

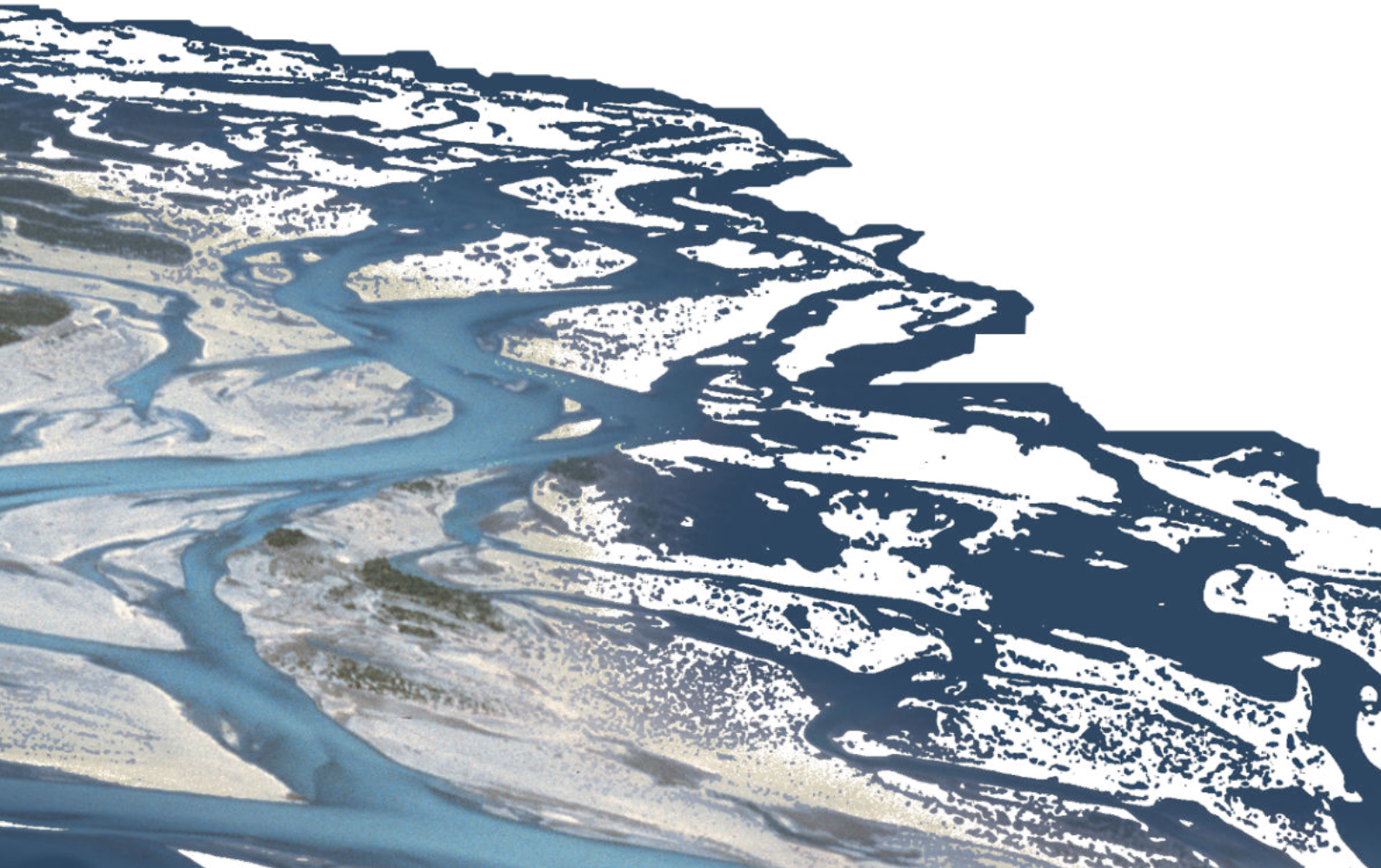


BASEMENT

**BASIC SIMULATION ENVIRONMENT
FOR MODELLING OF ENVIRONMENTAL
FLOWS AND NATURAL HAZARDS**

SYSTEM MANUALS

**VERSION 4.1.0
JUNE 2024**



Preamble

VERSION 4.1.0

June 2024

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Over the years, many enthusiastic engineers and developers have contributed to the development, testing and documentation of BASEMENT. An up-to-date overview of the current development team, along with current and former contributors, can be found on our website:

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Citation Advice

For System Manuals:

Vetsch D., Siviglia A., Bacigaluppi P., Brown, A., Bürgler M., Caponi F., Conde D., Gerke E., Halso M., Kammerer S., Koch A., Peter S., Vanzo D., Vonwiller L., Weberndorfer M. 2024. System Manuals of BASEMENT, Version 4.1.0. Laboratory of Hydraulics, Glaciology and Hydrology (VAW). ETH Zurich. Available from <https://www.basement.ethz.ch>. [date of access].

For Website:

BASEMENT – Basic Simulation Environment for Computation of Environmental Flow and Natural Hazard Simulation, 2024. <https://www.basement.ethz.ch>

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**BASIC SIMULATION ENVIRONMENT
FOR MODELLING OF ENVIRONMENTAL
FLOWS AND NATURAL HAZARDS**

TEST CASES

**VERSION 4.1.0
JUNE 2024**



BASEMENT

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Hydrodynamics

1.1 Introduction

The test catalogue is intended for the validation of the program. The catalogue consists of different test cases, their geometric and hydraulic fundamentals and the reference data for the comparison with the computed results. The test cases are built up on each other going from easy to more and more complex problems. The hydraulic solver is validated against analytical and experimental solutions using the test cases in Section 1.2. Common test cases are suitable for both, 1-D and 2-D simulations. Specific test cases are intended for either 1-D or 2-D simulations.

1.2 Common Test Cases

1.2.1 H_1: Dam break in a closed channel

1.2.1.1 Intention

The simplest test case check verifies the conservation property of the fluid phase and whether a stable condition can be reached for all control volumes after a finite time. Additionally, wet and dry problematic is tested.

1.2.1.2 Description

Consider a rectangular flume without sediment. The basin is initially filled in the half length with a certain water depth leaving the other side dry. After starting the simulation, the water flows in the other half of the system until it reaches a quiescent state (velocity = 0, half of initial water surface elevation (WSE) everywhere).

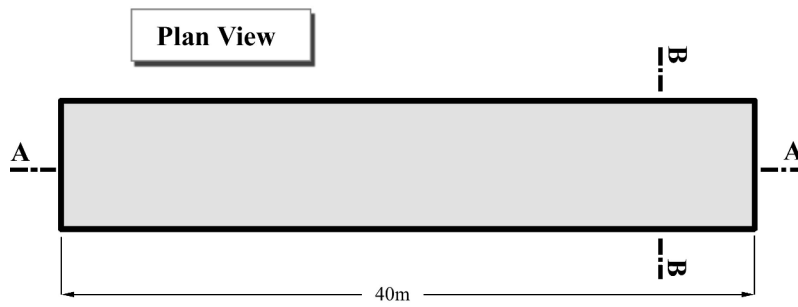


Figure 1.1 H_1: Dam break in a closed channel, plan view

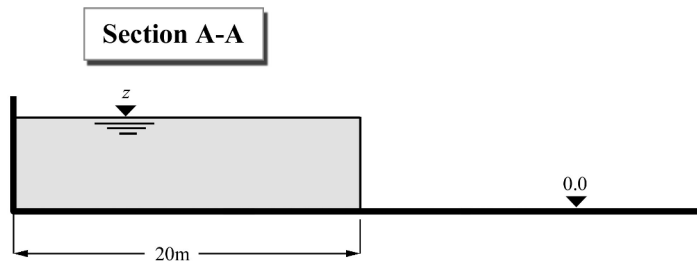


Figure 1.2 H_1: Dam break in a closed channel, section A-A

1.2.1.3 Geometry and Initial Conditions

Initial Condition: water at rest (all velocities zero), the water surface elevation is the same on the half of channel. This test uses a WSE of $z_S = 5.0$ m.

1.2.1.4 Boundary Conditions

No inflow and outflow. All of the boundaries are considered as a wall.

Friction: Manning's factor $n = 0.010$

1.2.2 H_2: One dimensional dam break on planar bed

1.2.2.1 Intention

This test case is similar to the previous one but this one compares the WSE a short time after release of the dam with an analytical solution for this frictionless problem. It is based on the verification of a 1-D transcritical flow model in channels by Tseng (1999).

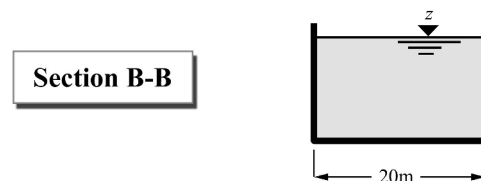


Figure 1.3 H_1: Dam break in a closed channel, section B-B

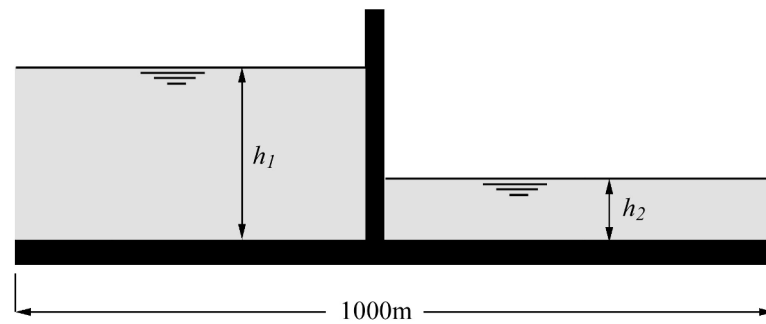


Figure 1.4 *H_2*: One dimensional dam break on planar bed

1.2.2.2 Description

A planar, frictionless rectangular flume has initially a dam in the middle. On one side, the water level is h_2 , on the other side, the water level is at h_1 . At the beginning, the dam is removed and a wave is propagating towards the shallow water. The shape of the wave depends on the fraction of the water depths (h_2/h_1) and can be compared to an analytical, exact solution.

1.2.2.3 Geometry and Initial Conditions

Two cases are considered:

- $h_2/h_1 = 0.001$; $h_1 = 10.0$ m (this avoids problems with wet/dry areas)
- $h_2/h_1 = 0.000$; $h_1 = 10.0$ m (downstream is initially dry)

The dam is exactly in the middle of the channel.

Since it is a one dimensional problem, it should not depend on the width of the model, which can be chosen arbitrary.

1.2.2.4 Boundary Conditions

All cases are frictionless, Manning factor $n=0$.

1.2.3 H_3: One dimensional dam break on sloped bed

1.2.3.1 Intention

Different from the previous cases, this problem uses a sloped bed with friction. The aim is to reproduce an accurate wave front in time. It is based on the verification of a 1-D transcritical flow model in channels by Tseng (1999).

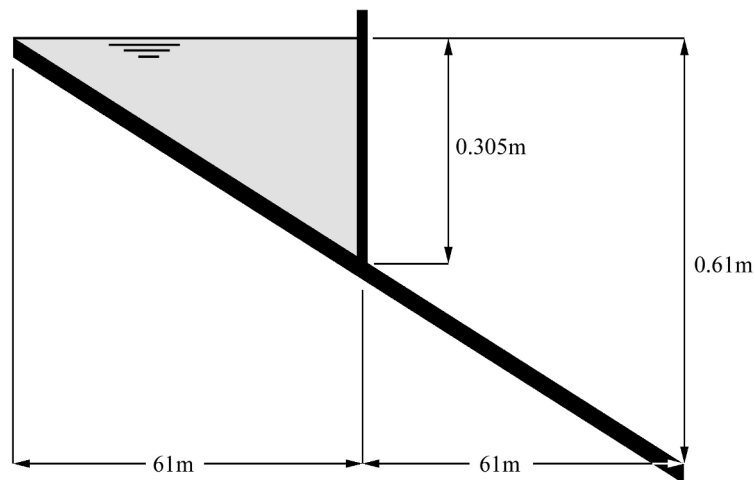


Figure 1.5 H_3: One dimensional dam break on sloped bed

1.2.3.2 Description

In the middle of a slightly sloped flume, an initial dam is removed at time zero (see Figure 1.5). The wave propagates downwards. Comparison data comes from an experimental work. Friction is accounted for with a Manning roughness factor estimated from the experiment.

1.2.3.3 Geometry and Initial Conditions

Length of flume: 122 m
 Width of flume: 1.22 m
 Slope: 0.61 m/122 m
 Initial water level: 0.035 m (at the dam location)

1.2.3.4 Boundary Conditions

Manning friction factor: 0.009

No inflow/outflow. Boundaries are considered as walls.

1.2.4 H_4 : Parallel execution

1.2.4.1 Intention

To test the parallel performance of hydraulic simulations on a multi-core shared memory computer a test case is set up. The aim is to demonstrate the increase in performance (the speedup) when running BASEMENT in parallel with an increasing number of cores.

1.2.4.2 Description

A hydraulic simulation is repeated with varying number of threads on a multi-core shared memory system. The simulation times are measured and compared to the sequential

execution time in order to evaluate the speedups.

1.2.4.3 Geometry, initial conditions and boundary conditions

A simple rectangular channel with constant slope is considered. The channel is discretized with a large number of cross sections (2000) in BASEchain and a large number of elements (16000) in BASEplane. There is an inflow located at the upper boundary of the channel and an outflow at the lower boundary. The inflowing discharge is constant over the time and steady state conditions within the channel are reached.

Large sized scenarios and evenly distributed work loads (steady state conditions) are set up in order to check for the full potential of the parallel implementation.

1.2.5 H_5: Controlled Boundary Condition

1.2.5.1 Intention

To verify and test the correct action of a PID-controller, steering a boundary condition to keep the water level at a certain cross section or element on the predefined level.

1.2.5.2 Description

The calculation includes a simple channel ending with a weir. In 2-D, two parallel channels are given. One channel is terminated with a weir, the other with a gate. The weir height and gate level is controlled during the simulation by the PID controller and is automatically updated to maintain the predefined water level.

For the 1-D simulation, the discharge in steady state is 100 m³/s. Over 5000 seconds it is increased up to 150 m³/s. The water level is fixed at QP_A18 to 112.6 m. The calculation also includes a feed forward component, directly translating the deviation of the inflow from steady state into an adaption of the weir height.

In 2-D, the discharge is increased from 300 m³/s to 450 m³/s and then lowered to 180 m³/s before it is again set to 300 m³/s. For the 2-D simulation, the target level is not constant, but dependent on the current inflow, which is measured upstream.

Inflow (m ³ /s)	Water level (m)
150	503.0
300	503.2
450	503.4

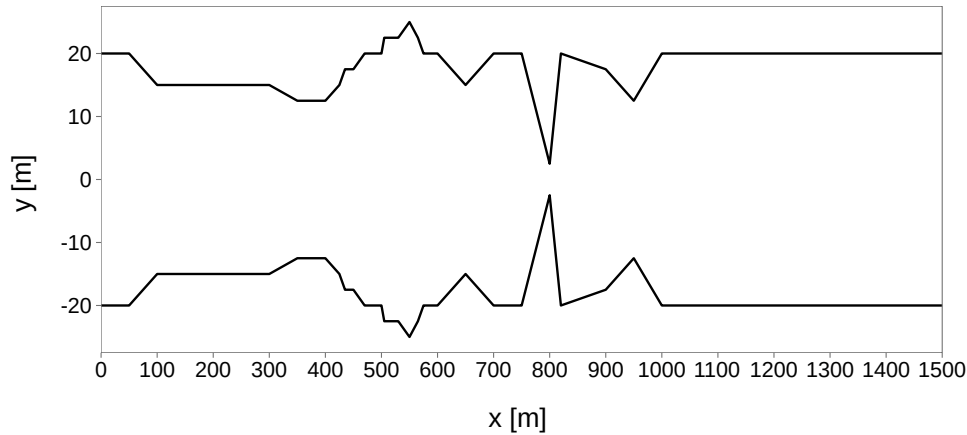


Figure 1.6 H_BC_1: Top view: cross-sections

1.3 BASEchain Specific Test Cases

1.3.1 H_BC_1: Fluid at rest in a closed channel with strongly varying geometry

1.3.1.1 Intention

This test case checks for the conservation of momentum. Numerical artefacts (mostly due to geometrical reasons) could generate impulse waves although there is no acting force.

1.3.1.2 Description

The computational area consists of a rectangular channel with varying bed topology and different cross-sections. The fluid is initially at rest with a constant water surface elevation and there is no acting force. There should be no changes of the WSE in time.

1.3.1.3 Geometry and Initial Conditions

The cross sections and bed topology were chosen as in Figure 1.6 and Figure 1.7. Notice the strong variations within the geometry. The water surface elevation is set to $z_S = 12$ m.

1.3.1.4 Boundary Conditions

All boundaries are considered as walls. There is no friction acting.

1.3.2 H_BC_2: bed load simulation with implicit hydraulic solution

1.3.2.1 Intention

The aim of this test case is to verify if the use of the implicit computation mode leads to the expected gain of computational time for a long sediment transport simulation.

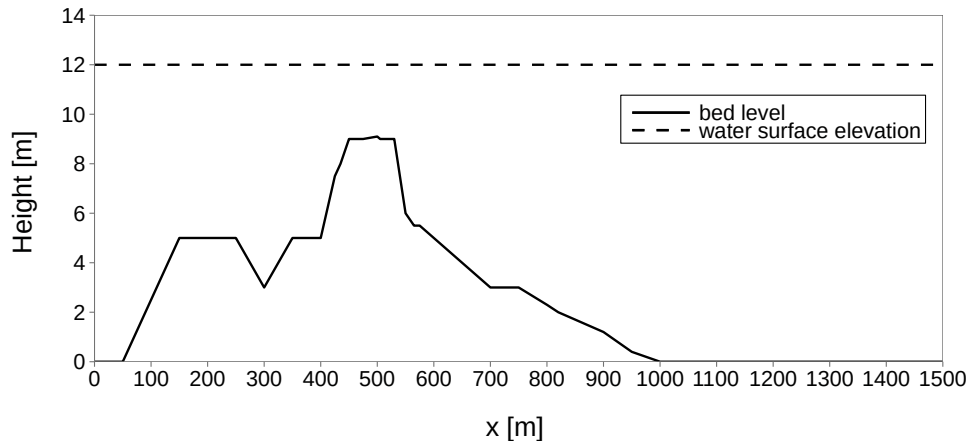


Figure 1.7 H_BC_1: Bed topography and water surface elevation

1.3.2.2 Description

The test case simulates a section of the river Thur near Altikon. At this place, there is a widening of which the morphological evolution should be evaluated.

1.3.2.3 Geometry and general data

The model is composed by 55 irregular cross sections, the mean grain size is 2.5 cm and the length of the transport generating hydrograph is 338 hours. The given time steps for the implicit simulation are 60, 120 and 180 seconds. The Program is allowed to reduce the time step if necessary, but this leads to time loss. The precisions of the results for which the iteration is interrupted are 0.1 m^2 for the wetted area and $0.1 \text{ m}^3/\text{s}$ for the discharge.

1.4 BASEplane Specific Test Cases

1.4.1 H_BP_1: Rest Water in a closed area with strongly varying bottom

1.4.1.1 Intention

This test in two dimensions checks for the conservation of momentum. Numerical artefacts (mostly due to geometrical reasons) could generate impulse waves although there is no acting force.

1.4.1.2 Description

The computational area consists of a rectangular channel with varying bottom topography. The fluid is initially at rest with a constant water surface elevation and there is no acting force. There should be no changes of the WSE in time.

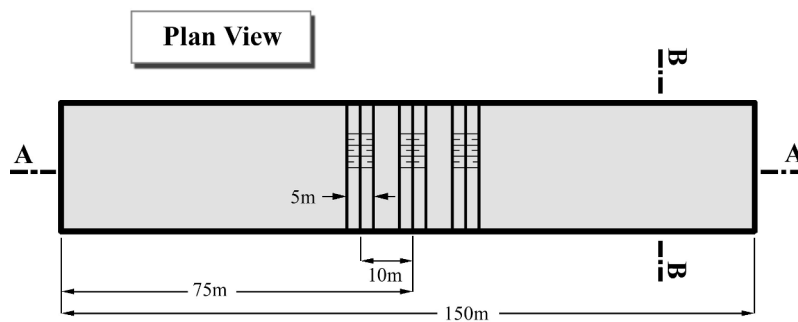


Figure 1.8 *H_BP_1: Rest Water in a closed area with strong varying bottom level, plan view*

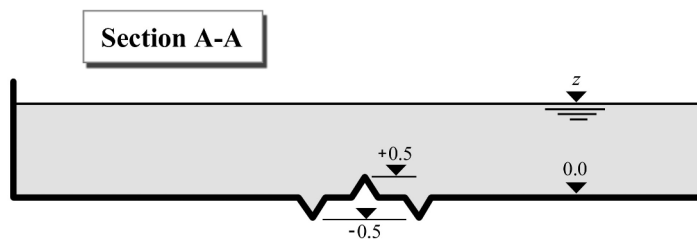


Figure 1.9 *H_BP_1: Rest Water in a closed area with strong varying bottom level, section A-A*

1.4.1.3 Geometry and Initial Conditions

Initial Condition: totally rest water, the WSE is the same and constant over the domain. The WSE can be varied e.g. from z_S (min) = 0.8 to z_S (max) 3.0 m .

1.4.1.4 Boundary Conditions

No inflow and outflow. All of the boundaries are considered as a wall.

Friction: frictionless test; Manning's factor $n = 0.0$.

