two wheels per side on each section, the wheel loads would remain constant even with slight irregularities within the main cast-in rail and wheel manufacturing tolerances. The sections were connected by two large bolts, one per side, with a sandwiched rubber block to provide flexibility in the joint. A horizontal flat seal was bolted across the joint and spliced underneath the vertical double bulb side seals.

The wheels were provided with two self-aligning bearings and sealing plates to prevent water ingress. The self-aligning bearings made allowance for deflection of the wheel axle, while providing high load carrying capability. The wheels had a crown radius of 15 times the wheel radius, to accommodate deflection of the gate when under load and prevent high contact stresses. The size of the wheels was determined using the DIN 19704 method. As the gate was a temporary installation, the wheels were manufactured from grade 1045 carbon steel. This steel had the desired tensile strength and was available in 350 mm diameter round bar, as required to manufacture the wheels. The running surfaces of the main rails were manufactured from 20 mm thick Sumiten 780S, a high strength weldable carbon steel. The thickness of the rail cladding would minimise welding distortion as machining of the rails could not be done due within the tight time constraints.

The gate sections were manufactured from grade 350 structural steel plate with the skinplate on the upstream side. The horizontal stiffeners were bound by a vertical wheel box on each side and a frame for mounting the seals. The top section was provided with an eye plate into which the hydraulic cylinder was connected.

A 45° angle was provided for the gate nose as it would now be used to control flow for an extended period of time. The 45° nose would have lower drawn down forces than the original 30° nose. A flat seal along the gate lip provided sealing when the gate was closed, while not causing vibration or other flow disturbance with the gate in the open position.

The forces on the gate were calculated using the load cases and load combinations recommended in USACE EM 1110-2-2701. Seismic loading was not considered due to the temporary nature of the installation. Mud and ice loading were also disregarded. Impact loading from floating debris was omitted as the entrance to the diversion conduit was screened. The limit state load case combinations used were reduced to:

$1.2D + 1.4H_s + 1.0H_d$

$1.2D + 1.2Q$ or $1.0R$

Where:

D = dead weight

H_s = hydrostatic loads

H_d = hydrodynamic loads

Q = operating forces

R = down pull forces

The limit state design method, as per AS 4100, was used to size the gate structure. A reliability factor $\alpha = 0.9$ was introduced over and above the AS 4100 resistance factor to make allowance for the higher uncertainty in loading conditions, as suggested by the USACE[2].

To determine the operating forces required to size the hydraulic actuator and appurtenant items, the vertical loading was calculated using the following load case:

$F_L = 1.2\,(D - F_s - F_w) + R$ (Gate lowering load case)

$F_R = 1.2\,(D + F_s + F_w) + R$ (Gate raising load case)

Where:

F_L = Lowering force required

F_R = Raising force required

D = Dead weight

F_s = Seal friction

F_w = Wheel friction

R = Down pull (P1)

The down-pull was calculated using graphs published in Erbisti[1] – refer to Figure 4 - according to the method proposed by Naudascher:

$P1 = (K_T - K_B)B.d.g.V_j^2/2g$

In the graph K_B represents the bottom down pull coefficient in relation to the gate opening. K_T was taken as 1 as the top of the gate was exposed to full reservoir head as for face-type gates. It would also produce more conservative values. The graph is applicable to certain gate size ratios:

e/d = 0 (lip length to gate thickness)

r/d = 0.4 (nose radius to gate thickness)

y_o/d = 6 (max opening to gate thickness)

The diversion gate designed had the following ratios:

