Assessing the accuracy of a two-dimensional hydraulic model for dambreak analysis

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ABSTRACT

Two-dimensional hydraulic modelling technology has advanced significantly in recent years, providing powerful and flexible tools that are now routinely used for a wide variety of flood risk assessments. Assessing the downstream impacts of catastrophic dam failure represents an extreme test for the accuracy and stability of hydraulic models.

Catastrophic dam failure can present an extreme risk to downstream infrastructure and public safety. Hence, it is important to have confidence in the estimated magnitude of potential impacts to design suitable, cost-effective mitigation measures. The highly visual output of two-dimensional models adds credibility to their results. However, validation data for extreme hydraulic conditions is rarely available, resulting in uncertainty in the accuracy of model predictions and in the risks associated with dam failure. By validating numerical model results against analytical solutions for cases of simple geometry and also against real-world data, an improved level of confidence can be obtained in the accuracy of the model representation of these extreme hydraulic conditions.

In this paper, we assessed the capability of the TUFLOW hydraulic modelling software package to accurately simulate an idealised dam break scenario by comparing the model results to analytical solutions. We also compared the model results for coastal inundation by a tsunami to real-world data from the 2004 Banda Ache (Indonesia) tsunami. The results showed that the HPC solver version of TUFLOW correctly captures the dam break flood fronts and the flood wave propagation and TUFLOW HPC is well suited for dam break flood modelling.

Keywords: *dambreak, hydraulic modelling, TUFLOW*

Introduction

Two-dimensional hydraulic modelling technology has advanced significantly in recent years, providing powerful and flexible tools that are now routinely used for a wide variety of flood risk assessments. Assessing the downstream impacts of catastrophic dam failure represents an extreme test for the accuracy and stability of hydraulic models.

Catastrophic dam failure can present a risk of extreme consequences to downstream infrastructure and public safety. Hence, it is important to have confidence in the estimated magnitude of potential impacts to design suitable, cost-effective mitigation measures. The highly visual output of two-dimensional models adds credibility to their results. However, validation data for extreme hydraulic conditions is rarely available, resulting in uncertainty in the accuracy of model predictions and in the risks associated with dam failure.

By validating numerical model results against analytical solutions for cases of simple geometry and also against real-world data, an improved level of confidence can be obtained in the accuracy of the model representation of these extreme hydraulic conditions.

The Two-dimensional Unsteady FLOW (TUFLOW) hydraulic modelling software package is one of several commercially available modelling packages used for dam break assessments. There are two main TUFLOW fixed grid solution schemes or solvers available; the Classic and Heavily Parallelised Compute (HPC) solvers. In the process of developing the HPC solver, TUFLOW developed an intermediate, Graphics Processing Unit (GPU) solver. However, the GPU solver has been superseded by the HPC solver and it is understood that TUFLOW is no longer actively developing the GPU solver. As a result, TUFLOW GPU was not considered for this study.

The TUFLOW Classic solver uses a second order semi-implicit scheme to solve the full two-dimensional (2D), depth averaged momentum and continuity equations for free-surface flow (BMT WBM 2017a). The Classic scheme uses a fixed time step, subject to a Courant Number criterion.

The HPC solver version of TUFLOW adopts a shock capturing numerical scheme to explicitly solve the conservative form of two-dimensional (2D) shallow water equations (BMT WBM 2017a, 2017b). As a result, TUFLOW HPC uses adaptive time stepping, iteratively changing model time step to achieve the fastest solution, subject to model control number criteria.

In this study, we assess the capability of the HPC solver version (2017-09-AC release) of the TUFLOW hydraulic modelling software package to accurately simulate an idealised dambreak scenario by comparing the model results to analytical solutions. We also compare the model results for coastal inundation by a tsunami to real-world data from the 2004 Banda Ache (Indonesia) tsunami.

Test scenarios

The dam break scenario considers the behaviour of the flood wave resulting from the sudden collapse of a dam wall holding a large reservoir of water upstream of a defined channel. The collapse of the dam wall releases a surge of water, characterised by a positive surge (the dam break wave) propagating downstream away from the dam and a negative surge (reduction in water surface level) propagating upstream into the reservoir. At any point in time, the dam break analysis attempts to determine the location of the positive and negative surge fronts and the water surface profile between them.