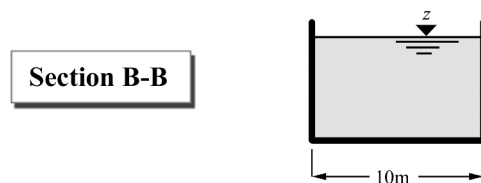


Figure 1.10 *H_BP_1: Rest Water in a closed area with strong varying bottom level, section B-B*

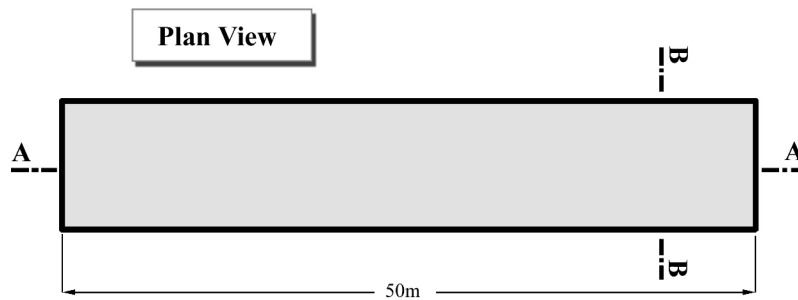


Figure 1.11 *H_BP_2: Rest Water in a closed area with partially wet elements, plan view*

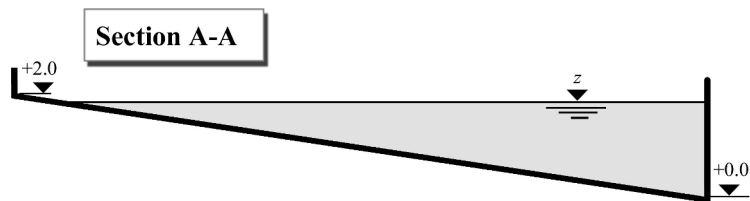


Figure 1.12 *H_BP_2: Rest Water in a closed area with partially wet elements, section A-A*

1.4.2 H_BP_2: Rest Water in a closed area with partially wet elements

1.4.2.1 Intention

This test case checks the behaviour of partially wet control volumes. The wave front respectively the border wet/dry is always the weak point in a hydraulic computation. There should be no momentum due the partially wet elements.

1.4.2.2 Description

In a sloped, rectangular channel, the WSE is chosen to be small enough to allow for partially wet elements. The water is at rest and no acting force is present.

1.4.2.3 Geometry and Initial Conditions

Initial Condition: totally rest water, the WSE is the same and constant over the whole domain. The WSE is $z_S = 1.9$ m.

1.4.2.4 Boundary Conditions

No inflow and outflow. All of the boundaries are considered as a wall.

Friction: frictionless test; Manning's factor $n = 0.0$.

The mesh (grid) can be considered as following pictures. In this form, the partially wet cells (elements) can be handled.

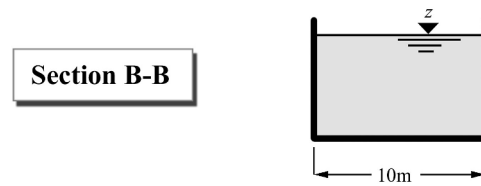


Figure 1.13 H_BP_2: Rest Water in a closed area with partially wet elements, section B-B

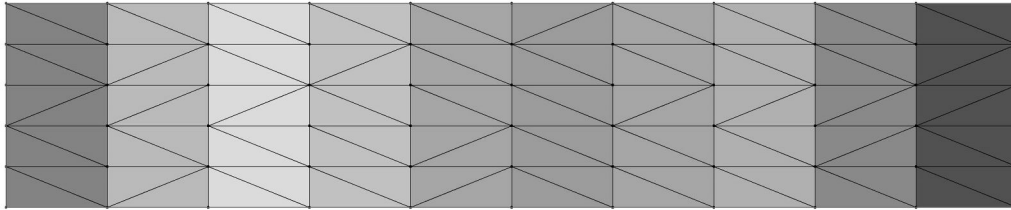


Figure 1.14 H_BP_2: Computational grid

1.4.3 H_BP_3: Dam break within strongly bended geometry

1.4.3.1 Intention

This test case challenges the 2-D code. The geometry permits a strongly two dimensional embossed flow. The results are compared against experimental measurements at certain control points.

1.4.3.2 Description

In a two-dimensional geometry with a jump in bed topology, a gate between reservoir and some outflow channel is removed at the beginning. The bended channel is initially dry and has a free outflow discharge as boundary condition at the downstream end.

1.4.3.3 Geometry and Initial Conditions

The geometry is described in Figure 1.16 and Figure 1.15, G1 to G6 are the measurement control points for the water elevation. Initial condition is a fluid at rest with a water surface elevation of 0.2 m above the channels ground. The channel itself is dry from water. At $z = 0$, the gate between reservoir and gate is removed.

1.4.3.4 Boundary Conditions

No inflow. At the downstream end of the channel, a free outflow condition is employed. All other boundaries are considered as walls.

The friction factor is set to 0.0095 (measured under stationary conditions) for the whole computational domain.

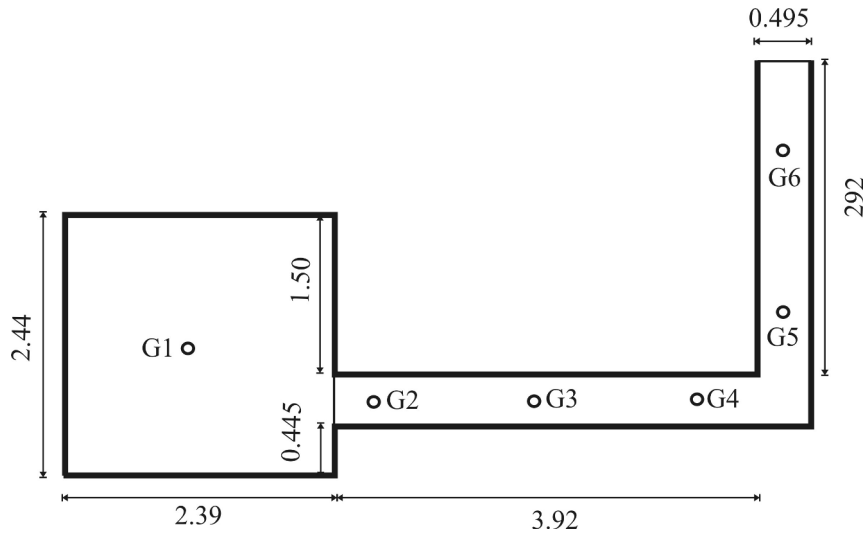


Figure 1.15 *H_BP_3: Strongly bended channel (plane view)*

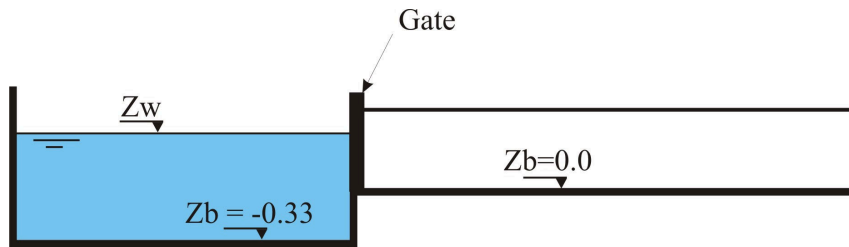


Figure 1.16 *H_BP_3: Strongly bended channel (side view)*

1.4.4 H_BP_4: Malpasset dam break

1.4.4.1 Intention

This final hydraulic test case is the well known real world data set from the Malpasset dam break in France. The complex geometry, high velocities, often and sudden wet-dry changes and the good documentation allow for a fundamental evaluation of the hydraulic code.

1.4.4.2 Description

The Malpasset dam was a doubly-curved equal angle arch type with variable radius. It breached on December 2nd, 1959 all of a sudden. The entire wall collapsed nearly completely what makes this event unique. The breach created a water flood wall 40 meters high and moving at 70 km/h. After 20 minutes, the flood reached the village Frejus and still had 3 m depth. The time of the breach and the flood wave can be exactly reconstructed, as the time is known, when the power of different stations switched off.

1.4.4.3 Geometry and Initial Conditions

Figure 1.18 shows the computational grid used for the simulation. The points represent “measurement” stations. The initial water surface elevation in the storage lake is set to +100.0 m.a.s.l. and in the downstream lake to 0.0 m.a.s.l. The area downstream of the wall is initially dry. At $t=0$, the dam is removed.

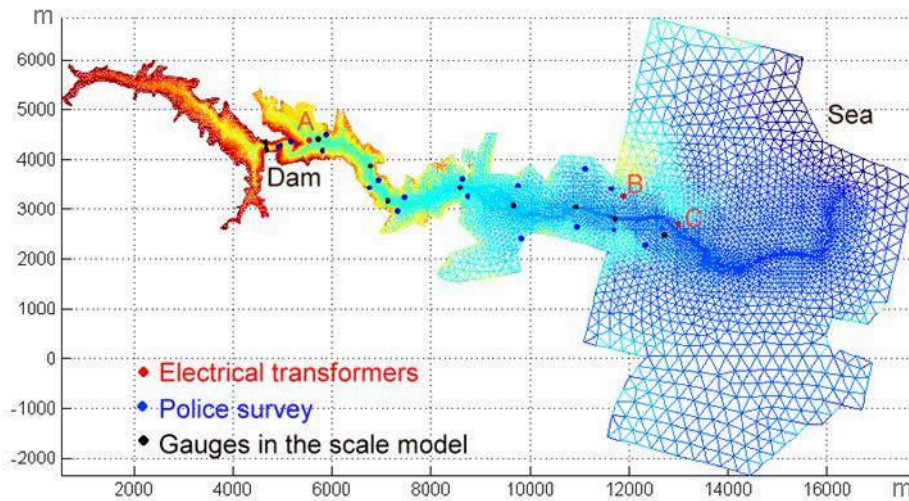


Figure 1.17 H_BP_4: Computational area of the malpasset dam break

1.4.4.4 Boundary Conditions

The computational grid was constructed to be large enough for the water to stay within the bounds. Friction is accounted for by a Manning factor of 0.033.

1.4.5 H_BP_5: Circular dam break wave

1.4.5.1 Intention

The circular dam break problem is a demanding two-dimensional test case with some distinct features. It is used to evaluate the capability to correctly model complex interactions of shock and rarefaction waves. The results are qualitatively compared to results obtained by Toro (2001), and other numerical studies, for this idealized dam break scenario. Also the results of the exact and approximate Riemann solvers are compared to each other.

1.4.5.2 Description

A virtual circular dam is located in the center of a computational domain. At the beginning, at time $t = 0.0s$, the dam is removed. The evolution of subsequent wave patterns is examined until about $t = 5s$ after the dam break.

1.4.5.3 Geometry and Initial Conditions

The computational domain has a width and height of 40m and is modelled with a uniform rectangular grid, which consists of 160'000 quadratic elements of the size 0.1m x 0.1m. The grid is selected large enough to fully capture the outward propagating primary shock wave during the simulation time of about 5s. The small element sizes shall enable the modelling of the circular flow patterns with sufficient accuracy.

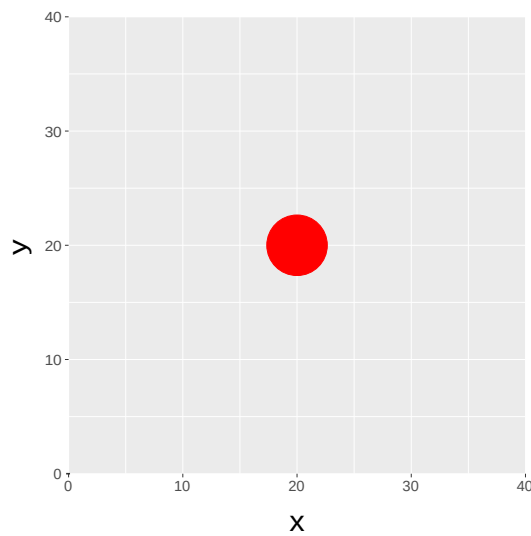


Figure 1.18 *H_BP_5: Computational area (rectangular grid) of circular dam break*

The initial height of the water column is 2.5m, whereas the surrounding initial water surface level is set to 0.5m. The water column behind the circular dam has a radius of 2.5m. The time step is chosen according to a CFL number of 0.9.

1.4.5.4 Boundary Conditions

Friction: frictionless test; Manning's factor $n = 0.0$.

1.5 Results

1.5.1 Common Test Cases

1.5.1.1 H_1: Dam break in a closed channel

The conservation of mass is validated. After $t = 1107$ s, the discharges still have a magnitude of 10^{-6} m³/s with decreasing tendency. Both, BASEchain and BASEplane deliver similar results.

1.5.1.2 H_2: One dimensional dambreak on planar bed

1.5.1.2.1 Results obtained by BASEchain

A comparison of the 1-D test case using $h_2/h_1 = 0.000$ with the analytical solution shows an accurate behaviour of the fluid phase in time.

1.5.1.2.2 Results obtained by BASEplane

In two dimension, the dam break test case was computed using $h_2/h_1 = 0.0$ and $h_1 = 10$ m. The length of the channel was discretized using 1000 control volumes. The CFL number

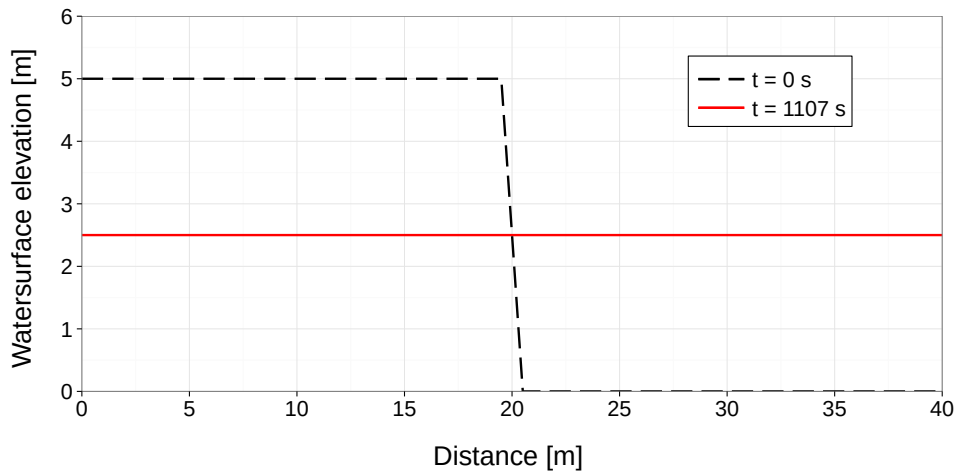


Figure 1.19 H_1: Initial and final water surface elevation (BC & BP)

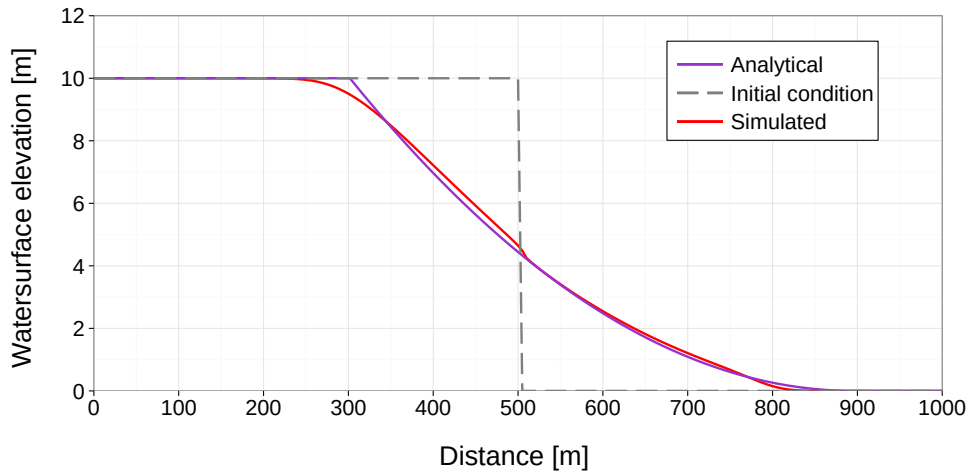


Figure 1.20 H_2: Water surface elevation after 20 s (BC)

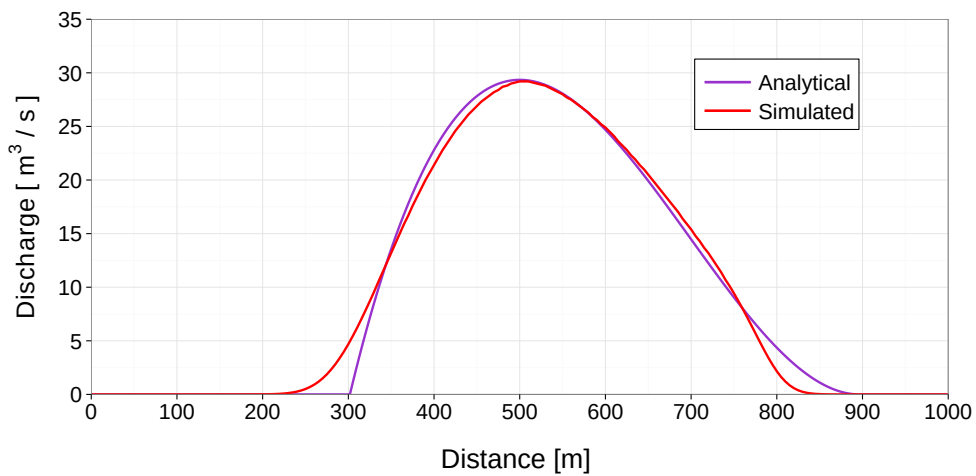


Figure 1.21 H_2: Distribution of discharge after 20 s (BC)

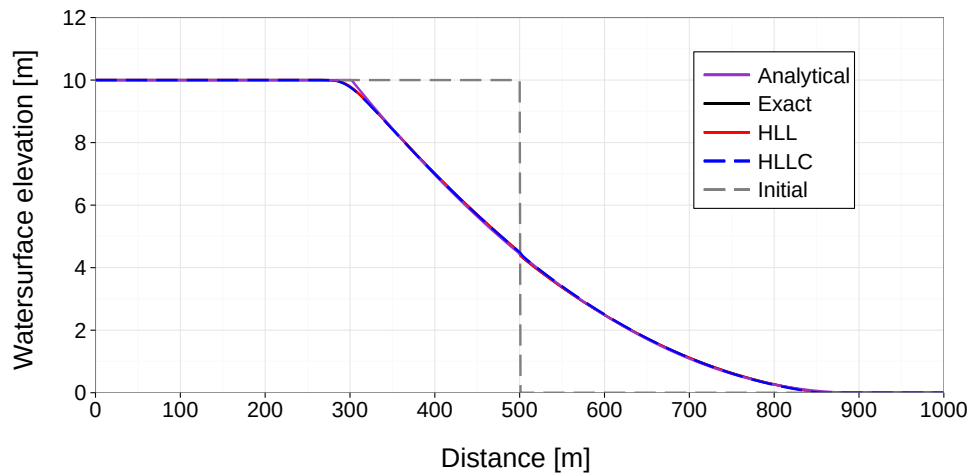


Figure 1.22 H_2: Flow depth 20 sec after dam break (BP)

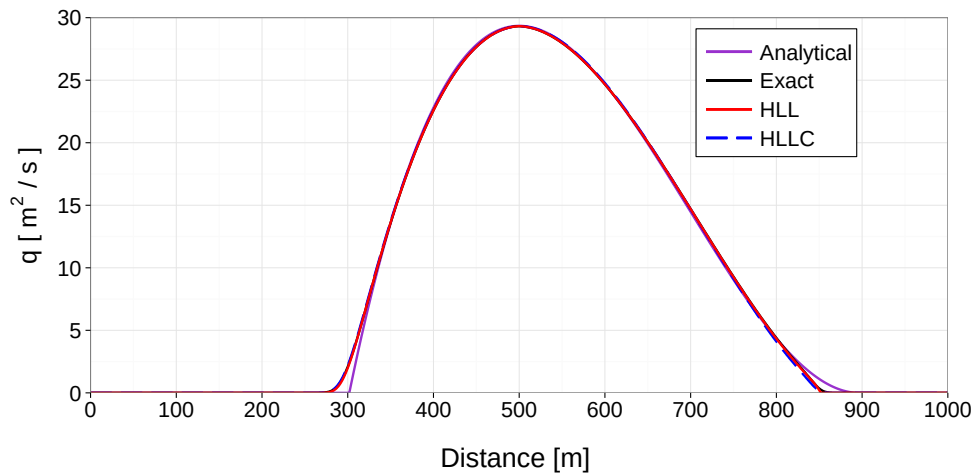


Figure 1.23 H_2: Discharge 20 sec after dam break (BP)

was set to 0.85. The results show a good agreement between simulation and analytical solution.

1.5.1.3 H_3: One dimensional dam break on sloped bed

1.5.1.3.1 Results obtained by BASEchain

The dam break in a sloped bed was compared against experimental results. The agreement is satisfying.

1.5.1.3.2 Results obtained by BASEplane

For two dimensions, the numerical results show a good agreement with the experimental measurements. Although in certain areas, the water depth is underestimated, the error is just at 7 % and only for a limited time. The comparison is still successful.