e/d = 0.03

r/d = 0

y_o/d = 10.3

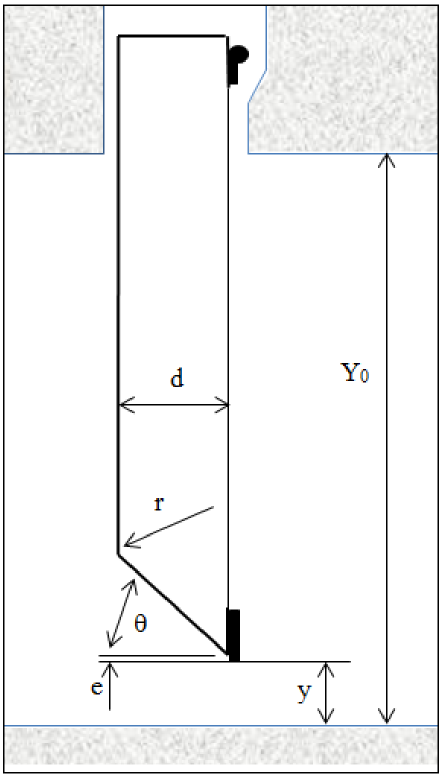

Figure 3: Geometric Parameters

Even though the ratios were markedly different, it was decided to use the information presented in the graph as an acceptable approximation, considering the number of other factors that would influence the result. These include the abrupt change from round to square conduit immediately upstream of the gate, angle of the gate to the flow and flow conditions downstream of the gate. CFD or model testing would result in additional costs and time delays that the risk profile of the installation did not require. To make allowance for the difference in gate geometry to that used to develop the graph and for the other influencing factors, it was decided to use the curve for a 30 degree gate nose, as this would result in a higher down-pull than for the 45 degree gate nose used. A 25% larger hoisting force thus resulted.

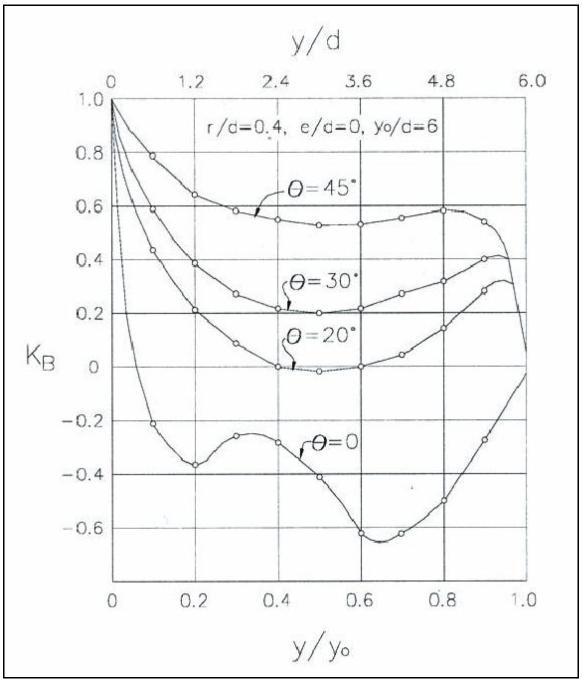

Figure 4: Variation of K_B with relative gate opening for various θ. *Erbisti*[1]

The down-pull is however also dependent on the flow velocity below the gate. The diversion conduit was designed for a maximum flow rate of 25 m^3/s. Lacking more accurate information, the discharge coefficients for various gate openings, as proposed by USACE[3], were used to determine the maximum required gate opening at the maximum water level. The flow velocity at this gate opening was calculated to determine the maximum down-pull. Using the lowering and raising load cases, the following were calculated, refer to Figure 5 (Flow rate capped at 25m^3/s):

Maximum hoist load when raising the gate: 350 kN

Minimum hoist load when lowering the gate: -110 kN.

The hydraulic cylinder was thus sized for an extension force of 110 kN and a retraction force of 350 kN.

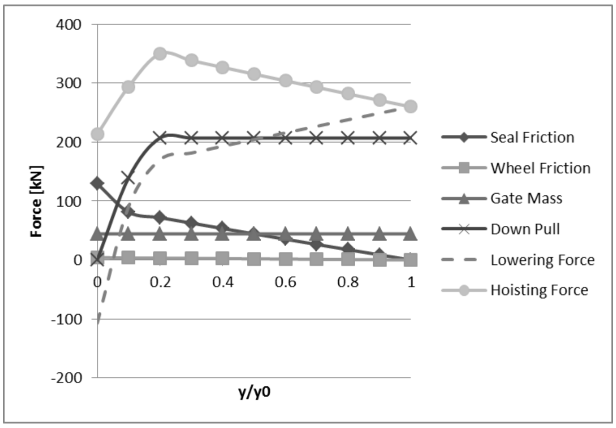

Figure 5: Forces on Gate at maximum head

The cylinder support structure was sized with a load factor of 1.2 times the calculated values.