A one-dimensional or pseudo-two-dimensional dam break test scenario is commonly used to check whether the numerical model results can match the results obtained from an exact analytical solution. The dam break event is simulated by the instantaneous removal of a dam wall holding the reservoir, allowing the dam break wave to propagate downstream.

The dam break problem has been considered by a number of studies, including Ritter (1892), Dressler (1952) and Chanson (2006, 2009). Ritter (1892) analysed the dam break surge as ideal fluid flow (non-turbulent) in a wide, frictionless horizontal channel (known as Ritter's Solution). Experimental data in later studies showed that while Ritter's Solution provides a reasonable approximation of the region behind the wave tip, the dam break wave tip is governed by flow resistance (Dressler 1952).

Chanson (2006) presented analytical solutions for the dam break surge flowing in either sloping or horizontal dry channels with fully turbulent motion, assuming a constant flow resistance factor (f). Chanson (2009) revisited the Chanson (2006) solution and presented analytical solutions for fully turbulent flow in either sloping or horizontal dry channels, assuming that f varies as a function of velocity and channel roughness (expressed as the equivalent sand roughness height k_s).

The capability and accuracy of the TUFLOW model was tested against two test scenarios. For the first scenario, the Ritter Solution and the solution presented by Chanson (2009) for a reservoir with no initial motion surging into a dry, horizontal channel were considered. The analytical solutions assumed the channel is sufficiently wide that there are no effects from bank friction.

On 26 December 2004, a magnitude 9 earthquake occurred off the west coast of Sumatra, Indonesia. The resulting tsunami wave struck the coast of Sumatra in Aceh province, causing widespread devastation. The second test scenario considered the Chanson (2006) analysis of the case of the 2004 tsunami wave as a simplification of the dam break wave problem and the comparison of analytical results with observations derived from video footage of the disaster taken in a street in Banda Aceh.

Methodology

Test Scenario 1

The analytical solutions and the HPC solver TUFLOW model were used to predict the progress and water surface profile of the dam break wave from the instant of failure (t = 0 s) to some point in time (in this case t = 10 s) for a still reservoir, 500 m long with an initial depth of 10 m. The reservoir is located upstream of a horizontal rectangular channel with very low bed friction.

For the purpose of this study, the following parameters and initial and boundary conditions were adopted for analytical analysis:

- Gravitational constant (g) = 9.8 m/s^2
- Density of water (ρ) = 998.2 kg/m^3
- Dynamic viscosity of water (μ) = 1.005x10^{-3} Pa.s
- Initial reservoir level (D) = 10 m
- Initial wave celerity (U'_0) = 0 m/s (i.e. water in the reservoir is initially still)
- Bed slope (S_0) = 0 (i.e. assuming a horizontal channel bed)
- Manning's 'n' value = 0.010 s/m$^{1/3}$ (used in the TUFLOW model to represent bed friction)
- Equivalent sand roughness height (k_s) = 7x10^{-6} m (used in the analytical solution to represent bed friction, this value was determined iteratively so as to achieve the best match with the TUFLOW model results)
- Channel length (x') = 1,200 m. Note, the dam is located 500 m from the start of the channel (i.e. the channel starts at x' = -500 m, the dam is located at x' = 0 m and the channel ends at x' = 700 m) This convention has been adopted to align with the analytical solution which assumes the dam break initiates at x' = 0 m.

Ritter's solution

Equation 1 gives the celerity of the positive wave front (the dam break wave propagating downstream along the channel):

$$U' = 2 \times \sqrt{gD} \tag{1}$$

Equation 2 gives the celerity of the negative wave front (the water surface level reduction propagating upstream into the reservoir):

$$C_0' = \sqrt{gD} \tag{2}$$

Equation 3 gives the parabolic profile of the free-surface profile between the leading edges of the positive and negative waves, at any given time t:

$$\frac{x'}{t \times \sqrt{gD}} = 2 - 3 \times \sqrt{\frac{d'}{D}} \quad for \quad -1 \leq \frac{x'}{t \times \sqrt{gD}} \leq +2 \tag{3}$$

where x' (in meters) is the distance from the dam wall and d' (in meters) is the flow depth, at time t.