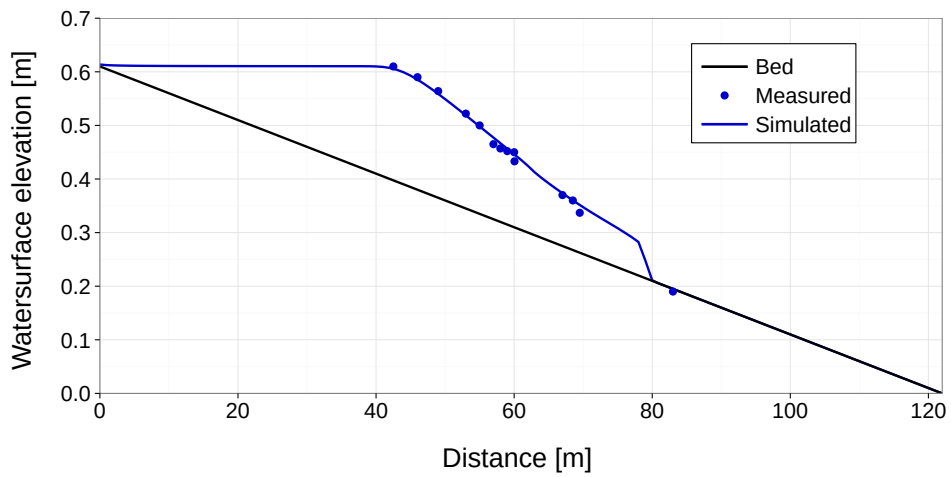


Figure 1.24 H_3: Water surface elevation after 10 s (BC)

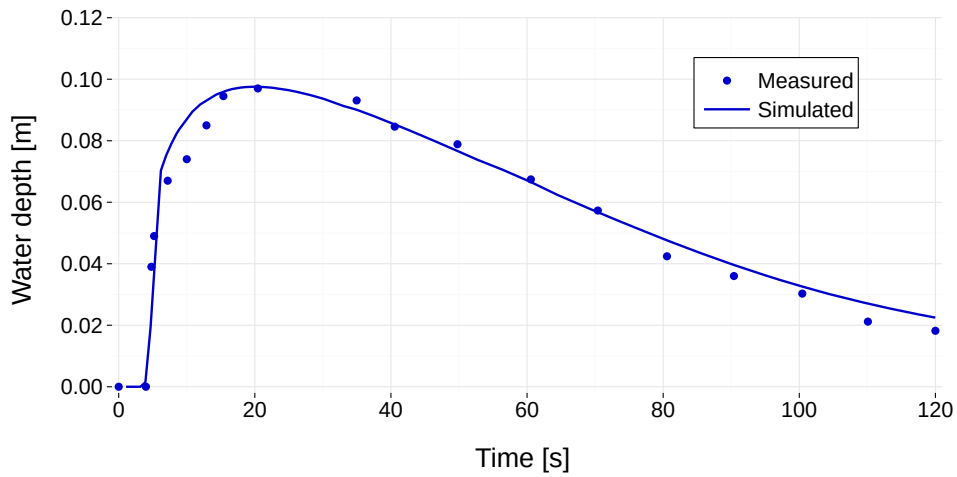


Figure 1.25 H_3: Temporal behaviour of water depth at $x = 70.1$ m (BC)

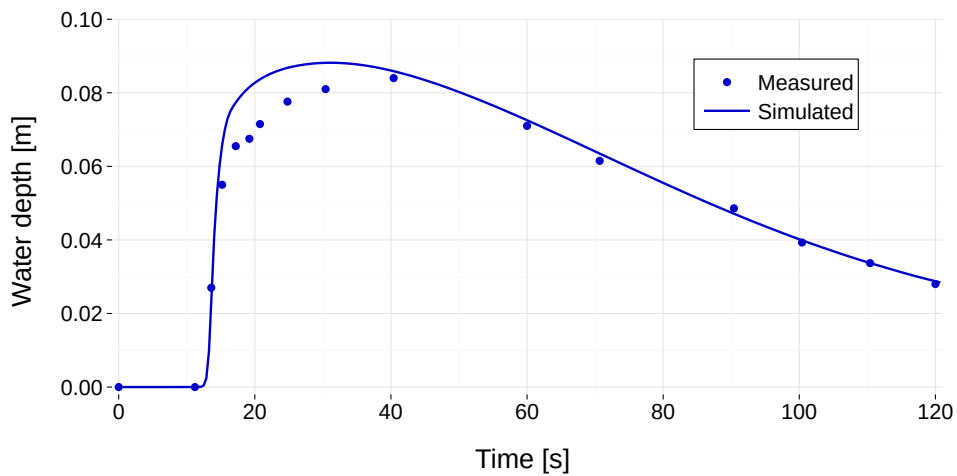


Figure 1.26 H_3: Temporal behavior of water depth at $x = 85.4$ m (BC)

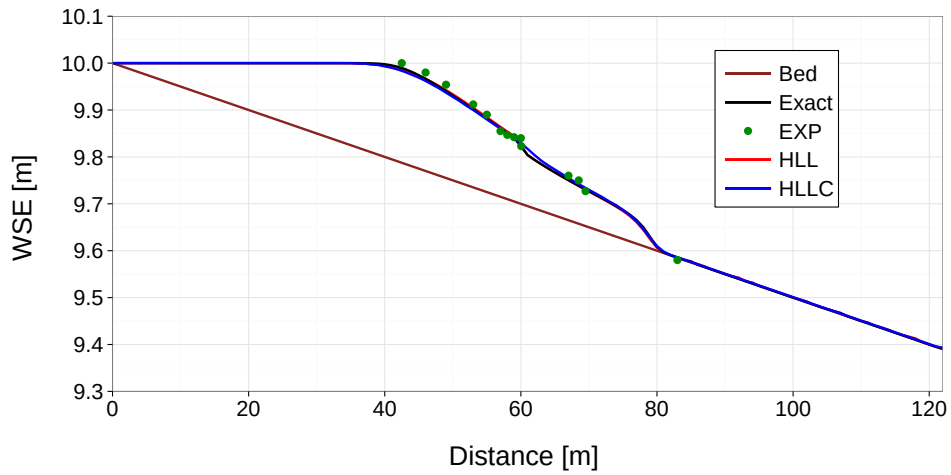


Figure 1.27 H_3: Cross sectional water level after 10 s simulation time (BP)

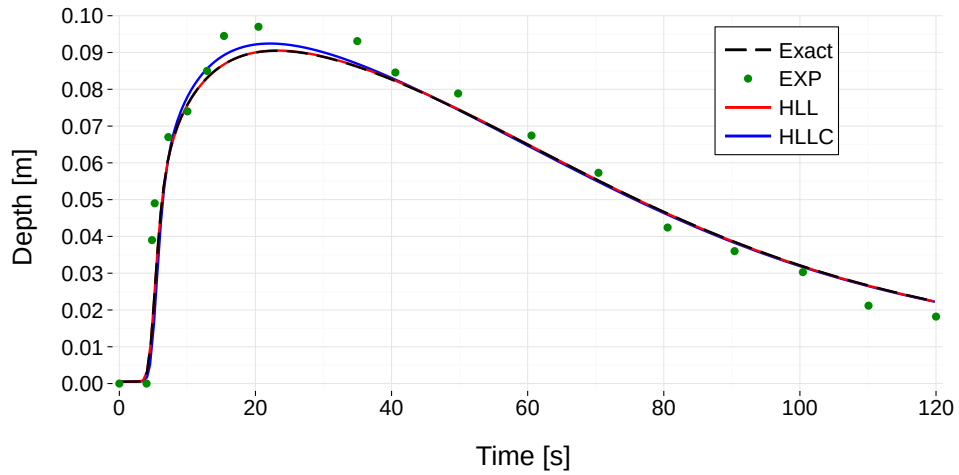


Figure 1.28 H_3: Chronological sequence of water depth at point $x = 70.1$ m (BP)

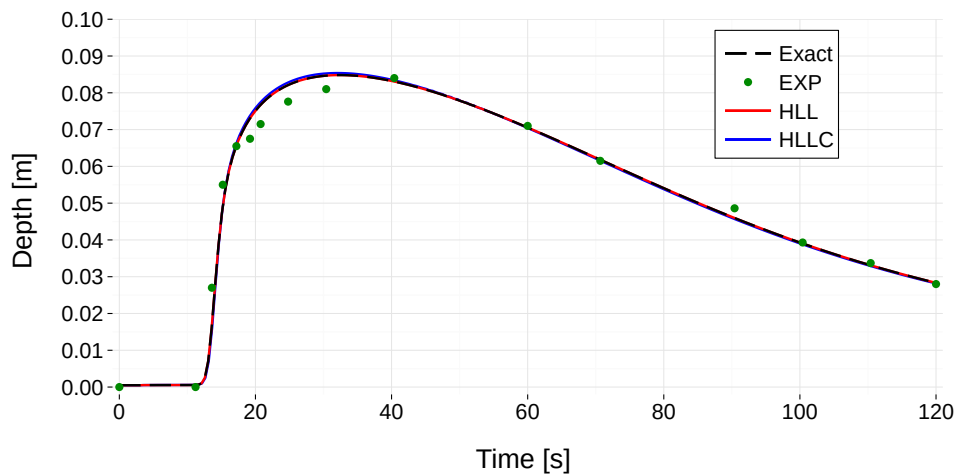


Figure 1.29 H_3: Chronological sequence of water depth at point $x = 85.4$ m (BP)

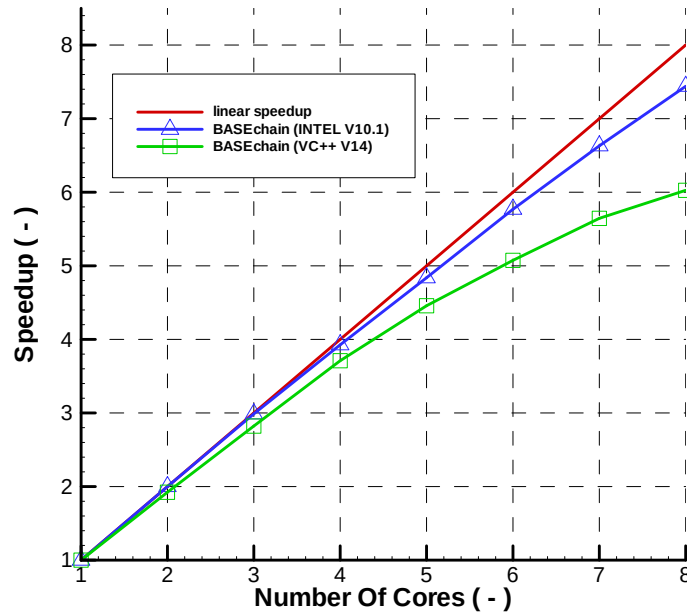


Figure 1.30 H_4 (BASEchain) – Parallel speedup for 1-D test case

1.5.1.4 H_4 : Parallel execution

1.5.1.4.1 General

Hydraulic simulations in a rectangular channel with steady state conditions are repeated multiple times and the execution times are measured. Thereby only the number of used threads is varied from one simulation to another. The selected model scenarios are suited well for parallel execution regarding size and load balancing in order to check the full potential of the parallel execution (in many practical model setups the observed speedups may be significantly lower).

1.5.1.4.2 System configuration

The simulations were performed on an Intel multi-core shared memory system with 8 cores. The used operating system was WinXP 64.

The simulation procedure is repeated with two different versions of BASEMENT. One version (blue) is compiled with the Intel C++ compiler (V 10.1), whereas the other version (green) is compiled with the Microsoft VC++ compiler (V14).

1.5.1.4.3 Results obtained by BASEchain

The results indicate an excellent speedup and scalability. The speedup increases nearly linearly with the number of used cores. The parallel speedups obtained by the Intel compiled binary are superior to those obtained by the VC++ compiled binary.

1.5.1.4.4 Results obtained by BASEplane

The results indicate a satisfactory speedup and scalability. The effect of increasing slope of the blue curve, when running this scenario with 8 cores, is probably due to caching effects. The parallel speedups obtained with the Intel compiled binary are superior to those obtained with the VC++ binary, if the number of cores exceeds 2.

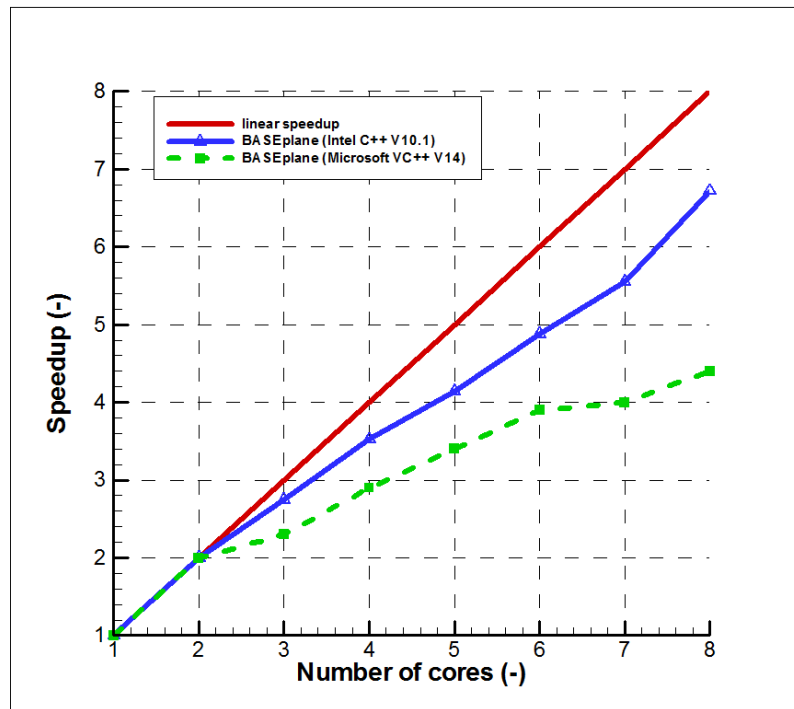


Figure 1.31 H_4 (BASEplane) – Parallel speedup for 2-D test case

1.5.1.5 H_5 : Controlled boundary conditions

1.5.1.5.1 Results for BASEchain

As can be seen in Figure 1.32, the controller is able to maintain the constant water level at 112.6 m precisely.

1.5.1.5.2 Results for BASEplane

Compared to the 1-D simulation, the 2-D test case is a more complicated problem as it involves discharge dependent targets and changes of discharge from $450 \text{ m}^3/\text{s}$ down to $180 \text{ m}^3/\text{s}$ within 5 minutes. This rapid change makes the strict maintaining of the water level difficult. In principle, this could be handled by a stronger reaction of the weir and gate, which would require also a stronger imposed upper limit of the time step to prevent numerical oscillations of the weir and gate height.

1.5.2 BASEchain Specific Test Cases

1.5.2.1 H_{BC_1} : Fluid at rest in a closed channel with strongly varying geometry

The test was successfully carried out. There was no movement at all – the water surface elevation remained constant over the whole area. No picture will be shown as there is nothing interesting to see.

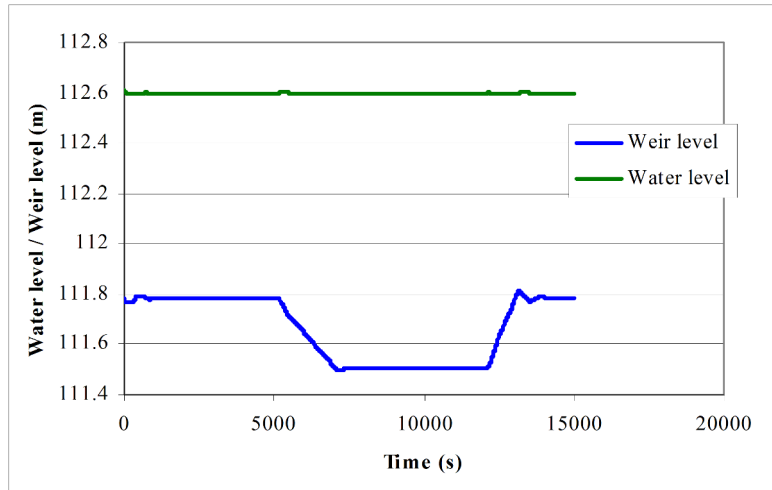


Figure 1.32 H_5 (BASEchain) Controlled weir with changing inflow.

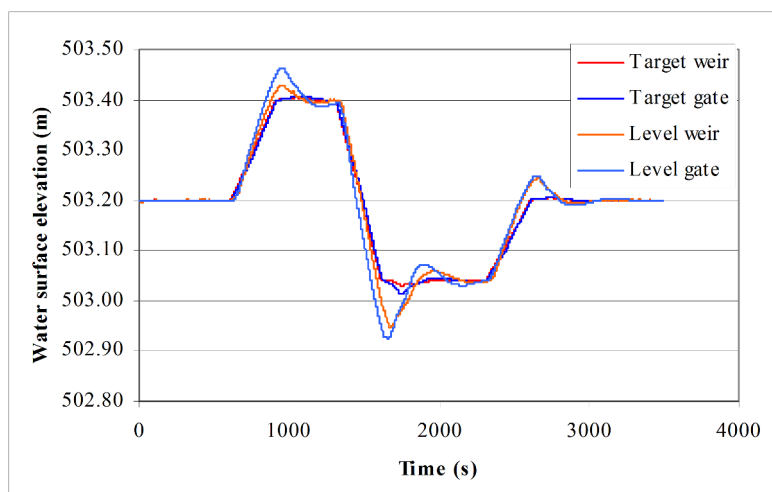


Figure 1.33 H_5 (BASEplane) Controlled weir and gate. The target levels and the actual levels with changing inflow are given.

1.5.2.2 H_BC_2: bed load simulation with implicit hydraulic solution

The time steps and simulation times for the explicit and implicit computations are listed in the table below. The reduction of simulation time is satisfying.

Table 1.2 *H_BC_2 : Performance of implicit calculations*

	Time step (seconds)	Simulation time (hours)	Speedup (times faster)
Explicit	2-5	13.94	
Implicit, base time step = 60	3-90	0.9	15
Implicit, base time step = 120	3-120	0.6	23
Implicit, base time step = 180	3-180	0.47	30

1.5.3 BASEplane Specific Test Cases

1.5.3.1 H_BP_1: Rest water in a closed area with strongly varying bottom

The test was successfully carried out. There was no movement at all – the water surface elevation remained constant over the whole area. No picture will be shown as there is nothing interesting to see.

1.5.3.2 H_BP_2: Rest Water in a closed area with partially wet elements

The test was successfully carried out. There was no movement at all – the water surface elevation remained constant over the whole area. No picture will be shown as there is nothing interesting to see.

1.5.3.3 H_BP_3: Dam break within strongly bended geometry

The computational area was discretized using a mesh with 1805 elements and 1039 vertices. The vertical jump in bed topography between the reservoir and the channel was modelled with a strongly inclined cell (a node can only have one elevation information). Figure 2.1 shows the water level contours and the velocity vectors. The following figures compare the time evolution of the measured water level with the simulated results at the control points G1, G3 and G5.

The results are showing an accurate behaviour expect at the control point G5, where some bigger differences can be observed. They are caused by the use of a coarse mesh around that area. Using a higher mesh density, the water level in the critical area after the strong bend is better resolved and delivers more accurate results. Figure 1.40 shows a comparison at point G5 for a coarse and a dense mesh.

