Two-Dimensional Flow Modeling of Hydraulic Structures in a 2D ADI Scheme

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ABSTRACT

In 1998, the TUFLOW 2D Alternating Direction Implicit (ADI) solver of the Shallow Water Equations (SWE) was modified to offer much improved flexibility in representing hydraulic structures. These modifications included staged energy losses, horizontal and vertical constrictions on the 2D elements, and additional energy loss once the structure soffit is surcharged. The added functionality has been used to model box culverts, bridges, and floating pontoons in 2D.

More recently Layered Flow Constrictions were developed that provide the ability to define hydraulic structures with multiple elevation based layers where each layer has its own blockage and energy loss characteristics. For example, Layered Flow Constrictions can represent a bridge as four layers: beneath the bridge deck, the bridge deck, the bridge rails, and flow over the top of the rails.

A description of the adaptations to the 2D ADI scheme, and discussion on the issues and approaches to modeling hydraulic structures using a 2D solution are provided. A brief outline is presented of research and testing being carried out by the authors to provide guidelines for modeling 2D structures.

1. INTRODUCTION

Representing hydraulic structures such as bridges and banks of culverts is one of the more challenging aspects a modeler faces. The flow patterns through a structure are complex and under some conditions can be three-dimensional (3D) in nature, therefore necessitating major assumptions when applying 1D or 2D solution schemes. A key issue is

Dynamic 1D schemes usually substitute the momentum equation with equation(s) representing the flow passing through the structure based on the upstream and downstream water levels. This is reasonably straightforward for some structures such as broad-crested weirs. For more complex structures such as a bridge with embankments and piers, the modeler relies on judgment as to the energy losses that occur. The estimation of the energy losses may be automated by the modeling software or derived from publications that provide suitable guidance. Either way, it is not uncommon for the modeler to either unwisely rely on the software or to have difficulty when deriving and applying loss coefficients.

2D schemes pose an additional level of complexity when modeling structures, because they inherently model a proportion of the structure's energy losses such as that from the expansion of flow downstream. Therefore, to apply the same energy losses as would be applied when using a 1D scheme is fundamentally wrong. Essentially energy losses applied to a 2D scheme by the modeler at a structure need to represent the losses from fine-scale features that the 2D element resolution cannot represent adequately, such as piers, boundary layer formation at abutments, and sub-grid scale turbulence through the structure and in the contraction and expansion. In addition, any energy losses in the vertical dimension (ie. 3D effects) would require additional energy losses to be applied by the modeler. The dilemma for the modeler is how much additional energy losses should be applied when using a 2D scheme as there are no guidelines available as there are for 1D schemes.

There is also an added complexity when 1D elements are embedded in a 2D scheme. Once again the modeler is faced with the dilemma of how much of the energy losses the 2D scheme is inherently modeled, and therefore, by how much should the energy losses applied to the 1D element be reduced to compensate for those losses covered by the 2D scheme.

The following sections present the modifications made to the 2D ADI scheme to offer increased flexibility for modeling structures, and discussion on representing different types of obstructions. On-going research and testing by BMT WBM, Aquaveo and FHWA is being carried out with the intent to provide guidelines on applying 2D ADI schemes to modeling hydraulic structures.

2. MODIFICATIONS TO 2D ADI SCHEME

2D Alternating Direction Implicit (ADI) schemes have been widely used for modeling 2D flow patterns in estuaries and coastal areas since the 1970s. In the 1990s they were increasingly applied for flood modeling, necessitating the need for improved representation of structures such as bridges, culvert banks and embankments. They are still widely used today, and are often the preferred choice for 2D flood models. TUFLOW is one of the 2D ADI schemes that has been widely applied to flood modeling in Australia and the UK.

The 2D scheme has the unique ability amongst mainstream ADI schemes to be able to modify 2D cells to better represent hydraulic structures. "Lids" can be placed on cells to represent bridge decks, cell side widths can be reduced, and additional energy losses can be applied separately from the Manning's roughness value to compensate for a 2D scheme's inability to represent all energy losses associated with a structure.