Fully turbulent flow (Chanson 2009)

Chanson (2009) presented an analytical solution in dimensionless depth, length and velocity terms. Equations 4 to 6 define these dimensionless terms as functions of initial reservoir depth D:

$$d = \frac{d'}{D} \tag{4}$$

$$x = \frac{x'}{D} \tag{5}$$

$$U = \frac{U'}{\sqrt{gD}} \tag{6}$$

where d', x' and U' are the dimensional depth, distance and velocity terms respectively.

Equation 7 presents the relationship between dimensionless (positive) wave front celerity U and time t:

$$\frac{32}{13} \frac{\left(1 - \frac{U}{2}\right)^{7/2}}{U^2 \left(3.65 \times 10^{-5} \times k_s + \frac{2.5 \times 10^{-3}}{Re_d U}\right)^{1/4}} = t \tag{7}$$

where $\mathrm{Re_d} = \frac{\rho}{\mu}\sqrt{\mathrm{gD}^3}$ is the dam reservoir flow Reynolds number and is a function of initial flow conditions and the fluid properties only and k_s is a dimensionless equivalent roughness height. The negative wave front celerity is given by Eq. 2.

At time t, the dimensionless distance to the positive wave front location x_s is given by Eq. 8, while the free surface profile is described (in dimensionless terms) by Eq. 9 and Eq. 10:

$$x_s = \left(\frac{3}{2}U - 1\right)t + \frac{32}{9} \frac{\left(1 - \frac{U}{2}\right)^{9/2}}{U^2 \left(3.65 \times 10^{-5} \times k_s + \frac{2.5 \times 10^{-3}}{Re_d U}\right)^{1/4}} \tag{8}$$

$$d = \frac{1}{9}\left(2 - \frac{x}{t}\right)^2 \quad for \ -t \leq x \leq \left(\frac{3}{2}U - 1\right)t \tag{9}$$

$$d = \left(\frac{9}{32}\left(3.65 \times 10^{-5} \times k_s + \frac{2.5 \times 10^{-3}}{Re_d U}\right)^{1/4} U^2 (x_s - x)\right)^{4/9} \quad for \ \left(\frac{3}{2}U - 1\right)t \leq x \leq x_s \tag{10}$$

TUFLOW model configuration

A TUFLOW HPC model was developed using the initial conditions defined for the dam break analytical solution. The adopted configuration consisted of a near frictionless channel 1,200 m long with a 10 m high dam at position x = 500 m (x' = 0 m). The TUFLOW model comprised a horizontal model domain 100 m wide x 1,200 m long and a model grid cell size of 0.2 m (0.2 m x 0.2 m square cells). A number of possible grid cell sizes, ranging from 10 m to 0.1 m were tested and the results were not particularly sensitive to the choice of model cell size, however smaller grid cell sizes yielded improved result resolution at the wave tip.

A fixed water level boundary (H = 10 m) was specified at the upstream model boundary, while a normal flow boundary was specified at the downstream model boundary. Note however, the model simulation times were kept sufficiently short that the dam break waves (positive or negative) were prevented from reaching the model boundaries prior to the simulation ending. No boundary conditions were specified along the remaining edges of the model domain. This had the effect of allowing any water to 'glass wall' along the edge of the model domain.

A uniform Manning's 'n' value of 0.010 was adopted across the model domain. TUFLOW cannot explicitly model a frictionless surface, however by way of comparison, Chow (1959) recommends adopting 'n' values for glass or smooth brass pipes between 0.009 and 0.013, so the 'n' value of 0.010 represents an extremely low bed friction value in the context of riverine flood modelling.

The reservoir and dam wall were represented in the TUFLOW model using an initial water level condition. The initial water level created a reservoir with an initial depth D = 10 m, held back by a virtual dam wall at model time t = 0 seconds. At the instant the model simulation starts (i.e. as soon as t > 0 seconds), the virtual dam wall disappears and the 10 m high mass of water collapsed downstream, simulating an instantaneous total failure of the dam wall.