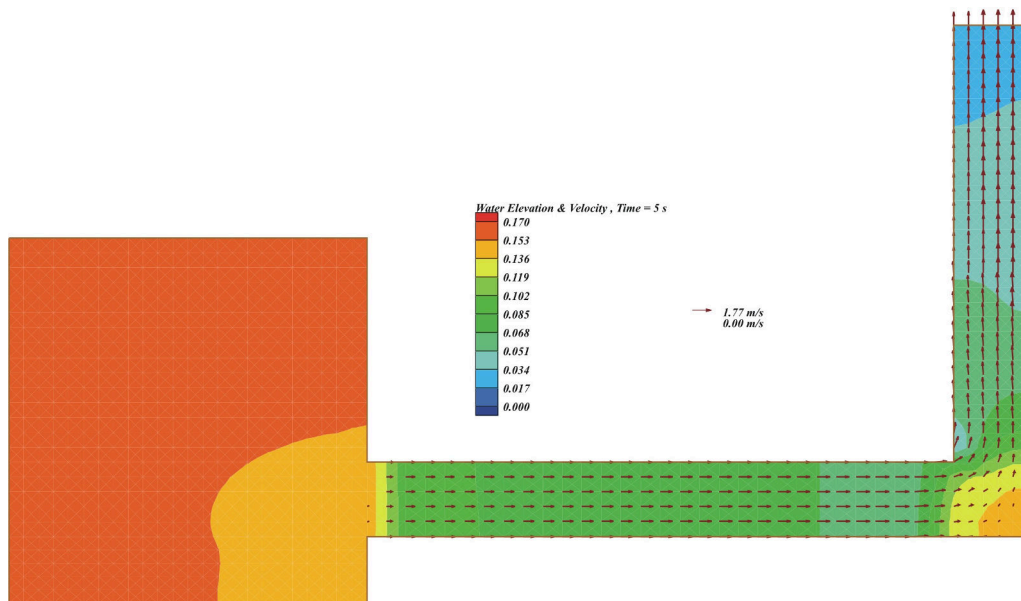


Figure 1.34 H_BP_3: Water level and velocity vectors 5 seconds after the dam break

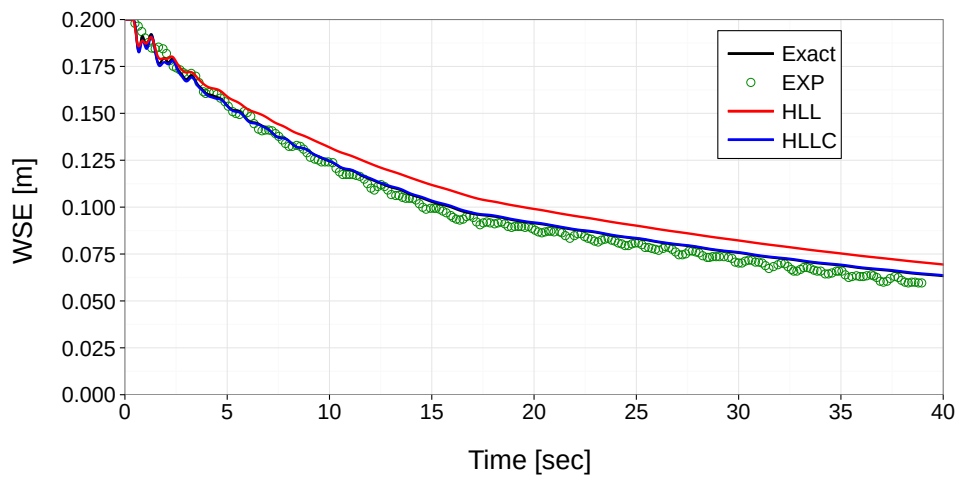


Figure 1.35 H_BP_3: Water surface elevation at G1

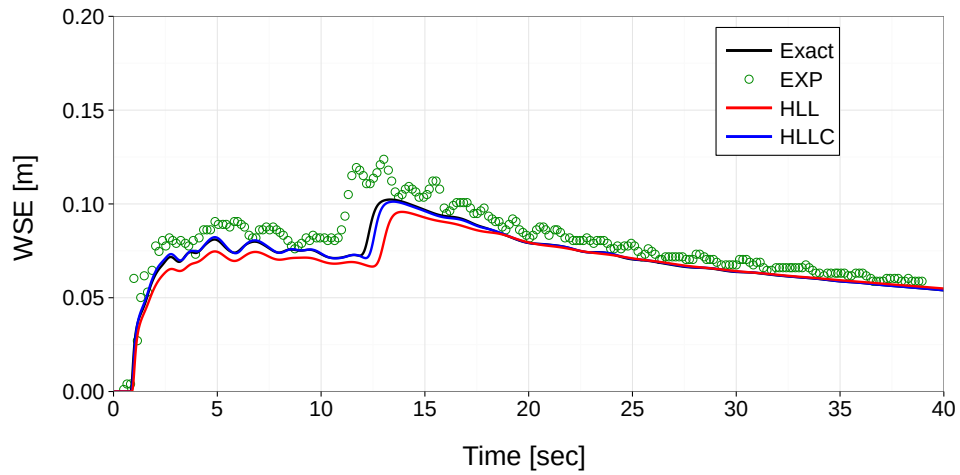


Figure 1.36 *H_BP_3*: Water surface elevation at *G3*

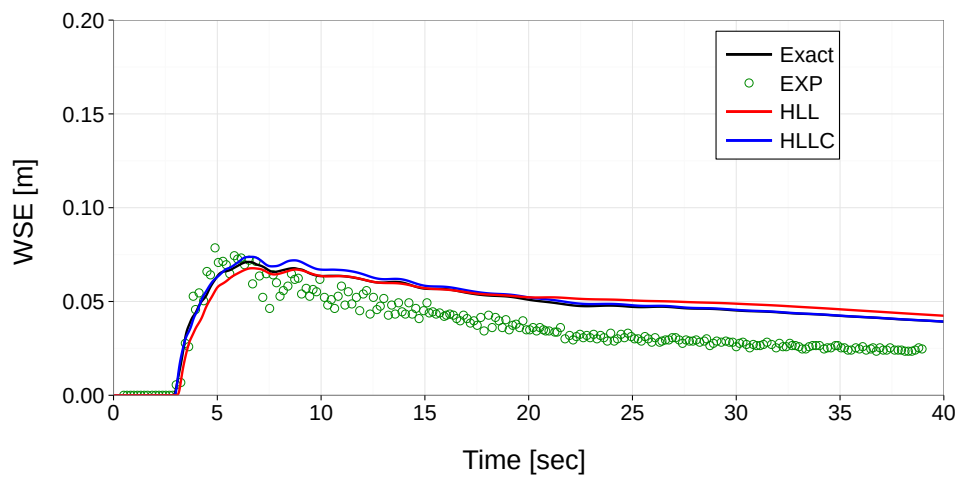


Figure 1.37 *H_BP_3*: Water surface elevation at *G5*

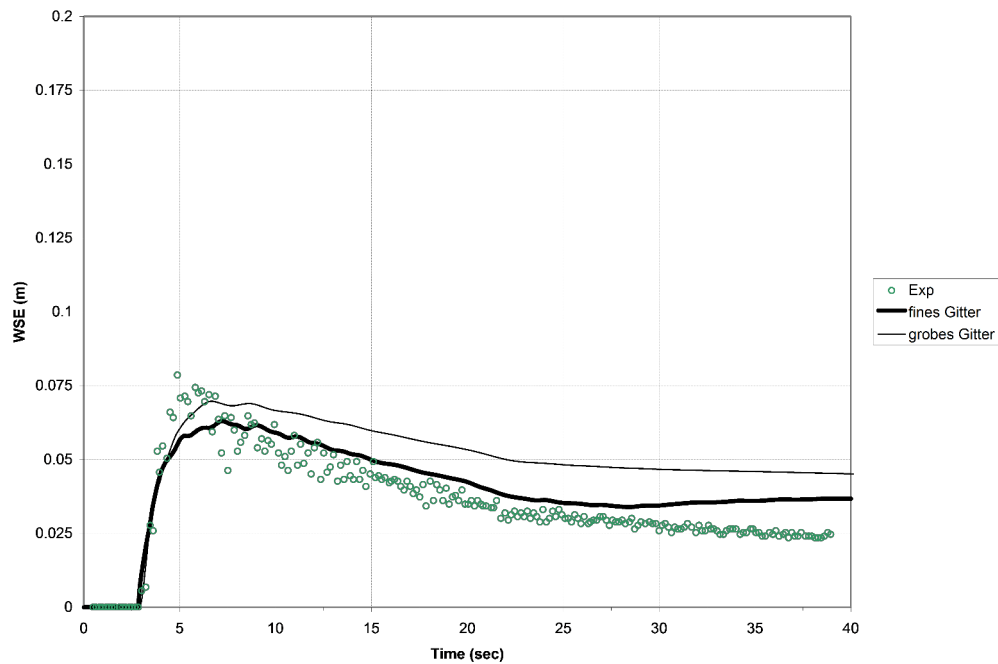


Figure 1.38 H_BP_5: Comparison of the water level at point G5 for a coarse and a dense grid.

1.5.3.4 H_BP_4: Malpasset dam break

The computational grid consists of 26'000 triangulated control volumes and 13'541 vertices. The time step was chosen according to a CFL number of 0.85. Figure 1.39 shows the computed water depth and velocities 300 seconds after the dam break. Figure 1.40 compares several computed with the observed data on water level elevation at different stations.

BASEplane results show a good agreement with the observed values as also other simulation results (Valiani et al. (2002) and Yoon and Kang (2004)). The differences between computed and measured data are maximally around 10%.

1.5.3.5 H_BP_5: Circular dam break

The obtained results for the circular dam break test case are plotted in two different ways. A 3-D perspective view of the depth is shown from Figure 1.41 to Figure 1.46 to illustrate the overall flow and wave patterns. Additional water surface and velocity profiles are plotted from Figure 1.47 to Figure 1.48 for distinct times.

The following flow patterns of the 2-D circular dam break are reported by Toro and other numerical studies and are also observed here.

After the collapse of dam at $t = 0.0$ s an outward propagating, primary shock wave is created. A sharp depth gradient develops behind this shock wave. Also, a rarefaction wave is generated which propagates inwards in the direction of the center of the dam break. The rarefaction wave finally reaches the center and generates a very distinct dip of the surface elevation at the center ($t = 0.4$ s) This dip travels outwards resulting in a rapid drop of the surface elevation at the center, which falls even below the initial outer water level ($t = 1.4$ s) and finally nearly reaches the ground ($t = 3.5$ s). A second shock wave develops

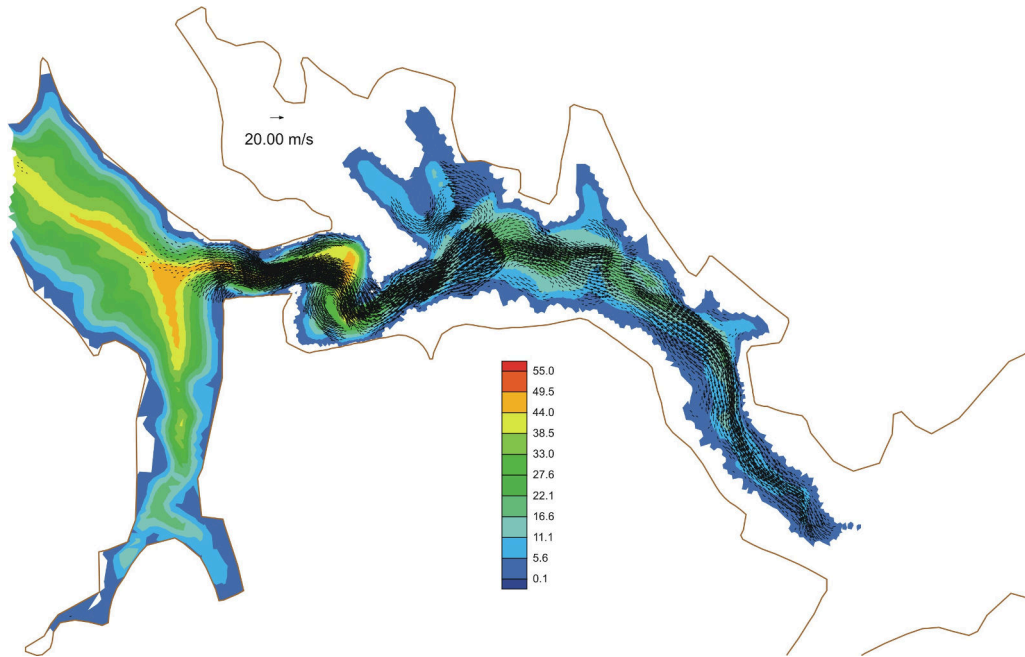


Figure 1.39 H_BP_4: Computed water depth and velocities 300 seconds after the dam break.

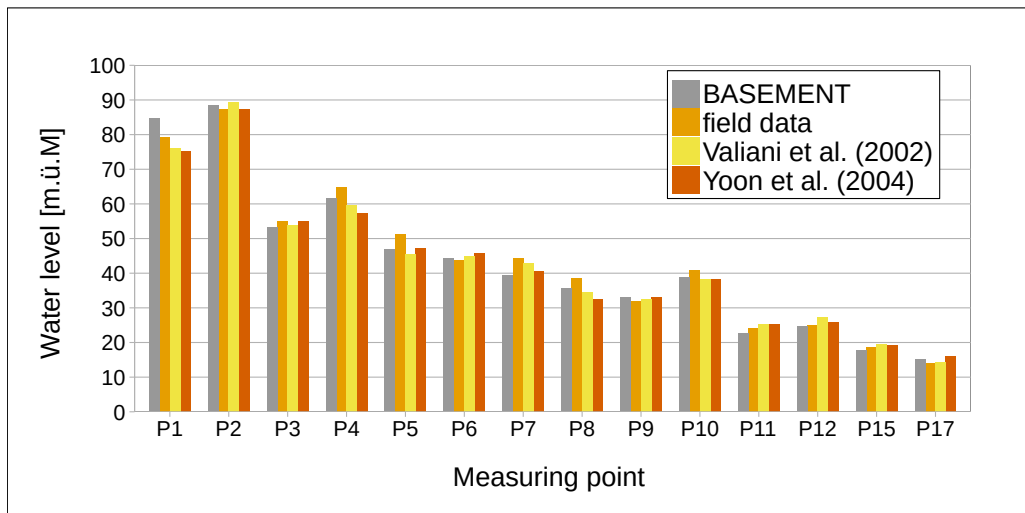


Figure 1.40 H_BP_4: Computed and observed water surface elevation at different control points

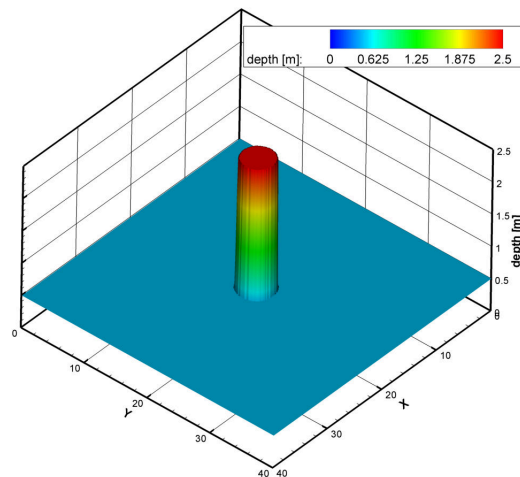


Figure 1.41 *H_BP_5*: Perspective view of the circular dam break wave patterns, $t=0.0s$

which propagates inwards while the primary shock wave continues to propagate outwards with decreasing strength. This secondary shock wave converges to the center and finally implodes. This generates a sharp jump in the surface water elevation at the center ($t = 4.7$ s).

As a result it can be stated that BASEplane is able to reproduce these distinct features of the flow and wave patterns of the 2-D circular dam break. Comparisons with the numerical results of Toro show qualitative agreement of the calculated water surface and velocities profiles. Generally, a more diffusive behaviour is observed compared to Toro's results. This may be attributed to the use of first order Godunov methods and to the use of a lower CFL number in the simulations. Despite the use of a rectangular grid, the cylindrical symmetry of the wave propagations is maintained well. Only at the first moments of the dam break, some water surface modulations can be seen at the crest of the primary shock wave which diminish with proceeding time.

The resulting water surface and velocity profiles of the approximate Riemann solvers match well the results of the exact Riemann solver. Both approximate Riemann solvers, HLL and HLLC, reproduce the flow and wave patterns.

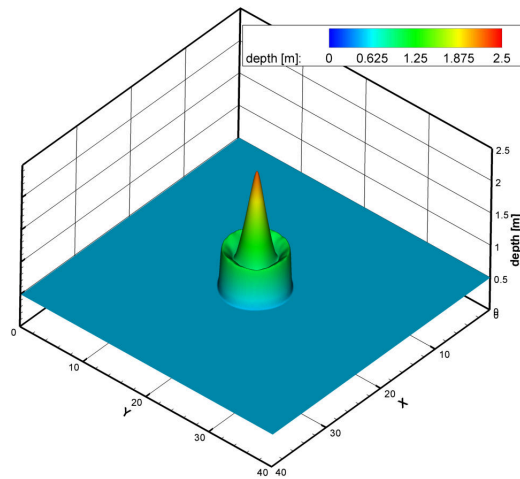


Figure 1.42 H_BP_5: Perspective view of the circular dam break wave patterns, $t=0.4s$

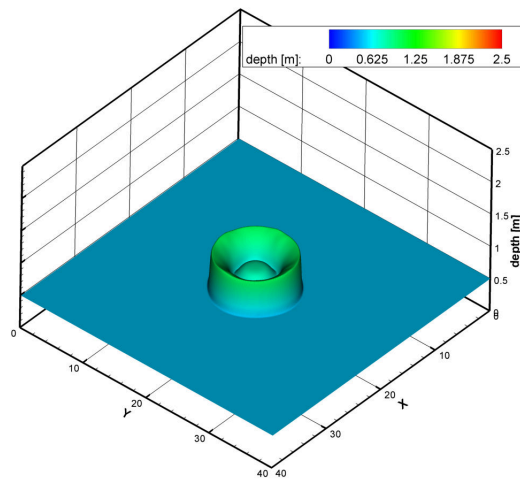


Figure 1.43 H_BP_5: Perspective view of the circular dam break wave patterns, $t=0.7s$

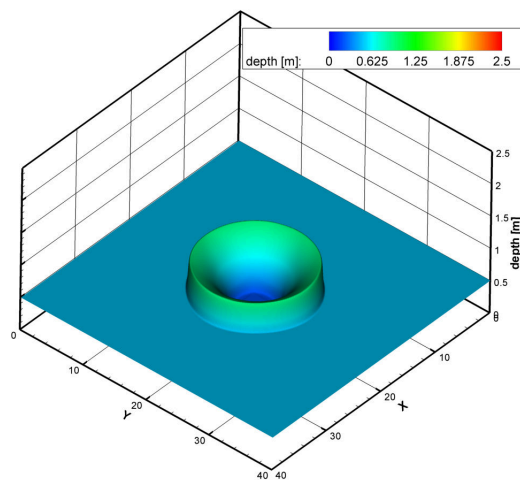


Figure 1.44 H_BP_5: Perspective view of the circular dam break wave patterns, $t=1.4s$

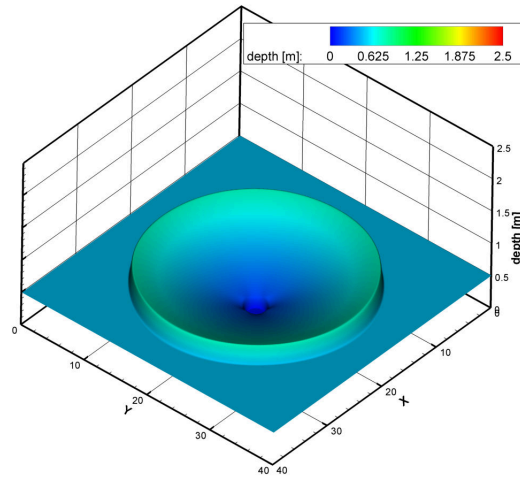


Figure 1.45 H_BP_5: Perspective view of the circular dam break wave patterns, $t=3.5s$

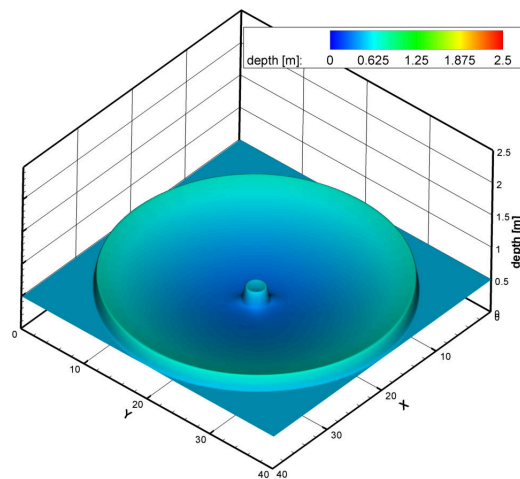


Figure 1.46 H_BP_5: Perspective view of the circular dam break wave patterns, $t=4.7s$