The design statistics for the gate were:

Gate size:	2.7 m x 3.2 m high
Design Head:	37.4 m
Hydrostatic Load:	388 tonnes
Number of wheels:	8
Load per wheel:	49 tonnes
Gate weight:	4.5 tonne

Max. Actuator lifting force: 35 tonnes

Pressure relief valve setting (raising): 19 MPa

Manufacture

The gate was manufactured by a structural steelwork company in Albury which had no previous experience in gate manufacture. Considering this, the company achieved an outstanding result in producing the gate and sealing frame structure within 6 weeks from date of order. The wheels and axles were outsourced to a specialist manufacturer. The hydraulic power pack was also manufactured by an Albury company, who had the cylinder manufactured in Melbourne. The gate seals were ordered from Brisbane. The gates were inspected at various stages during manufacture to confirm compliance with the drawings. After completion, the gate was assembled and installed inside the sealing frame to set up the guide pads. During the factory test, the sealing frame was positioned horizontally and the gate was moved inside the frame using a forklift. The cylinder had not been completed at this stage. After gate testing was completed, it received a nominal protective coat of etch primer after which it was transported to site. For ease of transport the gate was separated into two sections. The top and side seals were assembled on the top section. The power pack and hydraulic actuator were factory tested separately before delivery to site.

Installation

While the gate and sealing frame were being manufactured, the diversion conduit was constructed, leaving a 1m wide slot into which the frame was fitted. Once received on site, the one-piece frame was lifted into position by a 90 tonne mobile crane. While this was being done, the gate sections were bolted together and the seals assembled onto the bottom section. After the frame was placed in position, the gate was inserted into the frame. The sealing frame was designed to form part of the concrete formwork for embedment into the flow channel. This made the installation work much faster, and the secondary concrete was placed after the necessary reinforcing bars and tie rods were inserted. The gate was propped open to allow the diversion to operate until the gate actuator and hydraulic power pack were delivered and installed.

The power pack and actuator were installed and set up by the supplier. The power pack was located about 70m higher than the gate on the left abutment. Flexible hoses with quick release couplings were used to connect the power pack to the actuator. No position indication system was installed for the gate as this was considered unnecessary. Flow would be controlled by adjusting the gate opening depending on the flow measured at the weir downstream of the diversion outlet. During commissioning the rate of closure and opening of the gate was measured, which would allow its position to be estimated if required.

Operation

The gate operated as designed to pass several small floods at relatively low head. Some teething problems were experienced when the gate would not fully close even at maximum pressure relief valve setting. A site inspection confirmed grease had not been applied to the bottom bulb of the lintel seal. Once this was rectified the gate closed with no further problems and at a much reduced pressure.

The Ultimate Test

From 29th February to 4th March 2012, the Canberra region experienced unusually high rainfall. On the night of 29th February, the existing dam (approximately 100m upstream of the new dam) was overtopped. When engineers arrived at site on the morning of 1st March the existing dam was largely submerged by water impounded by the new dam which was still under construction. At the time it was 10m higher than the old dam. The flow rate through the diversion conduit was measured at $35m^3/s$, forty percent greater than the capacity it was designed for ($25m^3/s$). The gate was lowered to reduce the discharge to within the design limit. The gate was inadvertently closed more than required and the flow was reduced to $20m^3/s$. An attempt was made to reopen the gate but without success. The head on the gate at this time was 25m.

The inflows to the reservoir ultimately far exceeded the capacity of the diversion conduit and during the evening of 1st March, the partially constructed dam was overtopped. At the peak of the flood, the dam was overtopped by approximately 2m, with a peak discharge of around $350m^3/s$. The flood was estimated to have had an annual exceedance probability of 1 in 100.

When the gate was first unable to be raised, it was subjected to 25m head, which was 66% of its design head. At the peak of the flood the gate was exposed to a 34m head, approximately 90% of design capacity.

As the flood receded, another attempt was made to raise the gate to increase the rate of drawdown and achieve a flow through the diversion conduit as close to $25m^3/s$ as possible.

At the first attempt to raise the gate, the hydraulic pressure reached the pressure relief valve setting without moving the gate. After checking the calculations, it was decided to increase the pressure relief valve setting slightly from 19 to 24MPa, as this would still give an acceptable margin of safety on the highest stressed elements (lifting lug and actuator structure). With 30m head on the gate, it was able to be lifted with 20MPa, only slightly higher than the original pressure relief valve setting of 19MPa. .

At 20 MPa, the hydraulic actuator exerted a force of 350 kN, the maximum lifting force calculated for the design head of 38 m. This indicated that the gate was exposed to its design down pull force while at a head of approximately 80% its design value, at a gate opening of 15%.