Test Scenario 2

Fully turbulent flow (Chanson 2009)

For the purpose of analysis, Chanson (2006) simplified the tsunami wave as a dam break scenario where a still reservoir (having no initial motion) with depth D = 10.5 m, is located upstream of a horizontal channel with an assumed constant flow resistance factor f = 0.5. The observation point was assumed to be located at x' = 2,000 m. Based on the analytical solution, Chanson (2006) calculated that the tsunami wave reached the observation point at time t = 340 seconds with an instantaneous wave front velocity U' = 1.2 m/s, slightly lower than the 1.5 to 1.6 m/s estimated from the video footage.

The dam break simplification of the tsunami presented in Chanson (2006) was re-analysed using the analytical solution provided by Chanson (2009), assuming a variable flow resistance factor f based on a fixed (dimensionless) equivalent roughness height k_s and variable wave velocity U'. In order to match the results of Chanson (2006), a value of $k_s = 90$ was required and the tsunami wave was estimated to reach the observation point at t = 340 seconds with a wave front celerity of 1.6 m/s. This is slightly faster than the velocity calculated from the analytical solution by Chanson (2006) but is consistent with the velocity estimated from the video footage by Chanson (2006).

TUFLOW model configuration

A TUFLOW HPC model was developed with the initial conditions defined by Chanson (2009) for the simplified tsunami wave case. The TUFLOW model comprised a horizontal model domain 100 m wide x 6,500 m long and a model grid cell size of 0.5 m (0.5 m x 0.5 m square cells). The model domain length was set so that for the duration of the model run, neither the positive or negative dam break waves are able to reach the model boundaries.

A fixed water level boundary (H = 10.5 m) was specified at the upstream model inflow boundary, while a normal flow boundary was specified at the downstream model outflow boundary. No boundary conditions were specified along the remaining edges of the model domain.

The reservoir and virtual dam wall were represented in the TUFLOW model using an initial water level boundary condition with initial depth D = 10.5 m. At the instant the model simulation starts (i.e. as soon as t > 0 seconds), the virtual dam wall disappeared and the 10.5 m high mass of water collapsed downstream, simulating an instantaneous failure of the dam wall.

A single uniform Manning's 'n' value of 0.032 was adopted across the model domain. The value of 'n' was determined iteratively to obtain the best agreement with field observations and the Chanson (2009) analytical results.

Model results

Test Scenario 1

Figure 1 shows the water surface profiles predicted by TUFLOW when t equals 0.5, 1, 2, 5 and 10 seconds, compared to the analytical water surface profiles predicted by Chanson (2009) for the same intervals. The figure also shows the water surface profile predicted by the Ritter Solution for t = 10 seconds.

Figure 2 shows a dimensionless plot comparing the water surface profiles predicted by the Ritter Solution, Chanson (2009) and the TUFLOW model for t = 10 seconds.

The results show the following:

- TUFLOW is capable of modelling the rapidly varying flow conditions which occur in a dam break scenario;
- The TUFLOW model results show very good agreement with the water surface profiles predicted by Chanson (2009), with respect to the location of the wave fronts (both positive and negative) at each reported time as well the shape of the water surface profile; and
- The TUFLOW model results appear to predict a marginally shorter wave tip region than Chanson (2009), however there is very good agreement between the two with respect to the shape of the leading edge of the dam break wave.

Overall, agreement between the model results and the analytical solution is sufficiently accurate for practical purposes.