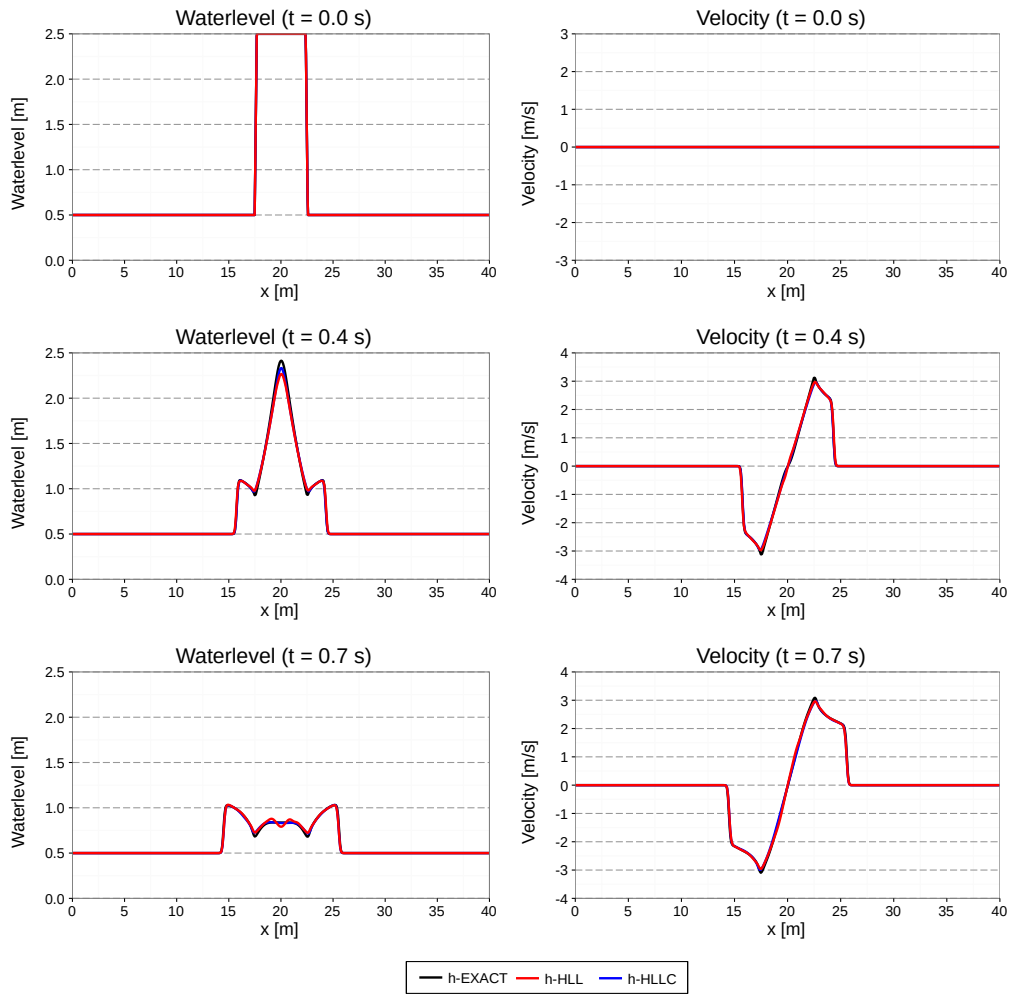


Figure 1.47 H_BP_5 : Water surface along $y=20$ m

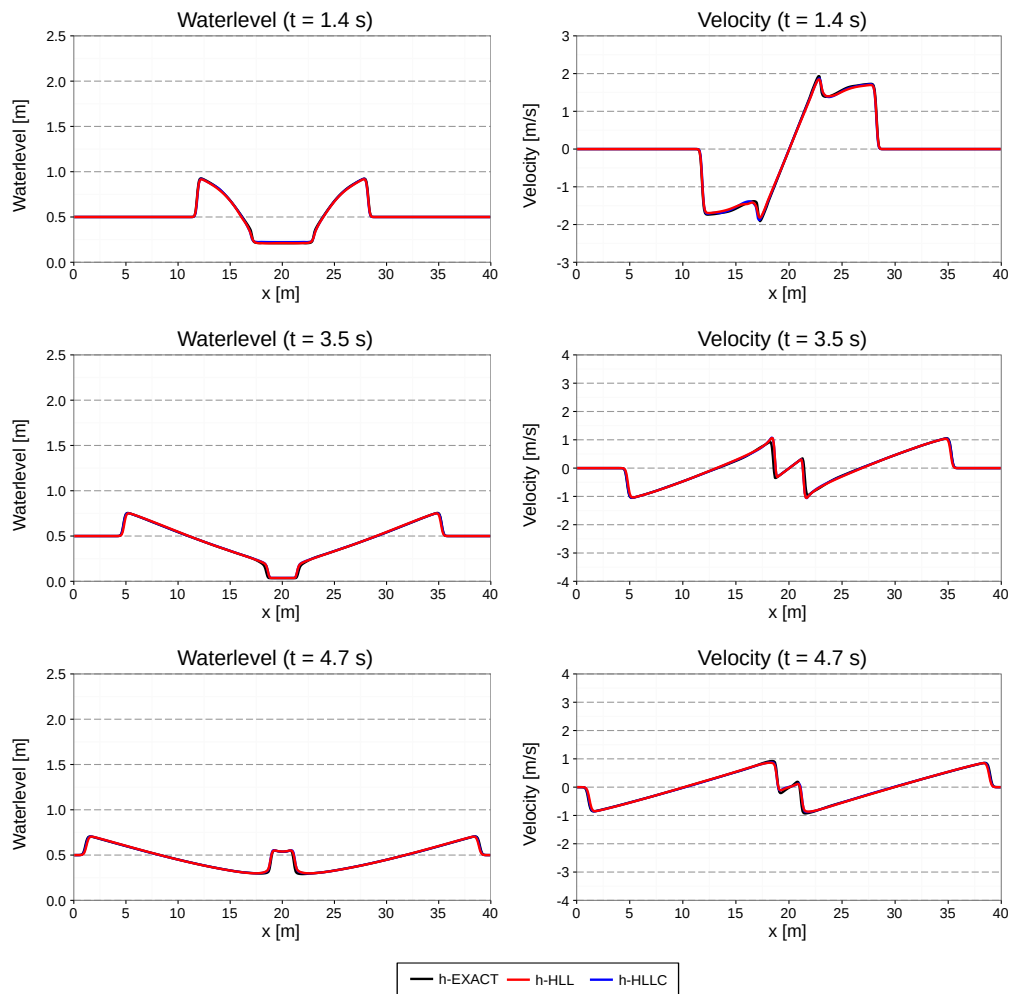


Figure 1.48 H_BP_5: Water surface along $y=20m$

2

Sediment Transport

2.1 Introduction

The test catalogue is intended for the validation of the program. The catalogue consists of different test cases, their geometric and hydraulic fundamentals and the reference data for the comparison with the computed results. The test cases are built up on each other going from easy to more and more complex problems. The sediment transport module is tested against some simple experimental test cases described in Section 2.2. Common test cases are suitable for both, 1-D and 2-D simulations. Specific test cases are intended for either 1-D or 2-D simulations.

2.2 Common Test Cases

2.2.1 ST_1: Soni et al: Aggradation due to overloading

2.2.1.1 Intention

This validation case is intended to reproduce equilibrium conditions for steady flow followed by simple aggradation due to sediment overloading at the upstream end. The test is suitable for 1-D and 2-D simulations and uses one single grain size.

2.2.1.2 Description

Soni et al. (1980) and Soni (1981) performed a series of experiments dealing with aggradations. With this particular test, they determined the coefficients a and b of the empirical power law for sediment transport. This test has been used by many researchers as validation for numerical techniques containing sediment transport phenomena (see e.g. Kassem and Chaudhry (1998), Soulis (2002) and Vasquez et al. (2005)).

The experiments were realized within a rectangular laboratory flume. First, a uniform equilibrium flow is established as starting condition. Then the overloading with sediment starts, resulting in aggradations.

2.2.1.3 Geometry and general data

Length of flume	l_f	20	[m]
Width of flume	w_f	0.2	[m]
Median grain size	d_m	0.32	[mm]
Relative density	s	2.65	[-]
Porosity	p	0.4	[-]

2.2.1.4 Equilibrium experiments

In total, a number of 24 experiments with different initial slopes S have been performed by Soni. Measured values are equilibrium water depth h_{eq} and the sediments equilibrium discharge $q_{B,eq}$. The flow velocity u_{eq} has been computed manually by Soni.

Concerning initial conditions for the equilibrium runs, “the flume was filled with sediment up to a depth of 0.15 m and then was given the desired slope”. The equilibrium is reached, when a uniform flow has established respectively “when the measured bed- and water surface profiles were parallel to each other.” In the average, the equilibrium needed about 4 to 6 hours to develop.

2.2.1.5 Boundary conditions

water flow: constant upstream flow discharge q_{in} and a weir on level 0 at the downstream end. Alternatively, a ghost cell may be used downstream, where the total flux into the last cell leaves the computational domain.

sediment: periodic boundary conditions are applied. The inflow $q_{B,in}$ upstream equals the outflow $q_{B,out}$ downstream.

From now on, we refer to the Soni test case #1, as the entire data for all experiments would go beyond the scope of this section. Measured data for the equilibrium are

q_{in}	4.0	$[m^3/(s \cdot m)] \times 10^{-3}$
S	3.56	$[-] \times 10^{-3}$
h_{eq}	5.0	$[m] \times 10^{-2}$
$q_{B,eq}$	12.1	$[m^3/(s \cdot m)] \times 10^{-6}$
u_{eq}	0.4	$[m/s]$

The establishment of the same equilibrium conditions is achieved by calibrating e.g. the hydraulic friction. As soon as the simulation data looks similar to the measured results, the aggradation can be started.

2.2.1.6 Aggradation experiments

After the equilibrium has been reached, the sediment feed was increased upstream by an overloading factor of $q_B/q_{B,eq}$. This factor is different for each experiment. For test case #1, it was set to 4.0. The flow discharge remains the same as in the equilibrium case. Due to the massive sediment overloading, aggradation starts quickly at the upstream end. Measured data is available for the bottom elevation at certain times.

2.2.2 ST_2 : Saiedi

2.2.2.1 Intention

Similar to the Soni test case, this validation deals with aggradation due to sediment overloading. However, compared to Soni, the sediment input is considerably greater than the carriage capacity of the flow and an aggradation shock is forming. The test verifies whether the computational model can handle shocks within the sediment phase. Again, a single grain size is used.

2.2.2.2 Description

The experiments were conducted in a laboratory flume located at the Water Research Laboratory, School of Civil Engineering, University of New South Wales, Australia. Geometric details and results are reported in Saiedi (1981a) and Saiedi (1981b). Saiedi did two separate tests, one in a steady flow and one in a rapidly unsteady flow with varying sediment supply. Only the steady case is of our interest here.

2.2.2.3 Geometry and general data

The sediment used was of fairly uniform size with the median grain size $d_{50} = 2$ mm, relative density $s = 2.6$ and porosity at bed $p = 0.37$.

The test section was about 18 m long in a 0.61 m wide glass-sided flume with a slope of 0.1 %. The flow was fed with a sediment-supply of constant rate using a vibratory feeder. The sediment input rate was chosen to be greater than the transport capacity of the flow, therefore resulting in the formation of an aggradation shock sand-wave travelling downstream. The downstream water level was maintained constant by adjusting the downstream gate.

2.2.2.4 Calibration

Before starting the sediment feed, at first, the aim is a uniform flow which fulfils a measured flow discharge q and the corresponding water depth h . This can be achieved by adjusting e.g. the hydraulic friction coefficient from Manning n . From the experiments, Saiedi proposes a calibration estimate of $n=0.0136 + 0.0170 q$. Note that there is no sediment layer at the calibration phase.

As initial conditions, start with a fluid at rest and a uniform flow depth of $h_0 = 0.223$ m on the sloped flume. The flow feed rate upstream is constant at $q_{in} = 0.098$ m³/s. At the

downstream boundary, the water level is kept constant at $h = 0.223$ m “by adjusting the downstream gate”.

2.2.2.5 Aggradation

As soon as a uniform flow with constant water depth is established, the sediment feed upstream can be started. It remains constantly on $q_B = 3.81$ kg/min. The results for the steady state computation are available at $t = 30$ min and $t = 120$ min. To avoid cluttering, the plots of the measured bed levels have been averaged.

2.2.3 BeST_3 : Guenter

2.2.3.1 Intention

The Günter test series deals with degradation in a laboratory flume. The experiments were conducted using a multiple grain size distribution. The reported results allow for a validation of the bed topography and the behaviour of heterogeneous sediment transport models.

2.2.3.2 Description

Günter performed some tests at the Laboratory of Hydraulics, Hydrology and Glaciology at the ETH Zurich using sediment input with a multiple grain size distribution. His aim was to determine a critical median shear stress of such a grain composition.

Günter was interested in the behaviour of different grain classes but also in the steady ultimate state of the bed layer, when a top layer has developed and no more degradation occurs with the given discharge. As initial state, a sediment bed with a higher slope than the slope in the steady case is used. There is no sediment feed but a constant water discharge. The bed then starts rotating around the downstream end resulting in a steady, uniform state with an armouring layer.

The validation is based on the resulting bed topography and the measured grain size distribution of the armouring layer at the end of the simulation.

2.2.3.3 Geometry and general data

Guenter actually investigated several test cases with different grain compositions and boundary conditions. This test case corresponds to his experiment No.3 with the grain composition No.1.

The experiment was conducted in a straight, rectangular flume, 40 m long, 1 m width with vertical walls. At the downstream end, the flume opens out into a slurry tank with 8 m length, 1.1 m width and 0.8 m depth (relative to the main flume), where the transported sediment material is held back. The sediment bed has an initial slope of 0.25 % with an initial grain size distribution given by

d_g [cm]	Mass fraction [%]
0.0 - 0.102	35.9
0.102 - 0.2	20.8
0.2 - 0.31	11.9
0.31 - 0.41	17.5
0.41 - 0.52	6.7
0.52 - 0.6	7.2

2.2.3.4 Simulation procedure and boundary/initial conditions

First of all, the domain gets filled slowly with fluid until the highest point is wet. The weir on the downstream end is set such that no outflow occurs. After the bed is completely under water, the inflow discharge upstream is increased successively during 10 minutes up to the constant discharge of 56.0 l/s. At the same time, the weir downstream is lowered down to a constant level until the water surface elevation remains constant in the outflow area. There is no sediment inflow during the whole test.

Using this configuration, the bed layer should rotate around the downstream end of the soil. The experiment needed about 4 to 6 weeks until a stationary state was reached. The data to be compared with the experiment are final bed level and final grain size distribution.

2.3 BASEchain Specific Test Cases

2.3.1 ST_BC_1: Advection of suspended load

2.3.1.1 Intention

This test is intended to verify the quality of the advection schemes. The aim is to minimize the numerical diffusion even over long distances.

2.3.1.2 Description

In a rectangular channel with steady flow conditions the advection of the suspended material is observed, once for a vertical front of concentration (case A) and once for a concentration with a Gaussian distribution (case B). The Quickest, Holly-Preissmann and MDPM-Scheme are tested. The diffusion is set to 0 and there is no sediment exchange with the soil.

2.3.1.3 Geometry and initial conditions

- The computational area is a rectangular channel with 10 km length, 30 m width and a slope of 0.5 ‰. The cell width Δx is 40 m.
- The initial condition for the hydraulics is a steady discharge of 10 m³/s
- The initial conditions for the suspended load are the following:

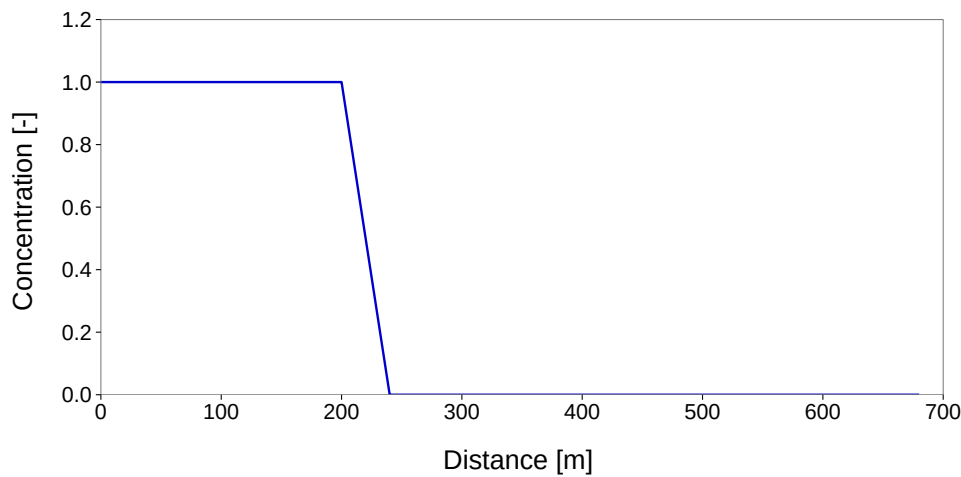


Figure 2.1 *ST_BC_1: Initial condition for case A*

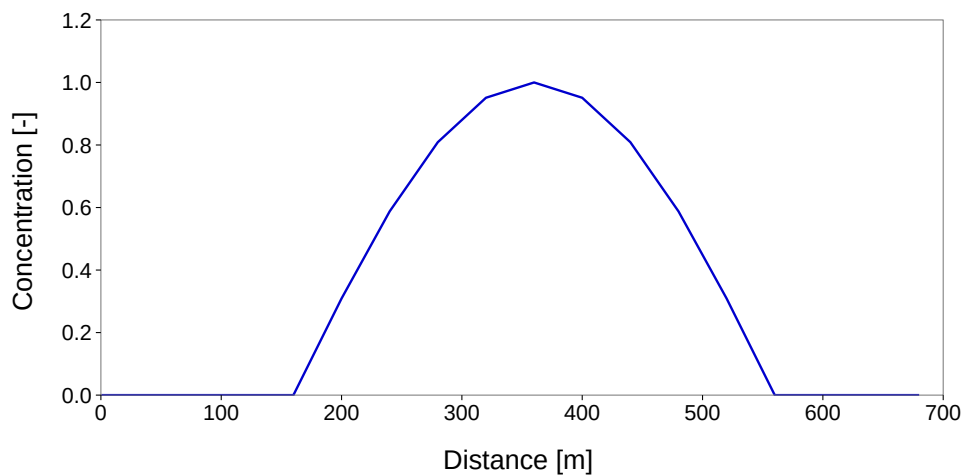


Figure 2.2 *ST_BC_1: Initial condition for case B*

Case A: The concentration is 1 for the first 200 meters of the flume and 0 for the rest.

Case B: The concentration has a Gauss-distribution on the upstream part of the flume.

2.3.1.4 Boundary conditions

- The friction expressed as k_{Str} is 80.
- The hydraulic upper Boundary is a hydrograph with steady discharge of $10 \text{ m}^3/\text{s}$.
- The hydraulic outflow boundary is h-q-relation directly computed with the slope.
- The upper boundary condition for suspended load is a constant inflow concentration of 1 for case A and 0 for case B.
- The lower boundary condition is an outflow concentration corresponding to the concentration in the last cell.

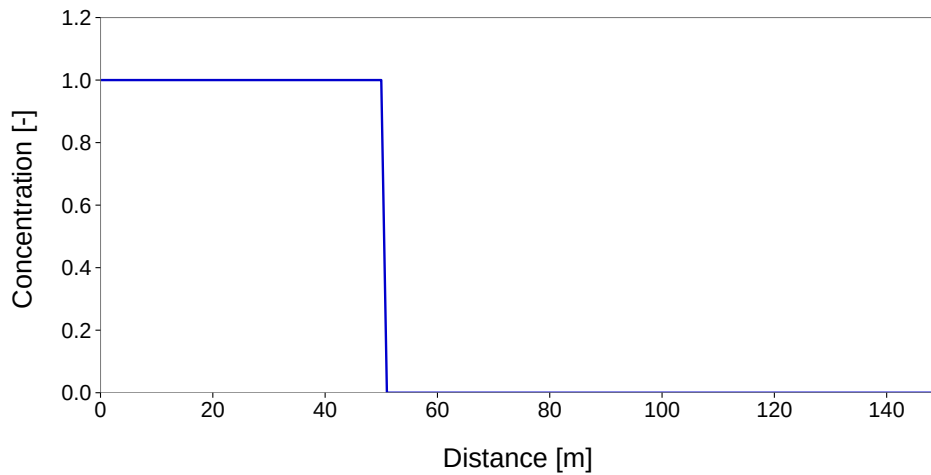


Figure 2.3 ST_BC_2: Initial condition for case A

2.3.2 ST_BC_2: Advection-Diffusion

2.3.2.1 Intention

This test is intended to verify the combination of advection and diffusion for suspended load for a given diffusion factor Γ .

2.3.2.2 Description

In a rectangular channel with steady flow conditions the behaviour of the suspended material is observed, once for a vertical front of concentration (case A) and once for a concentration with a Gaussian distribution (case B). The Quickest, Holly-Preissmann and MDPM-Scheme are tested. There is no sediment exchange with the soil.

2.3.2.3 Geometry and initial conditions

- The computational area is a rectangular channel with 1000 length, 20 m width and a slope of 1 ‰. The friction expressed as k_{Str} is 30. The cell width Δx is 1 m.
- The initial condition for the hydraulics is a steady discharge of 50 m³/s.
- The initial conditions for the suspended load are:

Case A: The concentration is 1 for the first 50 meters of the flume and 0 for the rest.

Case B: The concentration has a Gauss-distribution on the upstream part of the flume.

2.3.2.4 Boundary conditions

- The friction is expressed as k_{Str} is 30.
- The hydraulic upper boundary is hydrograph with steady discharge of 50 m³/s.
- The hydraulic outflow boundary is h-q-relation directly computed with the slope.

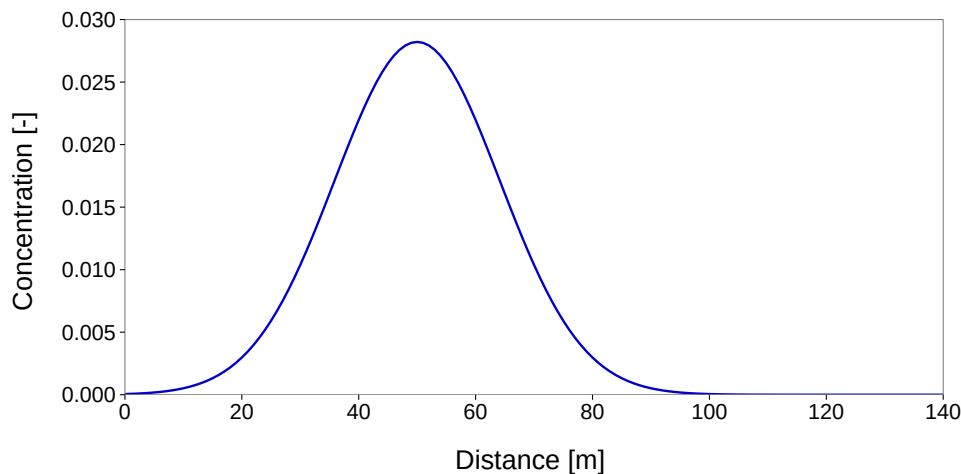


Figure 2.4 ST_BC_2: Initial condition for case B

- The upper boundary condition for suspended load is a constant inflow concentration of 1 for case A and 0 for case B.
- The lower boundary condition is an outflow concentration corresponding to the concentration in the last cell.

2.4 BASEplane Specific Test Cases

2.4.1 ST_BP_1: Advection of suspended load

2.4.1.1 Intention

This test is intended to verify the quality of the advection scheme. The aim is to minimize the numerical diffusion even over long simulation time or distance.

2.4.1.2 Description

In a rectangular channel with steady flow conditions the advection of the suspended material is observed, once for a vertical front of concentration (case A) and once for a concentration with a Gaussian distribution (case B). The MDPM-Scheme is tested. The diffusion is set to 0 and there is no sediment exchange with the soil.