At the time of the flood, the risk was considered too high to experiment with the gate position to determine if the pressure required to move the gate was a true reflection of the actual down pull load or due to some other obstruction (ie. debris on the wheels). As the gate was operated frequently in the downward direction during the flood event, it is unlikely that the load was caused by an obstruction, especially as the pressure remained fairly constant once the gate eventually started to lift. It is therefore assumed that the increased pressure required to lift the gate was due to hydrodynamic loading on the gate.

Discussion

Hydrodynamic loading on a gate depends on numerous aspects and their interaction with one other. They include the outlet layout, angle and shape of the gate nose, extension of the gate lip, thickness of the gate, top seal layout, gap between top seal and gate shaft, flow velocity below gate, conduit shape and aeration.

The possibility that the actual down pull forces would be greater than the theoretically calculated forces was recognised during the design. The calculated forces were therefore increased by using the next higher down pull load graph for the design. The resulting 25% higher actuator design load was expected to have sufficient additional capacity without being overly conservative. In addition, the possibility of a large flood occurring during the few months when the gate would be in operation was considered to be low. The risk was considered to be reasonably low without incurring extensive additional costs and time delays.

An estimated 1:100 AEP flood however passed over the partly constructed dam. It was assessed that, although the gate was exposed to only 66% of its design head, the maximum predicted down pull force was reached. Had the flood been larger or construction on the dam been advanced a few metres higher, the gate hoisting system would have become overloaded resulting in possible loss of gate control.

It is suggested that the main contributing factor to the large discrepancy between the calculated and observed values is due to the irregular conduit profile in which the gate operated. The gate was rotated at 8 degrees to the centreline of the conduit which would have resulted in unequal velocity distribution below the gate. In addition, a very abrupt transition existed directly upstream of the gate between the 3m diameter corrugated steel conduit and the rectangular gate shape. The abrupt change in geometry at the bottom corners of the conduit would result in highly turbulent flow in this area, especially at small gate openings.

The above effects are only two examples of various factors that could have influenced the draw-down forces on the gate. A large number of papers have been written on analytical methods for calculating down pull forces on gates. These are however all applicable to certain geometric constraints and conduit layout and are of particular value to rectangular conduits where the calculations can be reduced to a 2 dimensional analysis. In the case of the Enlarged Cotter Dam diversion conduit and gate, the flow effects in the operating range of the gate presented a distinctly 3 dimensional problem, resulting in errors when the 2D analysis methods were applied to it. This was anticipated and a conservative approach taken, but that it was not enough emphasizes the difficulty involved in estimating hydrodynamic forces without the aid of physical model testing or CFD.

Conclusion

The experience discussed above highlights the complexities involved in designing a flow control gate. In this case the risks associated with the design approach were accepted due to the temporary nature of the installation and low probability of the gate being exposed to very high water levels. Gates for permanent installations would however have a very different risk profile. Each installation therefore has to be assessed on its own merits.

Applying the lessons learnt from the reported project, the following general suggestions are offered relating to the design, construction and installation of gated outlets, in particular those requiring a long design life:

The Owner/Client

Control and guard gates are complicated structures that must receive the necessary attention during their life cycle. Gated structures often make up a relatively small portion of the overall project cost, but can play a disproportionately important role during the life of the structure. A poorly designed, manufactured, installed or maintained gate can result in increased risk levels and place unacceptable operating constraints on the outlet works.

The Manufacturer/Contractor

The complexity involved in the manufacturing and installation of a control gate should not be underestimated. Fine tolerances require high skill levels and good quality control. Factory testing of the completely assembled structure, normally before application of corrosion protection is generally required. The structure should be operationally tested once installed and well protected from damage by adjacent construction activities.

The Designer

The risks involved with the design method used must be well understood and communicated to all stakeholders. All design criteria should be clearly defined and should be thoroughly reviewed should any changes occur during the design.

The following guidelines for determining down pull forces on control gates are recommended:

- Published data for similar gates should only be used as a guideline and not applied outside of the geometric constraints for which they have been developed.
- A thorough understanding of fluid dynamics is required when designing the gate shape and conduit/inlet layout in which the gate is to operate.
- Theoretical calculations should only be used for initial sizing of components and should be supplemented by physical model testing. CFD analysis may be used in place of physical model testing in certain cases.

Acknowledgements

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* Bulk Water Alliance members comprise of ACTEW, GHD, Abigroup & John Holland