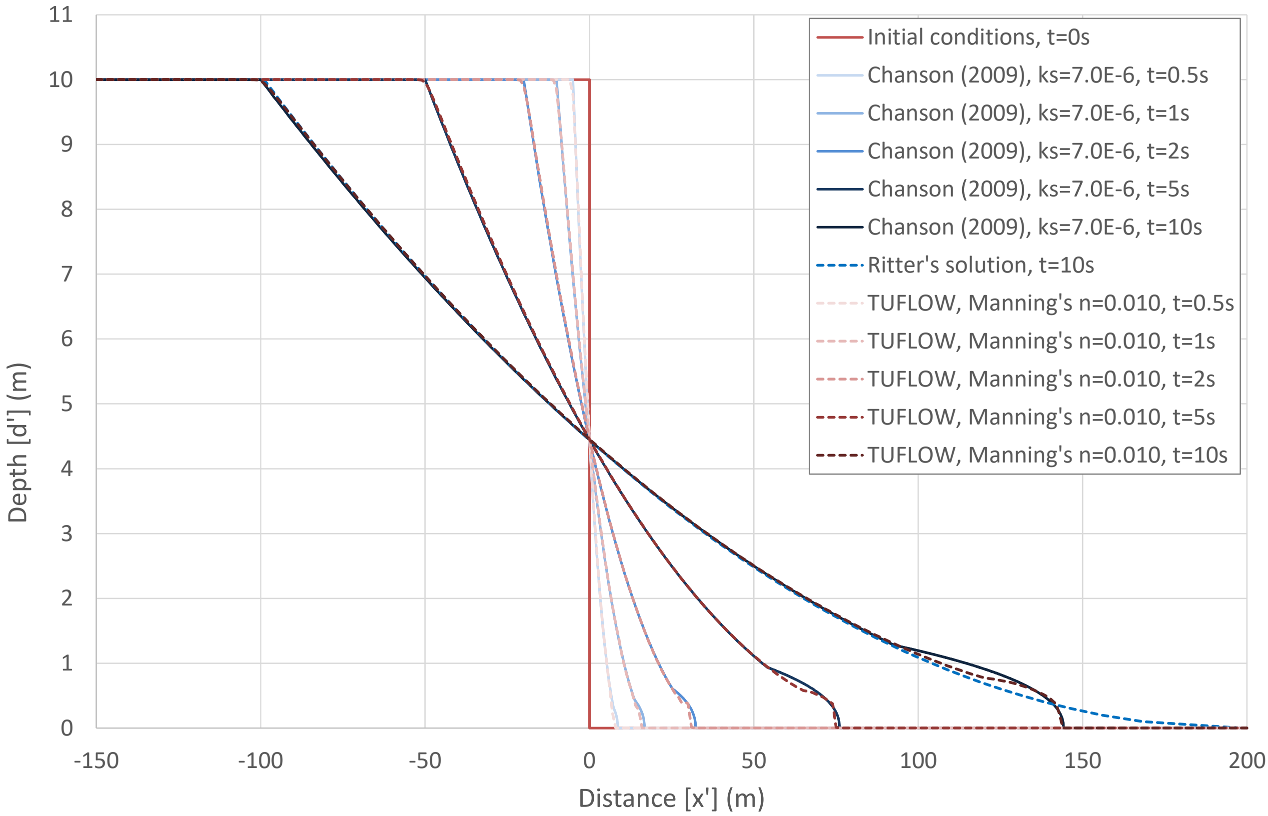

Figure 1 - Predicted water surface profiles for dam break problem at t = 0, 0.5, 1, 2, 5 and 10 seconds, Ritter Solution, Chanson (2009) and TUFLOW