2.4.1.3 Geometry and initial conditions

- The computational area is a rectangular channel with 1 km length, 10 m width and a slope of 7 ‰.
- The initial condition for the hydraulics is a steady discharge of 50 m³/s.
- The initial conditions for the suspended load are the following:

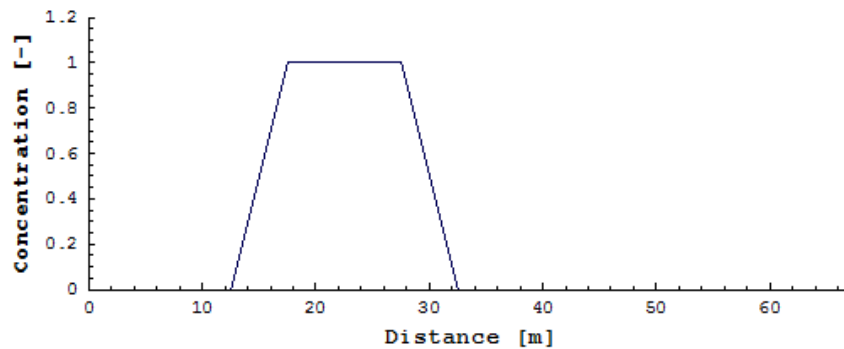


Figure 2.5 ST_BP_1: Initial condition for case A

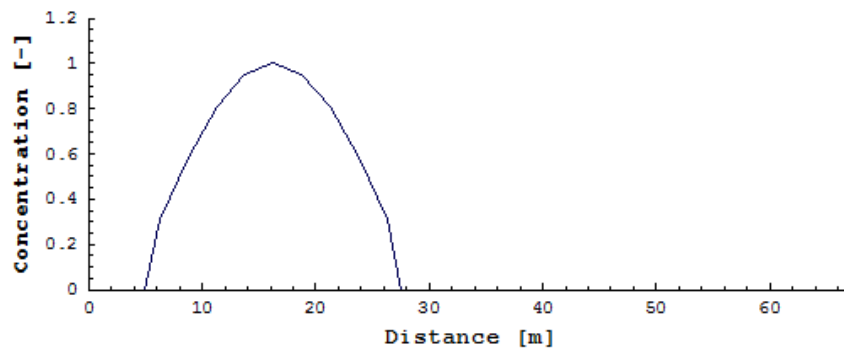


Figure 2.6 ST_BP_1: Initial condition for case B

Case A: The concentration is 1 for the first 30 meters at the upper end of the channel. During the simulation a constant sediment source is added to maintain between 15 and 20 meters from the upstream end to maintain a constant concentration.

Case B: The concentration has a Gauss-distribution on the upstream part of the flume.

2.4.1.4 Boundary conditions

- The friction is expressed as Manning factor n is 0.03.
- The upper boundary is a hydrograph with steady discharge of $50 \text{ m}^3/\text{s}$ with concentration 0.
- The hydraulic outflow boundary is zero_gradient.
- The lower boundary condition for suspended load is an outflow concentration corresponding to the concentration in the last cell.

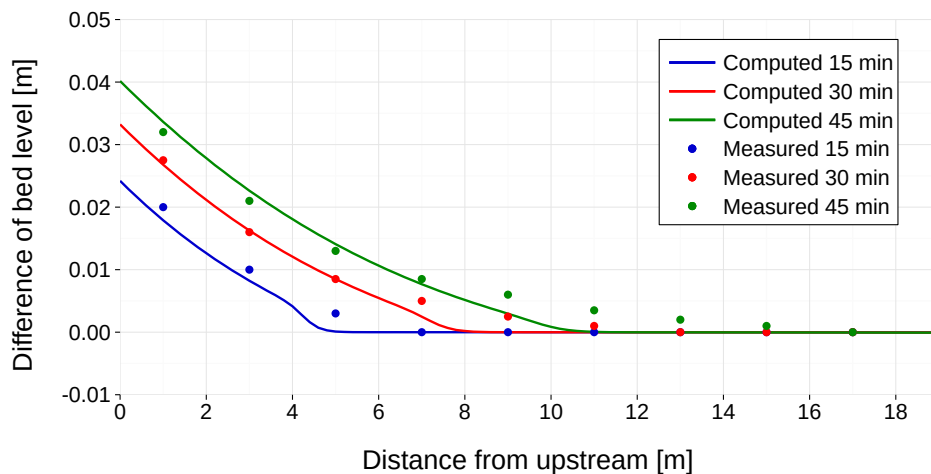


Figure 2.7 Soni Test with MPM-factor = 6.44 (BC)

2.5 Results

2.5.1 Common Test Cases

2.5.1.1 ST_1: Soni

2.5.1.1.1 Results obtained by BASEchain

The Soni test case has been simulated with the MPM approach like the one used for the next test case of Saiedi (see Section 2.2.2). As the equilibrium bed load of $2.42 \cdot 10^{-7} \text{ m}^3/\text{s}$ is known, the MPM-factor has been calibrated to obtain a good agreement for the equilibrium state. This leads to a value of 6.44 for the prefactor in the MPM-formula.

The results show a quite good agreement between experiment and simulation.

2.5.1.1.2 Results obtained by BASEplane

The Soni test case was modelled as single grain computation on a mobile bed with the transport formula of Meyer-Peter & Müller (MPM). The grain diameter is chosen as the mean diameter of the grain mixture used by Soni. The simulations were performed on an unstructured mesh with 1202 triangular elements.

In Soni's experiments at first an equilibrium transport was established within the laboratory flume. The corresponding transport rate observed by Soni is known to be $2.42 \cdot 10^{-7} \text{ m}^3/\text{s}$. Then the sediment inflow was increased to 4 times the equilibrium transport.

To be able to reproduce the experiments, the transport formula must be calibrated to achieve the same equilibrium transport rate. The calibration resulted in a reduction of the pre-factor of the MPM formula from 8 to about 3.3. The critical dimensionless shear stress for incipient motion in the MPM formula is not calibrated here and therefore, per default, determined from the Shields diagram.

The numerical results for the bed aggradations and the water levels are compared with the measurements by Soni. The situations after 15min, 30min and 40min are plotted in the following figures. Generally the numerical results show an acceptable agreement

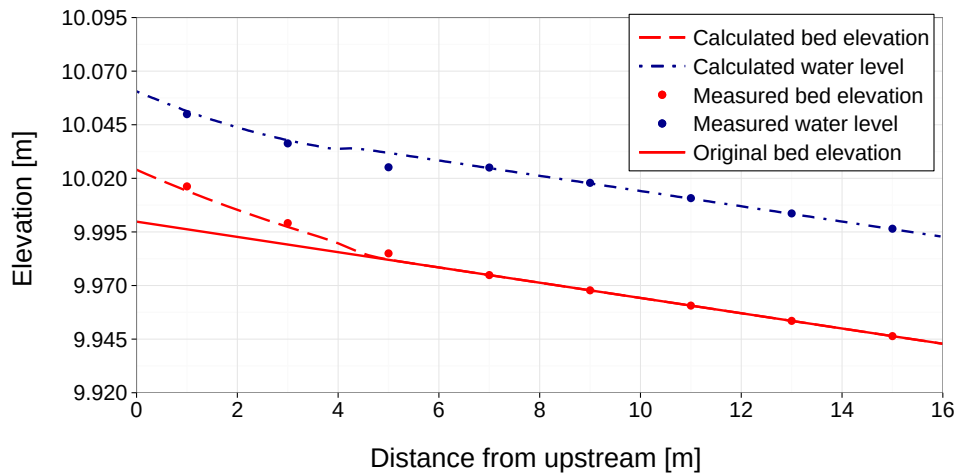


Figure 2.8 *ST_1: Soni Test – Bed aggradation and water level after 15 min (BP)*

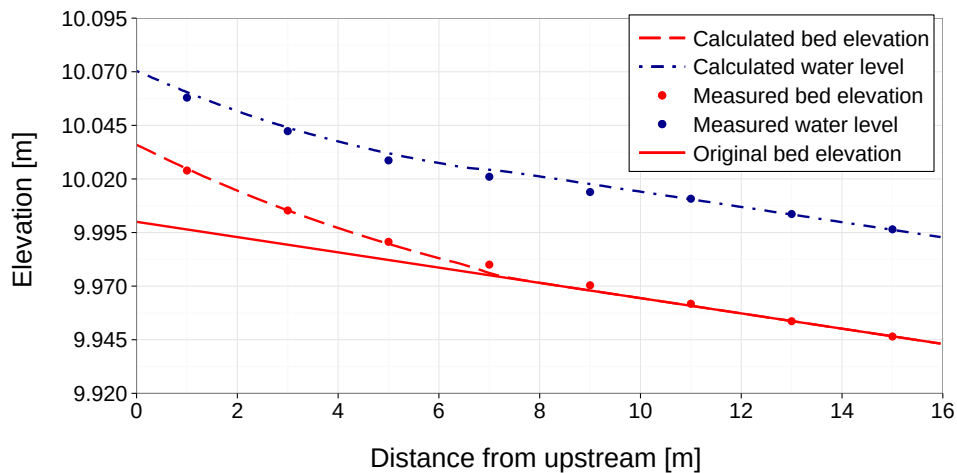


Figure 2.9 *ST_1: Soni Test – Bed aggradation and water level after 30 min (BP)*

with the measured values. Compared to the measurements, the toe of the aggradation front shows a less diffusive smearing behaviour. This may be attributed to the finer grain fractions within Soni’s grain mixtures, whose behaviour is not adequately modelled in single grain computation. Also the rather fine diameter of 0.32 mm can be seen as problematic concerning the applicability of the MPM formula, which is best suited for coarse sands and gravel.

2.5.1.2 ST_2: Saiedi

2.5.1.2.1 Results obtained by BASEchain

The Saiedi test was simulated using the Meyer-Peter Müller approach for the sediment flux, which can also be formulated as:

$$q_B = factor(\theta - \theta_{cr})^{3/2} \sqrt{(s-1)gd_m^{3/2}}$$

The factor is usually set around 8.0 and should be between 5 and 15 (Wiberg and Smith,

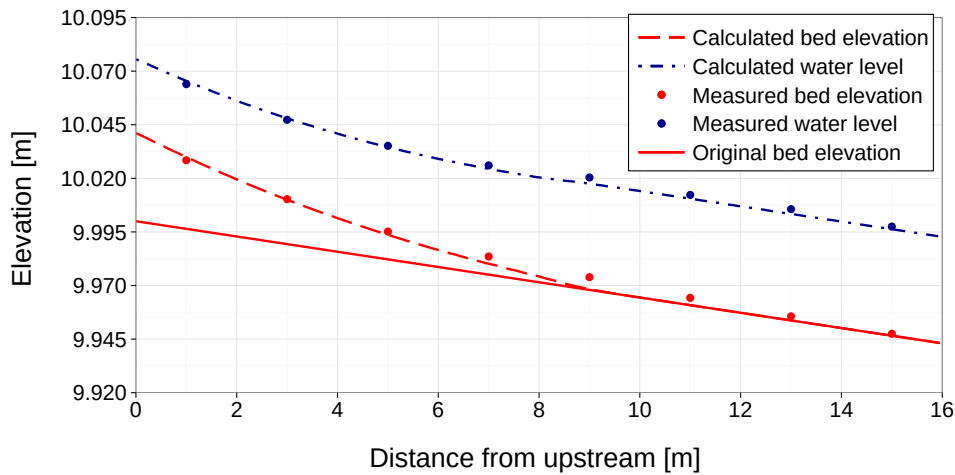


Figure 2.10 *ST_1: Soni Test – Bed aggradation and water level after 40 min (BP)*

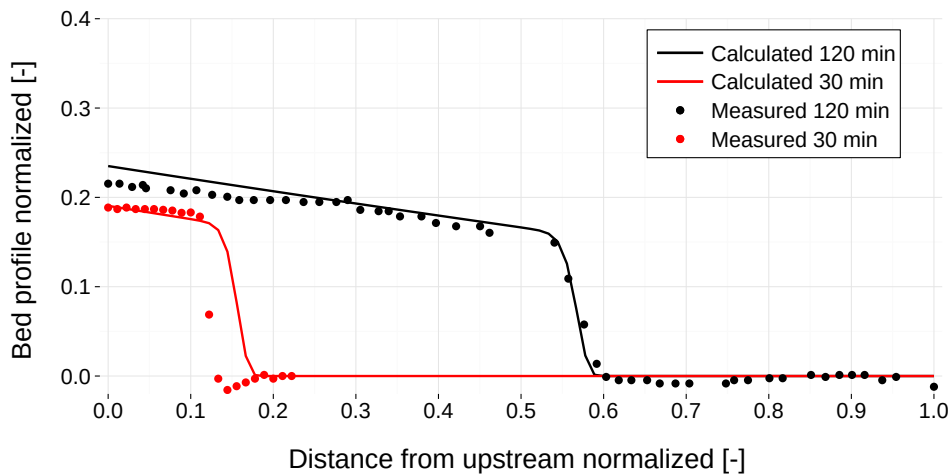


Figure 2.11 *Saiedi Test, with MPM-factor = 13 (BC)*

1989). In this case it was calibrated to 13.

The results present a good fit. This example shows that, to reproduce this type of transport, the approach of MPM approach needs calibration.

2.5.1.2.2 Results obtained by BASEplane

The Saiedi test case was simulated using a single grain approach on an unstructured mesh made of 768 triangles. The Meyer-Peter & Müller formula was used to determine the bedload transport. The simulation was performed on a fixed bed, where no erosion can take place.

To obtain a reasonable fit between the measured values and the simulation results the pre-factor of the transport formula again had to be reduced from 8 to about 5. Furthermore, the simulations show that the sediment is transported too rapidly out of the flume compared to the experiments. To compensate for this effect the critical Shields factor for incipient motion is increased to 0.055, instead of using the value from the Shields diagram.

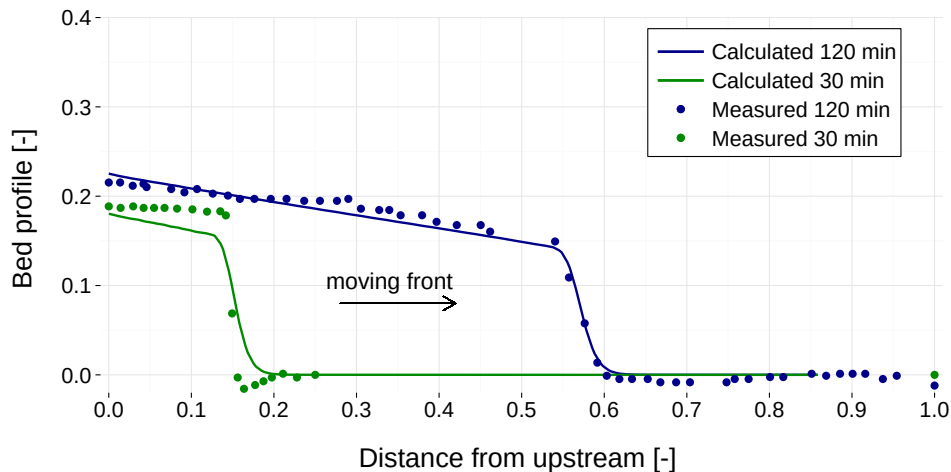


Figure 2.12 *ST_2 : Saiedi Test, propagation of sediment front (BP)*

With these adjustments, the shape and the propagation speed of the sediment front are captured well and Saiedi's results can be reproduced with good accuracy. The front of the sediment bore does not smear over the time but remains steep during the propagation.

2.5.1.3 ST_3: Guenter

2.5.1.3.1 Results obtained by BASEchain

For mixed materials, the Guenter test case has been performed. The initial slope was chosen to be 0.25 % - this corresponds to the full experiment of Guenter.

The eroded material is eliminated from the end basin by a sediment sink. The active layer height is 5 mm and the critical dimensionless shear stress (for beginning of sediment transport) is set to the default value of 0.047. After 200 hours, there are no more important changes recognizable. After the results of Guenter the slope at the final equilibrium state should be the same as the initial one.

The final slope in the numerical model is in good agreement with the final slope observed in the physical experiment. Moreover the grain sorting effect can be modelled quite well. The final grain size distribution is slightly coarser than the observed grain size distribution in the physical model (Figure 2.14).

There are many parameters which influence this result, especially the choice of the critical shear stress and the active layer thickness. Again, this example shows, one has to use different approaches for sediment transport with different values for the free parameters. Quite often, a sensitivity analysis may give a better insight in the behaviour of certain formulas and their parameters.

2.5.1.3.2 Results obtained by BASEplane

The Guenter test has been numerically modelled with 6 different grain classes. The sediment transport capacity has been determined with Hunziker's formula for graded transport. The critical dimensionless shear stress for beginning of sediment transport is set to the default value of 0.047 in Hunziker's formula. This bedload formula was not further adjusted for

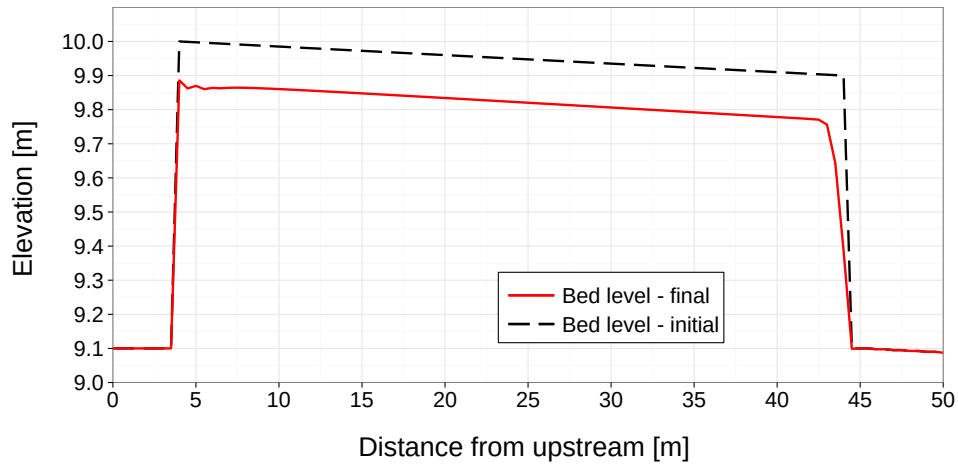


Figure 2.13 ST_3: Guenter Test: equilibrium bed level (BC)

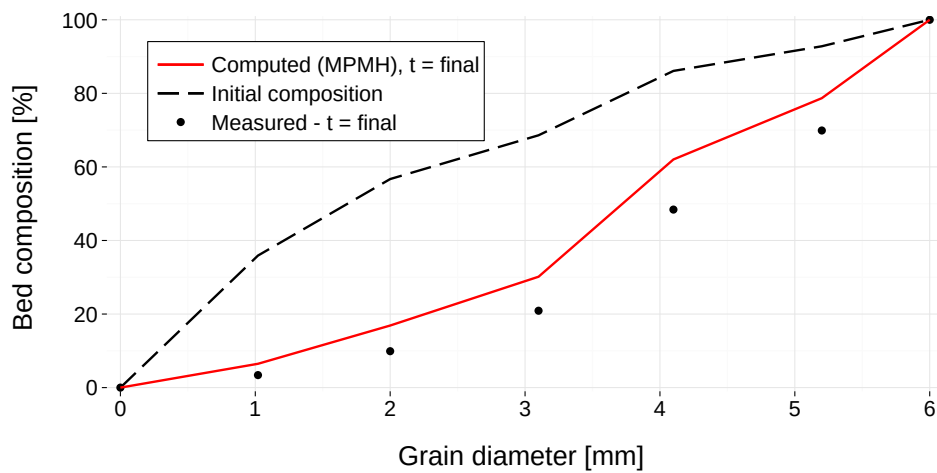


Figure 2.14 ST_3: Guenter Test: grain size distribution (BC)

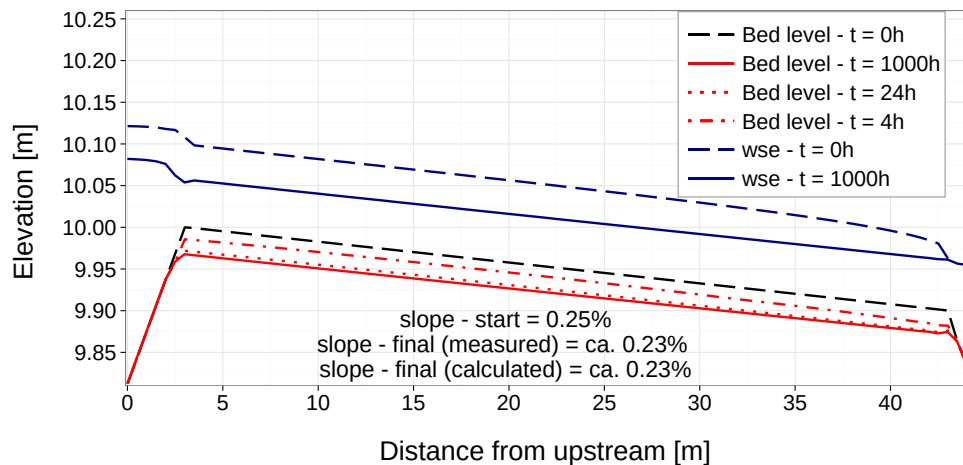


Figure 2.15 *ST_3: Guenter Test: equilibrium bed level (BP)*

the simulations and used with its default values for the pre-factor ($=1.0$) and the exponent of the hiding exponent ($=-1.5$).

The experimental flume has a mobile bed and is modelled with 312 rectangular elements. The channel parts in front and behind the experimental flume, are set to fixed bed elevations in this simulation. The sediment which leaves the mobile bed and enters the fixed bed section is removed using a sediment sink. The thickness of the bedload control volume is set to a constant value of 5 mm. The choice of the thickness of the bedload control volume shows large impacts on the simulation results. An increased thickness here results in larger erosion and a finer composition of the final bed armour.

The mobile bed is eroded during the simulation until finally an armouring layer of coarser materials is formed which prevents further erosions. The final slope of the bed is nearly constant with a value of 0.23%, which is slightly smaller than the original slope of 0.25%. This result is in agreement with the observations made by Guenter. Also the rotation of the bed surface around the downstream end of the flume can be observed during the simulation.

Figure 2.16 shows the measured and computed grain compositions, whereas the latter was taken from the upstream end of the flume. The simulated grain size distribution (red curve) shows a good qualitative agreement with the measured distribution by Guenter (blue dots). But a trend can be seen that the computed composition is slightly too fine. Finally, it can be said, that the numerical model seems capable of reproducing the sorting effects and seems able to simulate the formation of an armouring bed layer.

Beside the results obtained with the Hunziker's transport formula, Figure 2.16 presents also the resulting grain distributions obtained with Wu's transport formula (green curve). Here it can be seen that the finer fractions are eroded too strongly, but a qualitative agreement is obtained. For the simulations with the Wu formula the same critical shear stress of 0.047 was used, and the default settings of the bed load factor ($=1.0$) and the default exponent of the hiding-and exposure coefficient ($=-0.6$) were set. But to enable similar erosion volumes as obtained with the Hunziker's formula, the thickness of the bed load control volume was increased to 2.5 cm.