A description of the 2D scheme utilized is presented in Syme (1991), and the modifications to the equations to model obstructions such as bridge decks and partial cell blockages by reducing the cell flow widths are provided below. The equation numbers and symbols are the same as used in Syme (1991) for ease of cross-referencing. The modified equations and new symbols are:

$$q = \frac{-E_{43}\,g}{\Delta x} - \frac{f_{w_3} u_3^{q-1}}{2\Delta x} \qquad (3.3.8a)$$

$$r = \frac{2}{\Delta t} + g\,\frac{E_{40} + E_{43}}{\Delta x} + \frac{f_{w_3} u_3^{q-1} - f_{w_0} u_0^{q-1}}{2\Delta x} \qquad (3.3.8b)$$

$$s = \frac{-E_{40}\,g}{\Delta x} + \frac{f_{w_0} u_0^{q-1}}{2\Delta x} \qquad (3.3.8c)$$

$$H_{vy} = \frac{v_0^0 w_{v_0} \min\left(\frac{\zeta_0^0 + \zeta_4^0}{2} + \frac{h_1 + h_4}{2}, y_{v_0}\right) - v_2^0 w_{v_2} \min\left(\frac{\zeta_0^0 + \zeta_2^0}{2} + \frac{h_2 + h_3}{2}, y_{v_2}\right)}{\Delta y} \qquad (3.3.8d)$$

$$E_{40} = \frac{y_0}{\Delta x\, E_{20}} \qquad E_{43} = \frac{y_3}{\Delta x\, E_{23}} \qquad (3.3.9e)$$

$$\left.\begin{array}{l} f_{w_0} = w_{u_0};\ f_{w_3} = w_{u_3} \\ y_0 = f_{w_0}\left(h_{u_0} + \zeta_0^{q-1}\right) \\ y_3 = f_{w_3}\left(h_{u3} + \zeta_3^{q-1}\right) \end{array}\right\}\text{Soffit NOT surcharged} \qquad \left.\begin{array}{l} f_{w_0} = 0;\ f_{w_3} = 0 \\ y_0 = w_{u_0}\left(h_{u_0} + y_{u_0}\right) \\ y_3 = w_{u_3}\left(h_{u3} + y_{u_3}\right) \end{array}\right\}\text{Soffit surcharged}$$

w_u, w_v = Cell flow width factor at u and v points (eg. 0.6 would represent a 40% blockage)

y_u, y_v = Depth to cell soffit at u and v points

The bed resistance term is also modified through adjustment of the wetted perimeter to allow for additional friction from culvert side walls, and culvert/bridge soffits. Additional energy losses (as a proportion of the kinetic energy) are included by introducing the form loss coefficient, f_l, into the momentum equation as shown in the equation below for the X-axis momentum (refer to BMT WBM, 2008).

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} - c_f\, v + g\frac{\partial \zeta}{\partial x} + g\,u\left(\frac{n^2}{H^{4/3}} + \frac{f_l}{2g\Delta x}\right)\sqrt{u^2 + v^2} - \mu\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2}\right) + \frac{1}{\rho}\frac{\partial p}{\partial x} = F_x$$

3. HORIZONTAL OBSTRUCTIONS (EG. EMBANKMENTS)

Approach embankments to bridge and culvert crossings cause floodwaters to contract and expand, dissipating energy in the process. Most of the energy dissipation occurs in the expansion of the streamlines downstream. As a result, the water level increases upstream of the bridge causing a backwater effect.

AustRoads 2004 (based on Bradley, 1978) provides guidelines for deriving the loss coefficients and backwater afflux at bridges. For 2D models, it is not an option to assign these energy loss coefficients in the same manner as for 1D models. The 2D scheme inherently simulates these losses as it models the contraction and expansion of water through the embankments. The question for the modeler is how accurate is this 2D representation, and is there a need to adjust any parameters?

Consider a uniform rectangular channel, 400m wide, a longitudinal slope of 0.001, and a Manning's n of 0.03. Two embankment scenarios are simulated, one with approach embankments of 60m on both sides of the channel (leaving a 280m wide opening), and the other with 120m embankments giving an opening of 160m. A 10m regular grid is used for the 2D model, with the upstream inflow boundary set 500m upstream of the constriction, and the downstream stage-discharge boundary 1,500m downstream. The model was run to steady-state for flows from 250m^3/s to 2,000m^3/s at 250m^3/s intervals. Figure 1 shows the velocities and water level contours at 0.1m increments for the 120m embankment case with a flow of 1,000m^3/s.