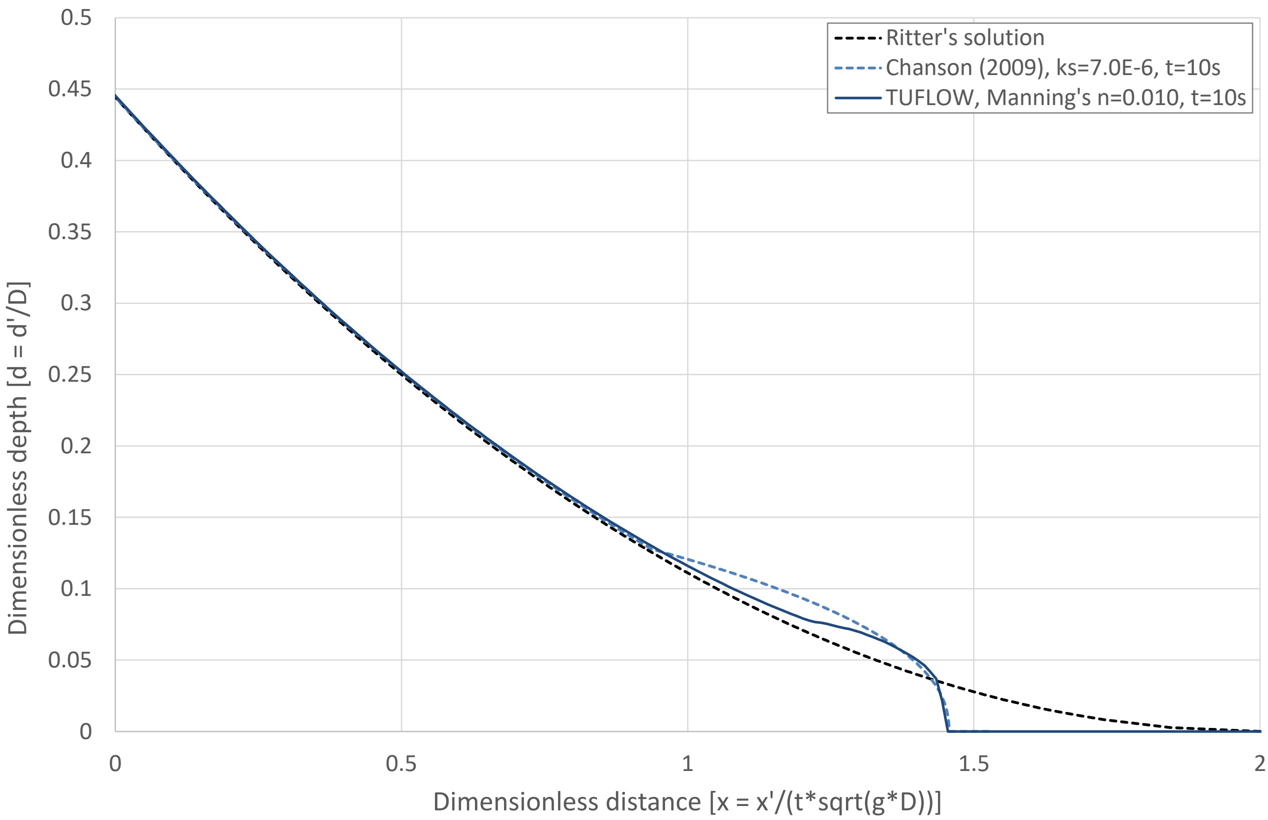

Figure 2 - Dimensionless water surface profile for dam break problem at t = 10 seconds, Ritter Solution, Chanson (2009) and TUFLOW

Test Scenario 2

Figure 3 is a dimensionless plot showing the water surface profile estimated by TUFLOW when t = 340 seconds, compared to the water surface profile estimated at the same time using the analytical solution from Chanson (2009). The figure also shows the Ritter Solution estimate of the water surface profile as well as the estimates of time and depth obtained from video footage by Chanson (2006), in dimensionless form.

The model results show very good agreement between the water surface profile predicted by TUFLOW, the analytical solution profile from Chanson (2009) and the field observations derived from video footage of the tsunami wave front.