To check for the mass conservation properties a comparison was made between the initial

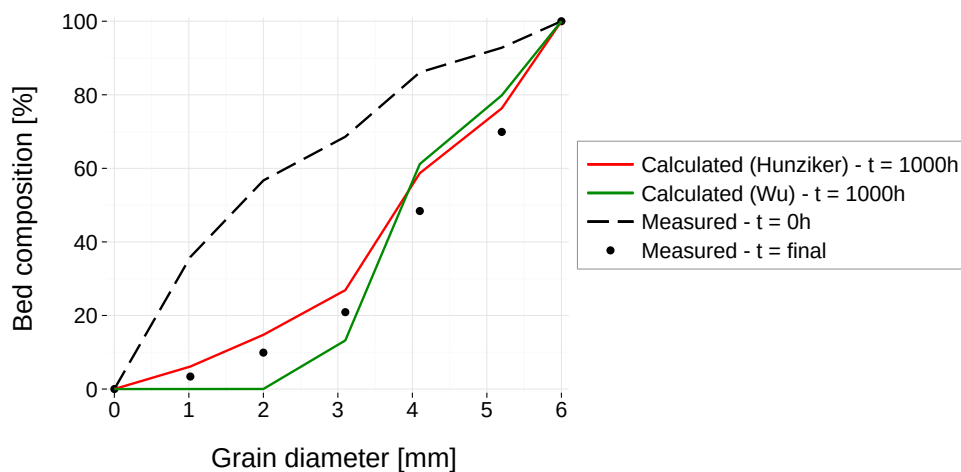


Figure 2.16 ST_3: Guenter Test: grain size distribution (BP)

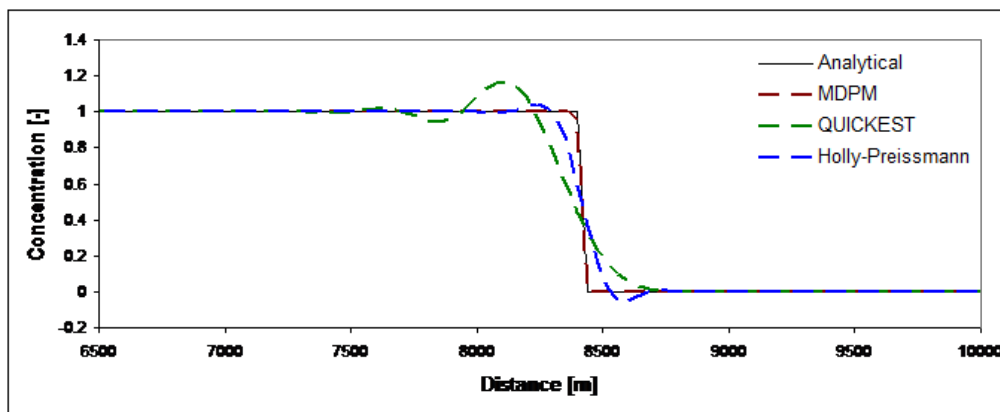


Figure 2.17 ST_BC_1: case A, concentration after 9060 s

sediment volumes in the flume and the final sediment volumes, under regard of all removed sediment volumes. Despite the long run time, the simulation proves to be conservative regarding the sediment transport. Since the experiment has a constant inflow rate and quasi-steady flow conditions, the ‘hydro_step’ approach can be used here which allows a reduction of several orders of magnitude in simulation time.

2.5.2 BASEchain specific Test Cases

2.5.2.1 ST_BC_1: Advection of suspended load

The advection test has been executed for the QUICK, the QUICKEST, the Holly-Preissmann and the MDPM-scheme. The results of the QUICK-scheme are not illustrated as they are very instable.

Case A: Figure 2.17 shows the concentration front after 9060 s or after 8200 m of way. The results show that the big issue of the advection simulation, the numerical diffusion, is almost completely avoided by the MDPM scheme.

Case B: Figure 2.18 shows the concentration front after 9772.5 s or after 8843 m of way. For

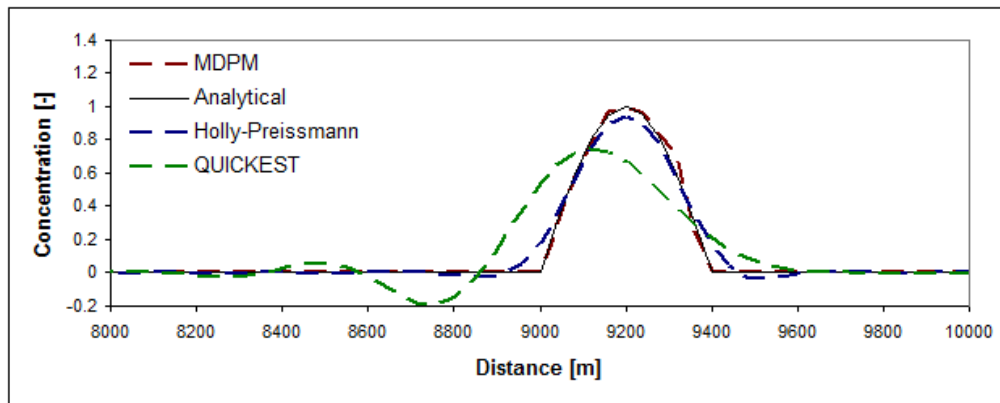


Figure 2.18 ST_BC_1: case B, concentration after 9772.5 s

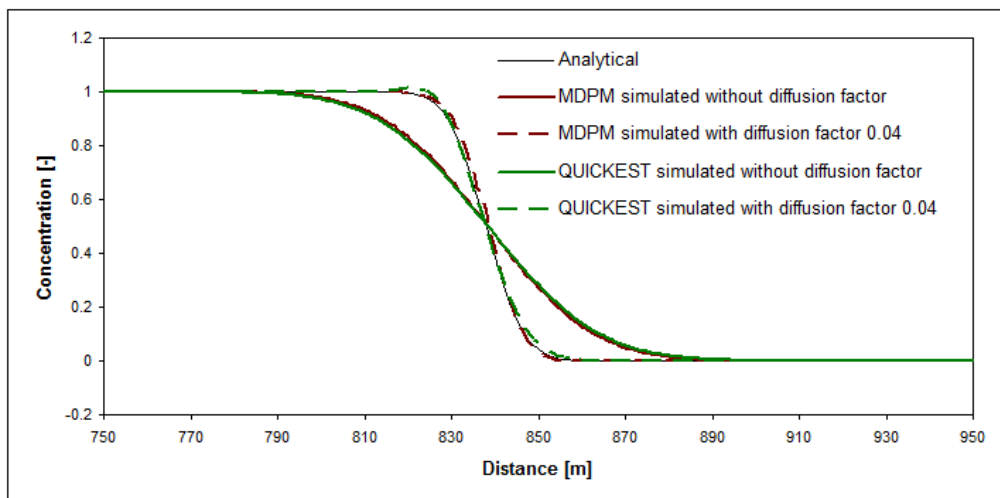


Figure 2.19 ST_BC_2: case A, concentration after 605 s

the MDPM scheme there are some local deviations from the analytical solution. These are due to the discretisation and do not increase with time and distance. The initial maximal concentration is conserved.

2.5.2.2 ST_BC_2: Advection-Diffusion

The Advection Test has been executed for the QUICKEST, and the MDPM-scheme. Figure 2.19 and Figure 2.20 show the concentration front of case A and the Gauss distribution for case B after 605 s or after 788 m away. The diffusion factor is 0.04 for case A and 0.1 for case B. The result of the simulation with the internally computed diffusion is also illustrated, but there is no analytical solution to compare.

The results are satisfying. The QUICKEST scheme gives here a result which is nearly as good as the one of the MDPM scheme, but this is due to the short simulation time. Its deviation from the exact solution due to numerical diffusion increases with the time like shown in test ST_BC_1.

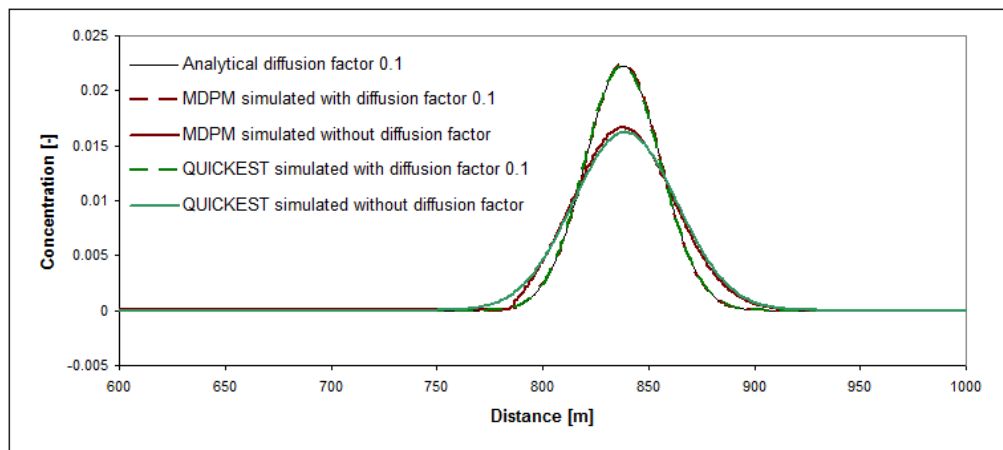


Figure 2.20 ST_BC_2: case B, concentration after 605 s

2.5.3 BASEplane specific Test Cases

2.5.3.1 ST_BP_1: Advection of suspended load

To test the advection of suspended sediment transport, the MDPM-scheme has been applied.

Case A: Figure 2.21 shows the concentration front after 200 s or after 730 m of distance travelled. The results show that there is no oscillation before and after the front. The diffusion is small and mainly due to the irregular discretisation.

Case B: Figure 2.22 shows the concentration front after 200 s or after 700 m of distance travelled. The maximum of the Gauss distribution is conserved and there are no oscillations near the steep gradients.

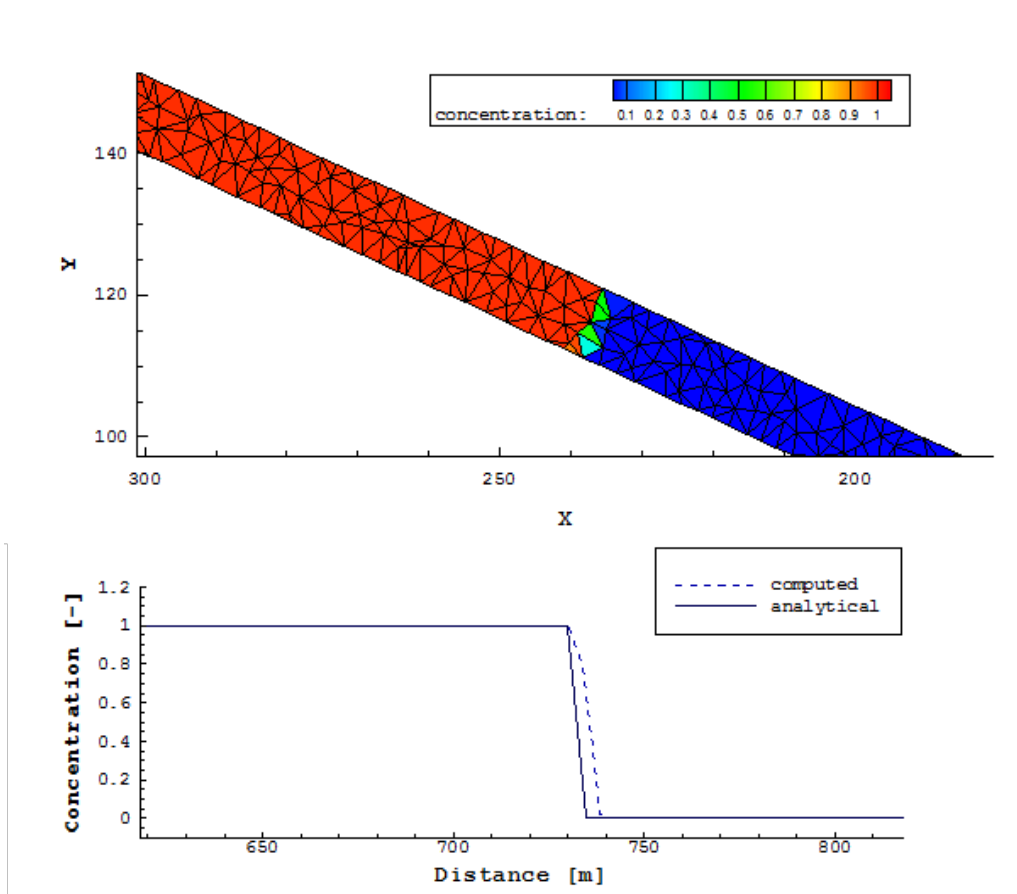


Figure 2.21 ST_BC_1: case A, concentration after 200 s

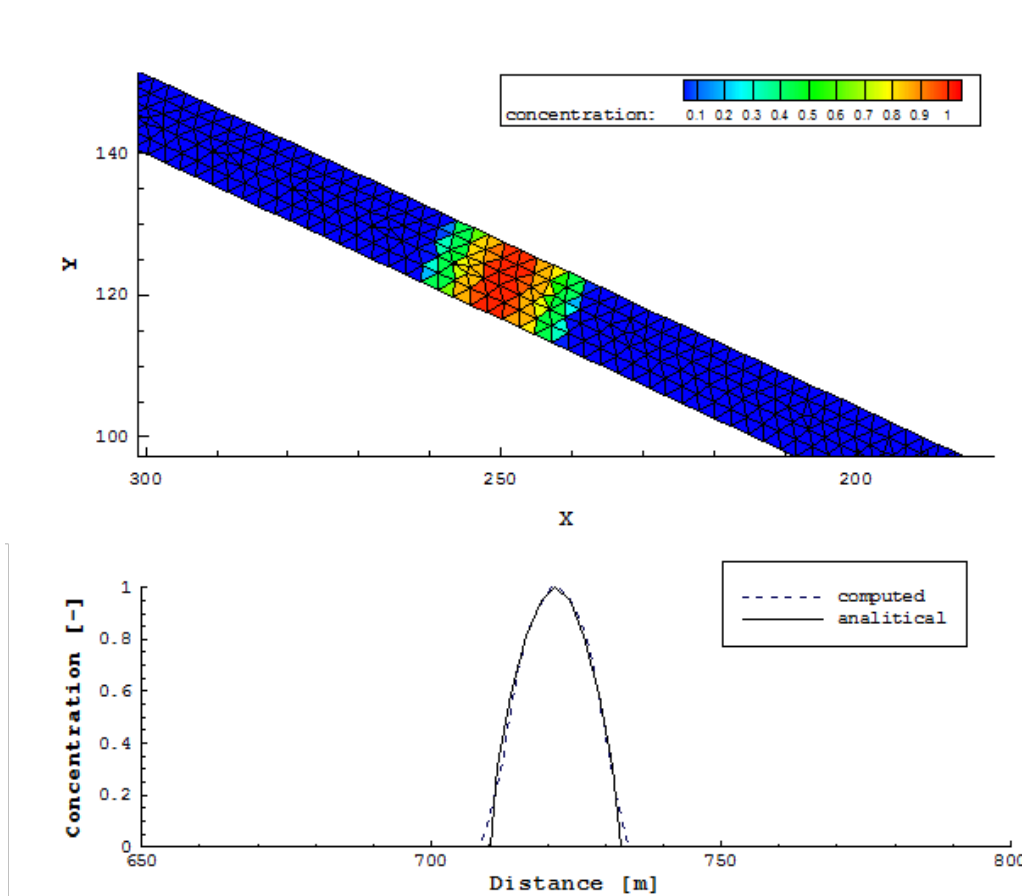


Figure 2.22 ST_BP_1: case B, concentration after 200 s

Model Coupling

3.1 Coupling of Domains of Same Type

3.1.1 COUPL_1: Sequential two-way coupling with backwater effects

3.1.1.1 Intention

This test is intended to verify and test the coupling mechanism of a sequential coupling with mutual data exchange between the sub-domains.

3.1.1.2 Description

Two sub-domains are simulated in a combined simulation. Sub-domain A is situated upstream of sub-domain B (Figure 3.1). Both sub-domains are coupled using a two-way coupling mechanism via an outflow hydrograph boundary and an inflow hydrograph boundary. Discharges are passed to the downstream sub-domain and water surface elevations are passed in upstream direction. Backwater effects travel in direction of the upstream sub-domain, caused by an outflow weir at the downstream end.

3.1.1.3 Geometry and initial conditions

- Case A: 1-D \rightarrow 1-D coupling
Both channels have trapezoidal cross sections and 1 km length, 40 m base width and a slope of 1.25 ‰.
- Case B: 2-D \rightarrow 2-D coupling
Both channels have rectangular cross sections, 1 km length, 40m width and a slope of 1.25 ‰.
- Initially the sub-domains are dry.

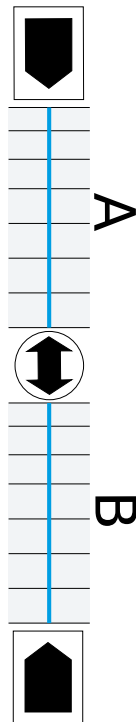


Figure 3.1 Sub-domains A and B

3.1.2 COUPL_2: River network modelling

3.1.2.1 Intention

This test is intended to verify and test the coupling mechanism of a junction and a bifurcation in a simple river network configuration.

3.1.2.2 Description

Five sub-domains are simulated in a combined simulation (Figure 3.2). Sub-domains A and D are situated upstream and have an inflow hydrograph defined. Both river branches merge together into the sub-domain B. At its downstream end sub-domain B splits up into sub-domains E and C. The junction and the bifurcation are simulated with one-way couplings, i.e. the upstream sub-domains are not influenced by the water elevations in the downstream sub-domains.

3.1.2.3 Geometry and initial conditions

- All channels have trapezoidal cross sections, 1 km length, 40 m base width and a slope of 1.25 ‰.
- Initially all sub-domains are dry.

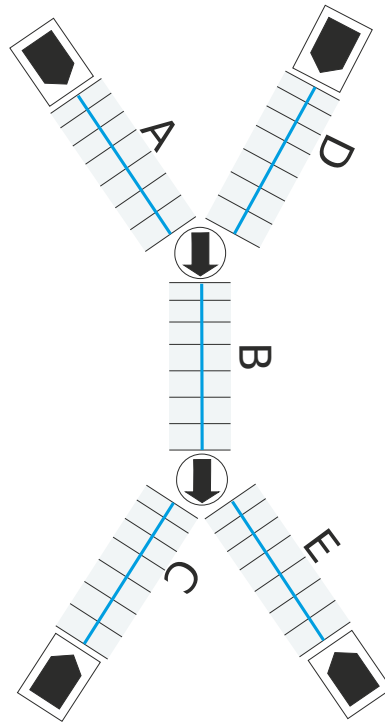


Figure 3.2 Five sub-domains

3.1.3 COUPL_3: Sequential coupling with sediment transport

3.1.3.1 Intention

This test is intended to verify and test the coupling mechanism of a sequential coupling in a morphological simulation with bed load and suspended load transport.

3.1.3.2 Description

Sub-domain A is situated upstream of sub-domain B (Figure 3.1). Both sub-domains are coupled using a 1-way coupling mechanism via an outflow h_q -relation boundary and an inflow hydrograph boundary. Both sub-domains simulate single grain bed load transport. The bed load and suspended load are exchanged over the sequential coupling using corresponding outflow and inflow boundary conditions. At the upstream end of sub-domain A discharge, bed load and suspended load enter with constant rates.

3.1.3.3 Geometry and initial conditions

- Both channels have trapezoidal cross sections and 1 km length, 40 m base width and a slope of 1.25 ‰.
- The initial conditions for the hydraulics are uniform flow conditions in both sub-domains.
- The initial conditions for the bed load transport are set to equilibrium conditions (using IODown and IOup boundary conditions).

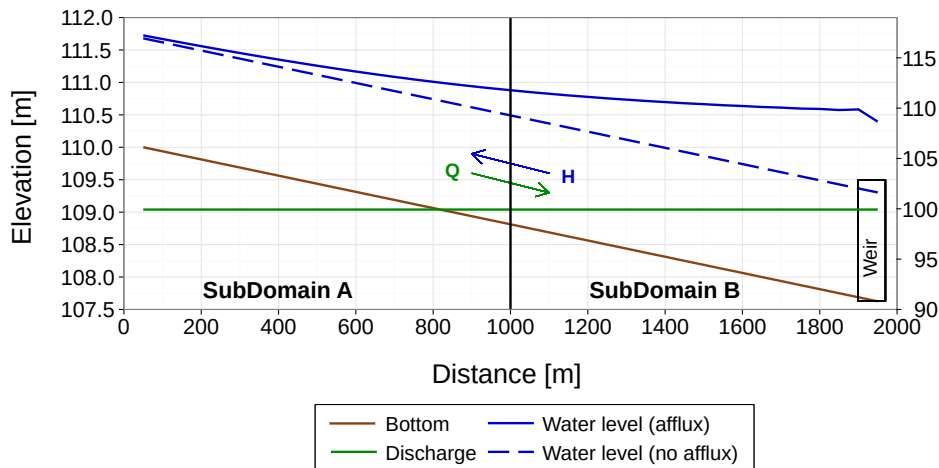


Figure 3.3 *COUPL_1_BC: Water surface elevation and discharge profiles of coupled BASEchain sub-domains A and B*

- The initial condition for the suspended sediment transport is set to concentration 0.0.