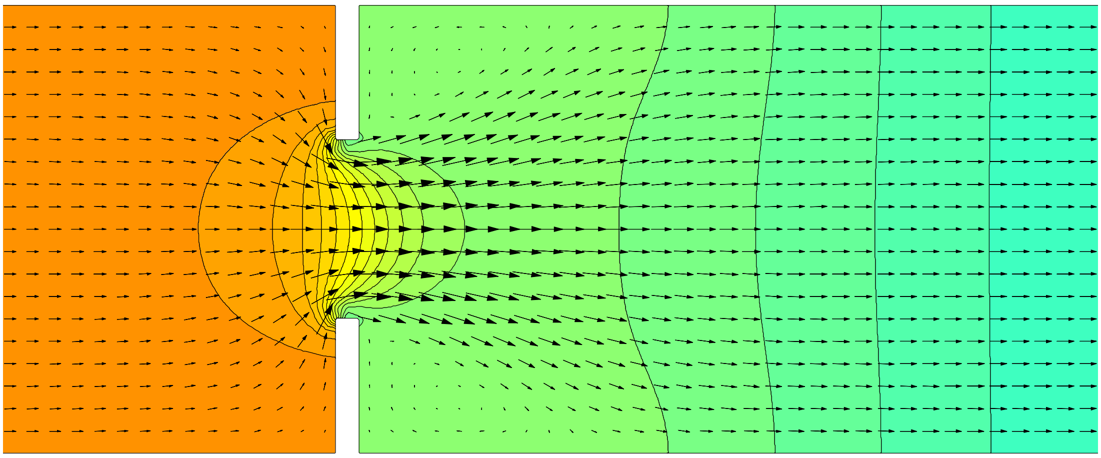

Figure 1 Flow Patterns and Water Level Contours Between Embankments

In accordance with AustRoads (2004), the maximum backwater was determined by comparing the centerline profiles for unrestricted flow (no embankment), and restricted flow (with embankments). Figure 2 shows the maximum backwater versus the normal (no embankment) flow velocity (V_n).

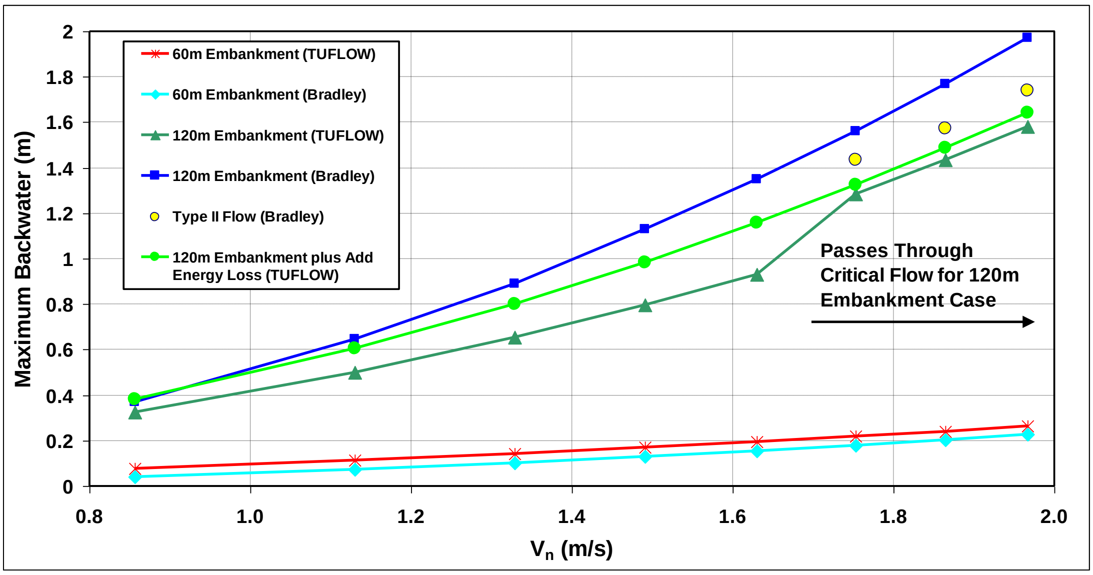

Figure 2 Backwater Comparisons

As can be seen, for the 60m embankment scenario, TUFLOW (red asterisks) gives a slightly higher afflux than the method by Bradley (light blue diamonds), which were determined using the lower curve in Figure 5.6 of AustRoads (2004). If the higher curve is used there is a closer match.