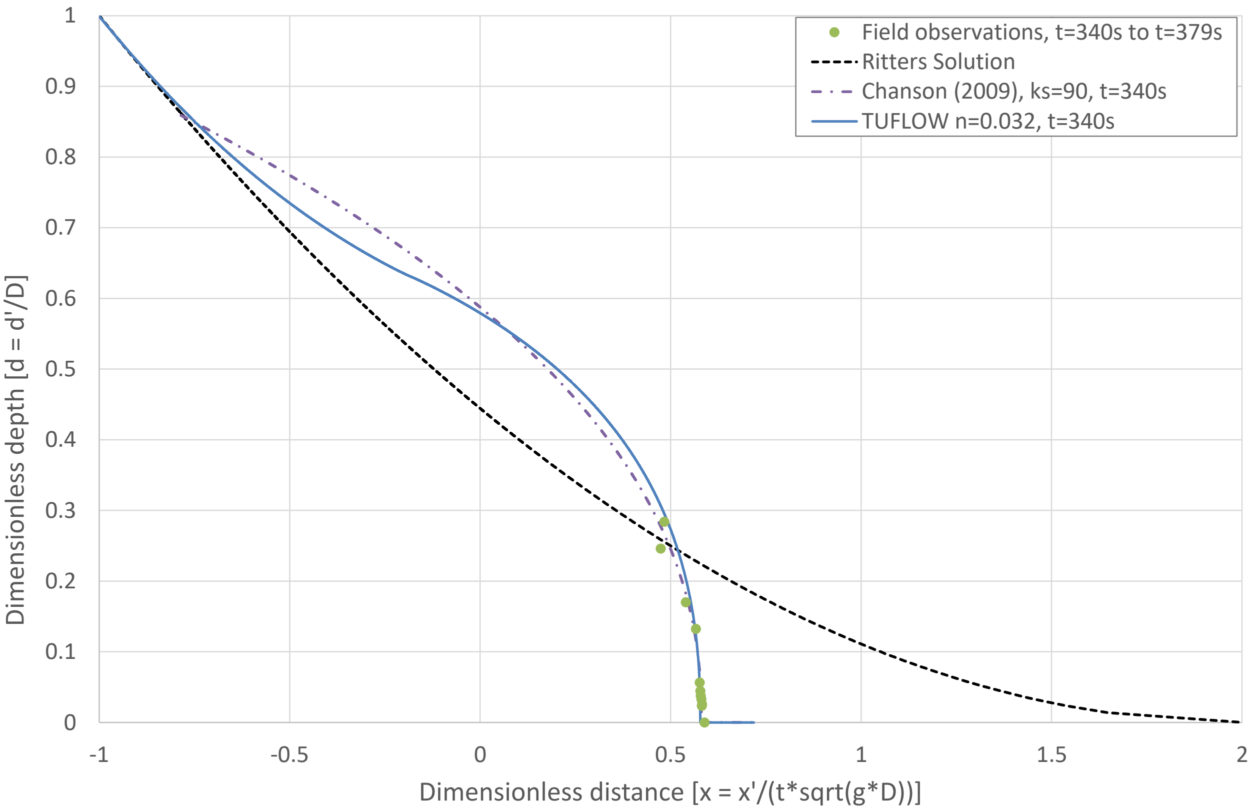

Figure 3 – Dimensionless water surface profile at t = 340 seconds, Ritter Solution, Chanson (2009) and TUFLOW

Conclusion and discussion

TUFLOW model results were compared with the analytical solution of an ideal dam break flow problem, as well as a set of field data from tsunami wave propagation onto a dry coastal floodplain. The results showed that the HPC solver version of TUFLOW correctly captures the dam break flood fronts and the flood wave propagation. This indicates that TUFLOW HPC is well suited for dam break flood modelling.

Sensitivity

Sensitivity testing of model cell size showed that the accuracy of model results was not particularly sensitive to model cell size, however the choice of model cell size determined the resolution of the wave tip region and the precision of locating the exact wave front. For example, the wave front location at t = 10 s might vary by 2 m between results from a 2 m grid cell size compared to a 0.2 m grid cell size.

Sensitivity testing of model grid cell size also showed that model run time was highly sensitive to adopted grid cell size, with for example, a Test Scenario 2 model run taking about 4 hours when using a 0.5 m grid cell size, 31 minutes using a 1 m grid cell size and only 5 minutes when using a 2 m grid cell size.

Sensitivity testing of Manning's 'n' values for the TUFLOW model revealed that although TUFLOW HPC accepts Manning's 'n' inputs accurate to five decimal places, values below 0.010 are automatically replaced with the (much higher) value of 0.025. This aspect of the TUFLOW software is not well documented and could be important for the investigation of hydraulics in low-roughness channels.

This study also attempted to assess the performance of the Classic solver version of TUFLOW. TUFLOW Classic uses an implicit solution scheme, with fixed time step, compared to TUFLOW HPC's explicit solution scheme with adaptive time stepping. Preliminary model runs found that the TUFLOW Classic model was very sensitive to the selection of model cell size and stable model results could not be achieved within the time available for the study. It is possible that with further refinement of assumptions, stable TUFLOW Classic model results might have been achieved.

In practice

The results of this study show that when using the TUFLOW hydraulic modelling software package, first preference should be given to using TUFLOW HPC for dam break analysis. The TUFLOW HPC with its explicit solution scheme and adaptive time stepping is unconditionally stable and conserves volume. As a result, the practitioner can quickly obtain stable model results and focus effort on reviewing and refining the model, rather than on troubleshooting a model producing unstable results.

Consideration should be given to balancing model resolution and model run times. Variations in model cell size can have a multiplier effect on the total number of grid cells and dramatically increase the model run time, as seen in this study.

Special care should be taken when modelling low roughness scenarios (Manning’s n less than 0.025) with the current version of TUFLOW HPC to ensure that the model does not apply default minimum roughness values without the modeller’s knowledge.

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