For the 120m case TUFLOW (dark green triangles) produces lower affluxes than the Bradley method (dark blue squares). There is also a rise in afflux as the flow immediately downstream of the constriction passes through critical conditions. The yellow circles are those values derived by the Bradley method for Type II flow (ie. passes through critical conditions). On this basis, it could be concluded that additional energy losses are needed to be applied to the 2D model. The light green circles are after applying additional energy losses to the elements within the constriction, resulting in affluxes closer to those estimated from the Bradley method.

4. VERTICAL OBSTRUCTIONS (EG. BRIDGE PIERS)

Bridges and culvert banks often include vertical obstructions to flow such as piers and the vertical sides of box culverts. These obstructions are usually smaller in dimension (in the horizontal, 2D plane) than the 2D elements, so the 2D solution is unlikely to represent the energy losses associated with the obstructions particularly well without adjustments by the modeler.

The Bradley method presents guidelines for estimating the energy loss coefficient applicable to different bridge piers and arrangements of piers. The loss coefficients can be incorporated into the 2D scheme by applying an additional energy loss across the whole constriction. It is incorrect to apply the coefficient to a single 2D element (within which the pier(s) are contained) as the 2D element only extends across a portion of the waterway, whilst the coefficients apply to the whole waterway.

5. ELEVATED OBSTRUCTIONS (EG. BRIDGE DECKS AND RAILS)

Bridge and culvert decks, rails, and pipe crossings pose a particular problem for 2D schemes. When the obstruction is surcharged, the flow area underneath remains fixed and additional energy losses occur due to the increased resistance and streamline deformation in the vertical. Two approaches have been built into the 2D scheme to address these situations.

The first approach developed in 1998 utilizes the modified 2D ADI equations as described in Section 2. 2D cells can be specified to have a soffit above which no (2D) flow occurs. To model any flow over the top requires using an embedded 1D element (eg. a weir). Additional energy losses once the surcharging commences can be specified by the modeler as a combination of increased friction (roughness) based on a Manning's n value for the underside of the obstruction, and/or an energy loss coefficient. This approach has been widely used and validated on numerous studies, such as the extensive modeling and calibration carried out for the Eudlo Ck hydraulic investigations (Syme, 2006). Figure 3 illustrates the performance of the 2D scheme for the 1992 flood, against which the model was calibrated.

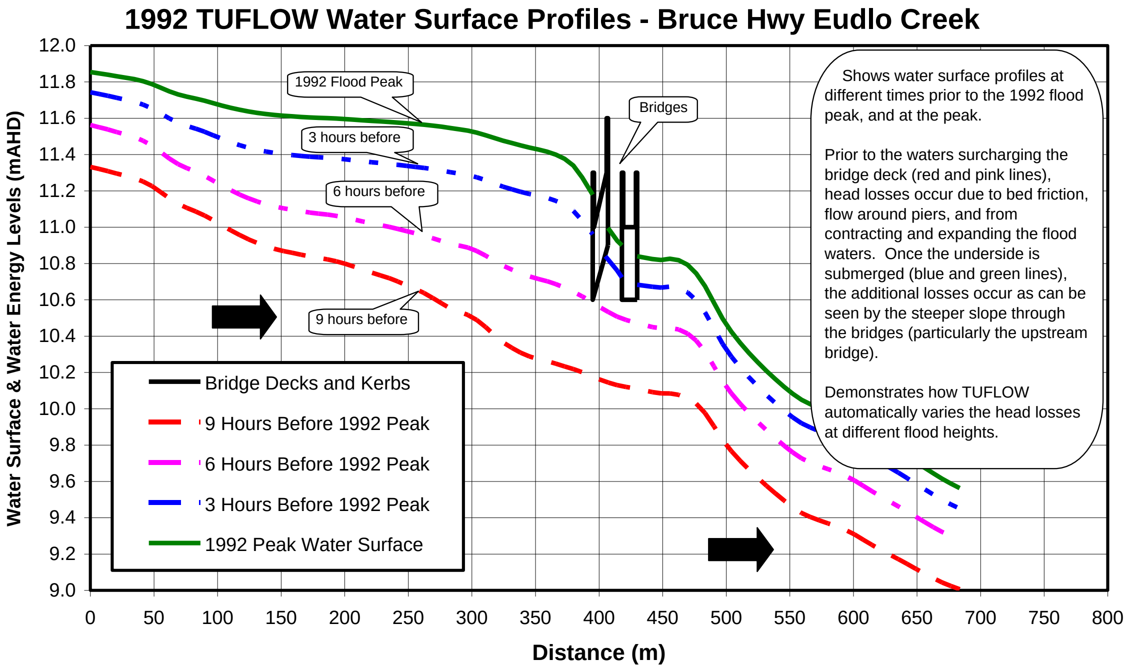

Figure 3 Application of 2D Scheme for Modeling Surcharged Bridges

The second approach, implemented in 2008, provides an option to vary the 2D element flow width, and the additional energy loss coefficient, with height. Up to three layers can be specified so as to represent, for example, below the bridge deck (Layer 1), the bridge deck (Layer 2), and the bridge rails (Layer 3). A fourth layer is applied automatically that represents unimpeded flow over the top of Layer 3. Each layer is assigned a blockage factor and an energy loss coefficient. The values from each layer are lumped together to give one overall blockage value and one overall loss coefficient, depending on the height of the water.

For example, as the water rises through Layer 1, only the Layer 1 parameters are applied. As the water rises through Layer 2, the Layer 2 values have an increasing influence, and so on through Layer 3 and Layer 4. Whilst this approach is clearly an approximation, it does provide the modeler with the ability to vary with height the blockage to flow and changes in energy losses. Testing, calibration where possible, and benchmarking of this feature needs to be carried out before any guidelines can be provided.

6. OTHER CONSIDERATIONS

Other factors that can influence the performance of 2D schemes to simulate hydraulic structures that are being investigated are:

- Element/cell size resolution. Different results can arise depending on the resolution of the 2D elements/cells (Barton 2001).
- The sub-grid scale turbulence (viscosity) term and the formulation used to derive the viscosity coefficient. This can be of particular relevance for fine resolution (<2m elements) models (Barton 2001).
- Orientation of 2D elements/cells if using a regular mesh, particularly if the cell resolution is coarse.
- Embedding of 1D elements can cause a duplication of energy losses. If the 1D element is several or more 2D elements wide, the 2D flow patterns that develop downstream of the structure as the water exits the 1D element and expands within the 2D domain will model expansion (outlet) losses. Therefore, there is a need to reduce the loss coefficient(s) applied to the 1D element to compensate for the duplicated energy losses, especially at the structure outlet (Syme, 2001).

7. REAL WORLD APPLICATIONS

US Federal Highway Administration (FHWA) and Aquaveo have commenced trial studies applying the features described in this paper to real world bridge crossings. The first of these is on the Cuyahoga River (FHWA 2008) where a HEC-RAS model has thus far been used for a bridge replacement project. A range of model configurations in both HEC-RAS and TUFLOW will be used to compare results and provide initial guidance for setting up bridges using the new Layered Flow Constrictions feature. Each model will be set up with flows that cause the flow to not submerge the bridge, submerge the bridge, and submerge the bridge with flow over topping it.

8. CONCLUSIONS

The application of 2D schemes for modeling hydraulic structures requires an appreciation by the modeler that the solution is an approximation of a 3D hydraulic problem. 2D schemes need to be adapted to allow the modeler to: add energy losses to represent fine-scale energy dissipation from sub-grid scale features such as bridge piers; specify soffits on 2D elements to represent bridge decks; vary energy losses with height to represent bridge decks, bridge rails and other horizontal obstructions; and vary the element flow widths with height to represent different levels of blockage of horizontal obstructions.

The 2D ADI solution scheme has been successfully adapted to include these features. On-going testing and benchmarking against other methods used to predict affluxes from hydraulic structures is being carried out by BMT WBM. The FHWA and Aquaveo are undertaking real-world applications to help develop guidelines for applying TUFLOW to bridge hydraulic assessments.

9. ACKNOWLEDGEMENTS

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