3.2 Results

3.2.1 Coupling Test Cases for Domains of Same Type

3.2.1.1 COUPL_1: Sequential two-way coupling with backwater effects

3.2.1.1.1 COUPL_1_BC: Results obtained by BASEchain

The coupling test case has been simulated starting from dry conditions in sub-domains A and B. Discharge is passed into downstream direction and water surface elevations are passed into upstream direction (two-way coupling).

After some time steady state conditions are reached in the coupled simulation. The backwater curve travels seamlessly from the downstream sub-domain into the upstream sub-domain. The discharge is constant over the whole domain. This indicates a correct two-way coupling which is capable to consider backwater effects from downstream.

3.2.1.1.2 COUPL_1_BP: Results obtained by BASEplane

As in the 1-D case, this coupling test case has been simulated starting from dry conditions in sub-domains A and B. Discharge is passed in downstream direction and water surface elevations are passed in upstream direction (two-way coupling).

After some time steady state conditions are reached in the coupled simulation. The backwater curve again enters seamlessly the upstream sub-domain. The velocity has no jumps at the interface between the sub-domains and it reduces in direction of the downstream weir.

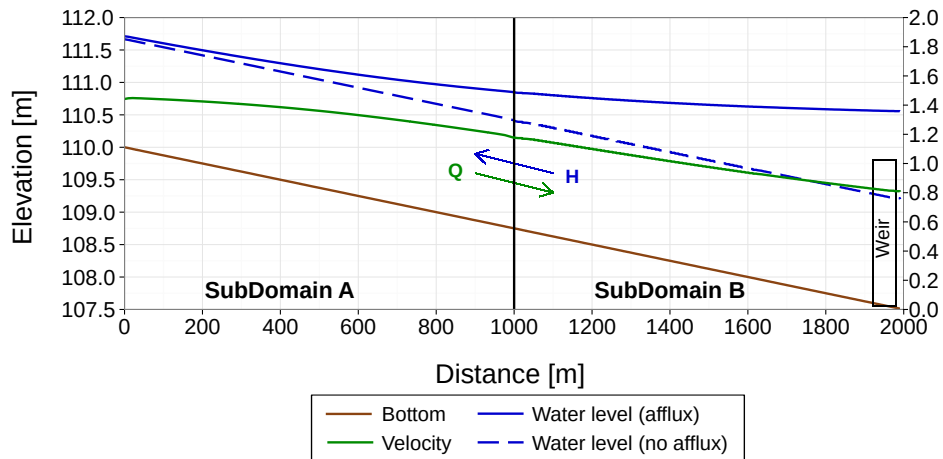


Figure 3.4 *COUPL_1_BP*: Water surface elevation and discharge profiles of coupled BASEplane sub-domains A and B

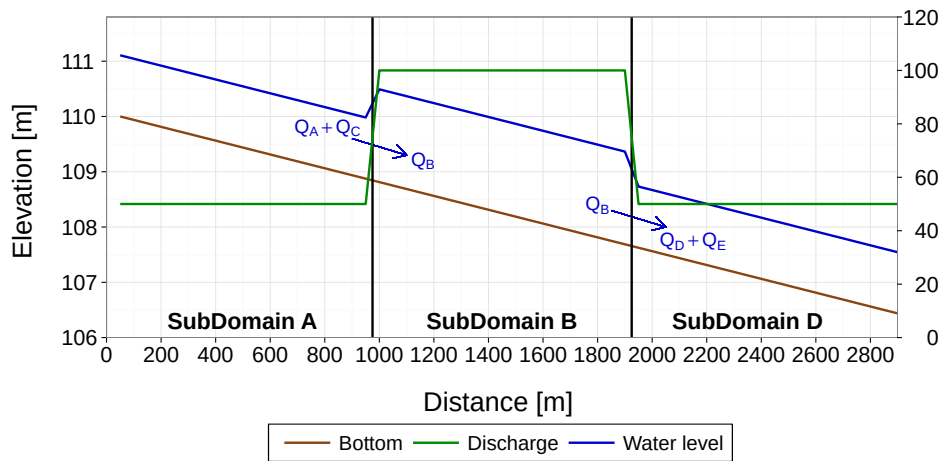


Figure 3.5 *COUPL_2*: Water surface elevation and discharge profiles in the coupled river network

3.2.1.2 COUPL_2: River network modelling

This test case has been simulated starting from dry conditions in all sub-domains. Sub-domains A and C have inflow hydrographs defined and sub-domains D and E have uniform outflow conditions defined. The discharge is passed in downstream direction using a one-way coupling, i.e. influences of downstream water levels are neglected here.

Figure 3.5 shows steady state conditions reached in the coupled simulation. The discharges leaving sub-domains A and C flow together at a junction and pass their discharge into sub-domain B. Sub-domain B splits up into two downstream sub-domains D and E (Figure 3.2). The mass conservation is fulfilled in this simulation and the discharges are distributed correctly among the sub-domains. The water levels show jumps at the coupling interfaces because their influence on the upstream sub-domains was neglected here.

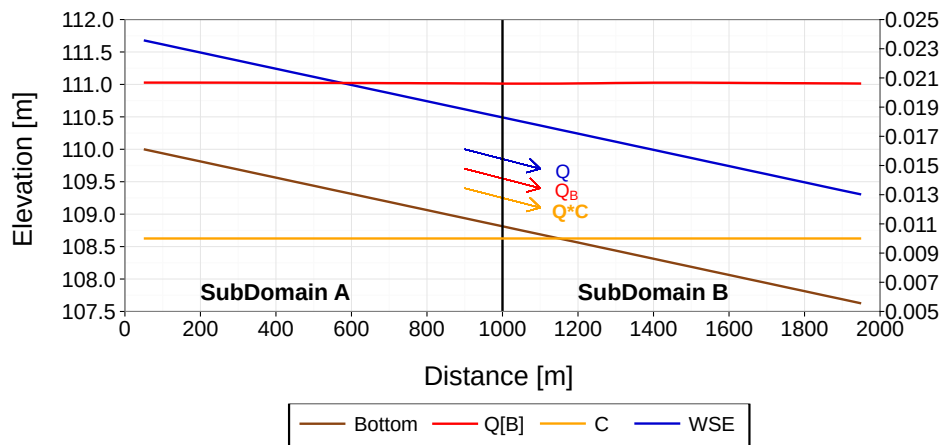


Figure 3.6 *COUPL_3: Bed load transport rate and concentration profile of coupled BASEchain sub-domains A and B*

3.2.1.3 COUPL_3: Sequential coupling with sediment transport

The sub-domains have been simulated starting from uniform flow conditions. Discharge, transported bed load and suspended loads are passed from the upstream sub-domain into downstream direction via boundary conditions. Inflowing discharge and inflow concentration profiles are constant over time. The bed load inflow is set in a way that equilibrium transport is achieved.

The simulation is run until steady state conditions are reached. As can be seen in Figure 3.6, the bed load transport rate is nearly constant in both sub-domains. Also the concentration profiles are the same in the upstream and downstream sub-domains and equal the input concentration profile.

Subsurface Flow

4.1 BASEsub1: Saturated, confined water flow in soil

As a first test case a steady-state subsurface flow on a mesh of $1 \times 0.1 \times 1$ m extension is selected with a cell size of $\Delta x = 0.01$ m. The soil's hydraulic conductivity is set to $k_f = 0.001$ m/s in the computational domain.

At the west boundary a hydrostatic pressure head of $h_w = 5$ m is set as boundary condition. At the east boundary a hydrostatic pressure head of $h_e = 2$ m is set. The other boundary cells are treated as bounce-back boundaries. The numerical constant ϑ is set to 3 and the time step size is selected as $\Delta t = 1$ s. This configuration results in a confined subsurface flow with constant pressure gradient of $\partial h / \partial x = 3$.

The obtained results are illustrated in Figure 4.1, for a cross sectional cut along the y-axis through the domain. The model is able to reproduce the analytical linear gradient of the pore-water pressure head within the domain.

4.2 BASEsub2: Water infiltration into partially-saturated soil

To test the flow in the partially-saturated zone, the unsteady downward propagation of an infiltration front is simulated. This test case was chosen as described by Vogel et al. (2001), in order to allow for comparison with their results obtained with a FE-model. The same test was also successfully modelled with a LBM-approach by Ginzburg et al. (2004).

The domain is discretized with $1 \times 0.1 \times 1$ m extension. The cell size is set to $\Delta x = 0.01$ m. As retention model the approach after Van-Genuchten and Mualem (VGM) is applied. The soil parameters are chosen as $\alpha = 0.8$ 1/m and $n_\nu = 1.09$ based on the tabulated values given in Vogel et al. (2001). The hydraulic conductivity is set to $k_f = 5.55 \text{E-}7$ m/s. A negative hydrostatic pore-water pressure distribution (= soil suction) is set as initial condition with a total head of $h_w + z = -10$ m. At the top of the domain a constant infiltration source

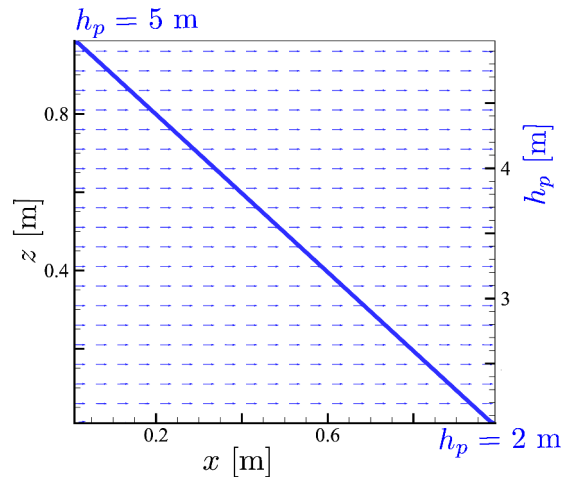


Figure 4.1 BASEsub1: Saturated confined flow through homogenous domain with linear pore-water pressure gradient.

is placed with $q_{inf} = 2.78\text{E-}7$ m/s, leading to the formation of an infiltration front. The moisture-formulation is used with $\vartheta = 3$ and a time step size of $\Delta t = 10$ s is selected.

The temporal evolution of the infiltration front was simulated with the air-entry pressure head $h_s = -1\text{E}7$ m. The propagation of the infiltration front through is depicted in Figure 4.2 and Figure 4.3. The propagation of the infiltration front obtained with BASEsub (left) is compared with the results obtained with the FE-model by Vogel (right), indicating only negligible deviations. The results also confirm the previously obtained results by Ginzburg.

4.3 BASEsub3: Unsaturated seepage flow

In this setup the 3-D unsteady seepage flow through a laboratory dam is modelled. The experimental investigations were made at the TU Berlin (see Pham Van (2009) for details). The homogeneous dam is 0.6 m high, 4.0 m long and 0.4 m wide. The sand dam material has a hydraulic conductivity of $k_f = 9.5\text{E-}4$ m/s (the value given in the reference of $0.95\text{E-}4$ m/s is supposed to be a typo). The saturation moisture content of $\theta_s = 0.49$ and a residual water content of $\theta_R = 0.01$ were measured in the laboratory.

The dam is discretized with cubic cells and a cell size $\Delta x = 0.01$ m. As initial condition the measured water content of $\theta_0 = 0.115$ is applied within the whole dam. The air entry pressure is set to $h_s = -0.035$ m. At the upstream embankment slope a time dependent pressure boundary is applied, simulating the rising water level in the reservoir left to the dam. At the downstream embankment slope a seepage boundary is set. The VGM-model is used with $\alpha = 14.5$ 1/m and $n = 2.68$ for sand material. These VGM parameters were chosen with respect to the listed values in Vogel et al. (2001) and are not based on laboratory measurements. For the simulation, the moisture-formulation of the Richard's equation is used with $\vartheta = 3$ and a time step size of $\Delta t = 0.25$ s is selected.

Measured and simulated results of the seepage line are depicted in Figure 4.4. The temporal development of the seepage line is in accordance between measurement and simulation throughout time.

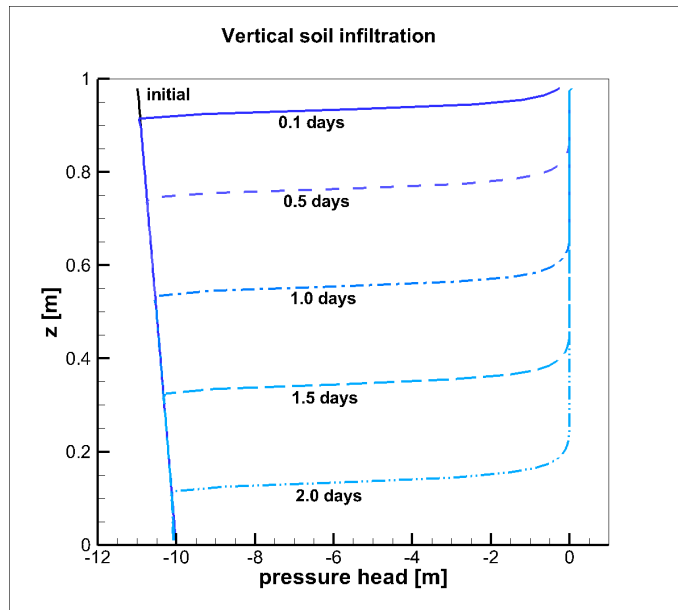


Figure 4.2 BASEsub2: Downward propagation of infiltration front into partially-saturated soil. Simulation results of BASEsub.

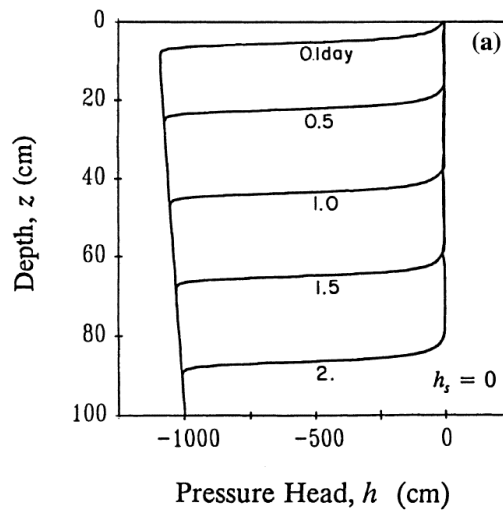


Figure 4.3 BASEsub2: Downward propagation of infiltration front into partially-saturated soil. Results of Vogel et al.

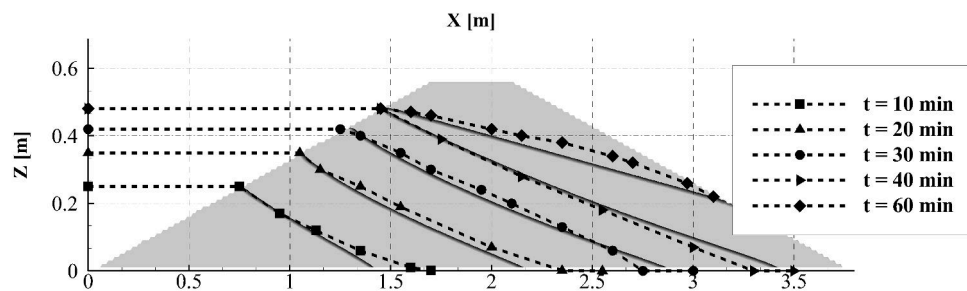


Figure 4.4 BASEsub3: Cross sectional view of measured (dashed) and simulated (bold) development of seepage line, caused by water infiltration due to a rising reservoir at the east dam side.

High-Performance Computing

5.1 Introduction and Backends

5.1.1 Introduction

These test cases present well-defined hydro- and morphodynamic numerical simulations that are used to assess the performance and accuracy of the simulations with BASEMENT High-Performance Computing (BASEHPC). The test cases have an analytical solution to which the numerical solution is compared in order to evaluate the accuracy of the results. The numerical simulations are executed on different backends that influence the performance of the simulation.

5.1.2 Backends

Different backends are used to execute the simulations of the test cases. The different backends are: a central processing unit (CPU) with a sequential application on 1 core, CPU with parallel applications (OpenMP) on 2, 4, 8, 16 and 32 cores and graphic processing units (GPU) with a compute unified device architecture (CUDA) with single and double precision. The features of the GPU card are shown in Table 5.1.

Table 5.1 Features of the GPU hardware used for the numerical simulations

Card	K20	P100	RTX 2080Ti	GTX 1080 Ti	GTX 1070 Ti	GTX 1050 Ti
Memory [GB]	5	12	11	11	8	4
Architecture	Kepler	Pascal	Turing	Pascal	Pascal	Pascal
Bandwidth [GB/s]	208	549	616	484	256	112
CUDA cores	2496	3584	4352	3584	2432	768

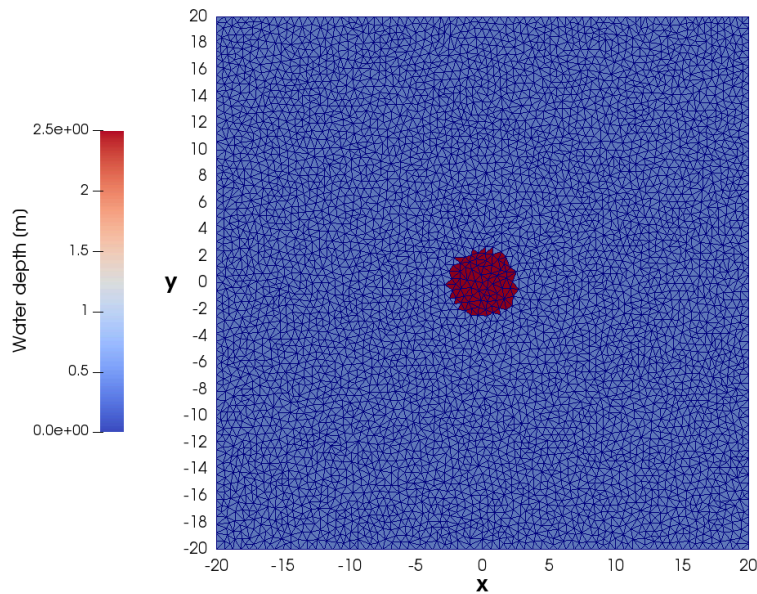


Figure 5.1 Computational domain of the circular dam break (10k cells) with initial water depth.

5.2 Circular dam break

5.2.1 Description

The circular dam break problem represents a 2D Riemann problem based on the sudden collapse of an idealized circular dam over a horizontal bottom. The aim is to evaluate the ability of the model to solve the wave propagation, i.e. the complex interaction of shock and rarefaction waves induced by a dam break event. The results are quantitatively compared with a reference solution obtained as described in Toro (2001).

5.2.2 Geometry and Initial Conditions

The computational domain is a squared area of size 40 x 40 m and composed of unstructured triangular cells. The circular dam has a diameter of 5 m and is located at the center of the computational domain ($x = 0$, $y = 0$). Initially, the water is at rest and the depth inside the circular dam is 2.5 m and 0.5 m over the surrounding domain. No friction and no slope (horizontal bottom) is considered and the CFL number is set to 0.9. As the simulation starts (time 0.0 s), the dam is removed and the subsequent wave pattern is observed during 4.7 s, after which the simulation stops. Different mesh resolutions are used in the test case, the smallest mesh resolution contains exactly 9'927 cells (10k), the second 49'450 cells (50k), the third 99'416 cells (100k), the fourth 497'092 cells (500k) and the finest mesh resolution contains 994'092 cells (1000k). Figure 5.1 shows the initial conditions of the circular dam break with the computational domain of 10k cells.

5.2.3 Results

The evolution of the water depth is described along a reference cross-section located between $(x = -20, y = 0)$ and $(x = 20, y = 0)$, see Figure 5.2. The reference solution is obtained from Toro (2001) using the exact Riemann solver on a mesh of about 1000 cells. After the collapse of the circular dam at $t = 0.0$ s, the primary shock wave propagates outwards. At the same time, a rarefaction wave that propagates towards the center of the dam is observed. The rarefaction wave will implode at the grid center before $t=0.4$ s and then travel in outward direction inducing a rapid drop of the water elevation which will reach a level below the initial outer water surface elevation ($t=1.4$ s) in the center area. The primary shock wave travels outwards with decreasing strength while a secondary shock wave develops in opposite direction towards the center and finally generates a jump in the water depth at the grid center ($t=4.7$ s).

The results on Figure 5.2 show how the solution obtained with BASEMENT version 3 (first order HLLC method) correctly converges to the reference solution as the grid is refined. The cylindrical symmetry of the wave propagation in BASEMENT is maintained, even if water surface modulations are observed along the primary shock wave.

The relative error is computed for the water depth (e_H) and speed (e_u) using eq. 5.1 and for various reference elevations. The result is displayed in Figure 5.3.

$$e_X = \frac{|X_{BM} - X_{ref}|}{X_{ref}} \quad (5.1)$$

Where X stands either for the water surface elevation H or the velocity u with X_{BM} the result of the simulation with BASEMENT and X_{ref} the reference value of Toro (2001).

The relative L^2 norm error (eq. 5.2, e.g Vanzo et al. (2016)) is calculated for each mesh size using the water surface elevation of the simulation result of BASEMENT (H_{BM}) and the references solution (H_{ref}) of Toro (2001). The result is shown on Table 5.2. The relative norm error decreases for finer meshes.

$$L^2 = \sqrt{\frac{\sum_{i=1}^N (H_{ref}(i) - H_{BM}(i))^2}{\sum_{i=1}^N H_{ref}(i)^2}} \quad (5.2)$$

Table 5.2 Relative L^2 norm error of the water surface elevation H compared to the reference solution of Toro (2001) at $t=4.7$ s.

	10k	50k	100k	500k	1000k
L^2	0.1134	0.0523	0.0453	0.0184	0.0145

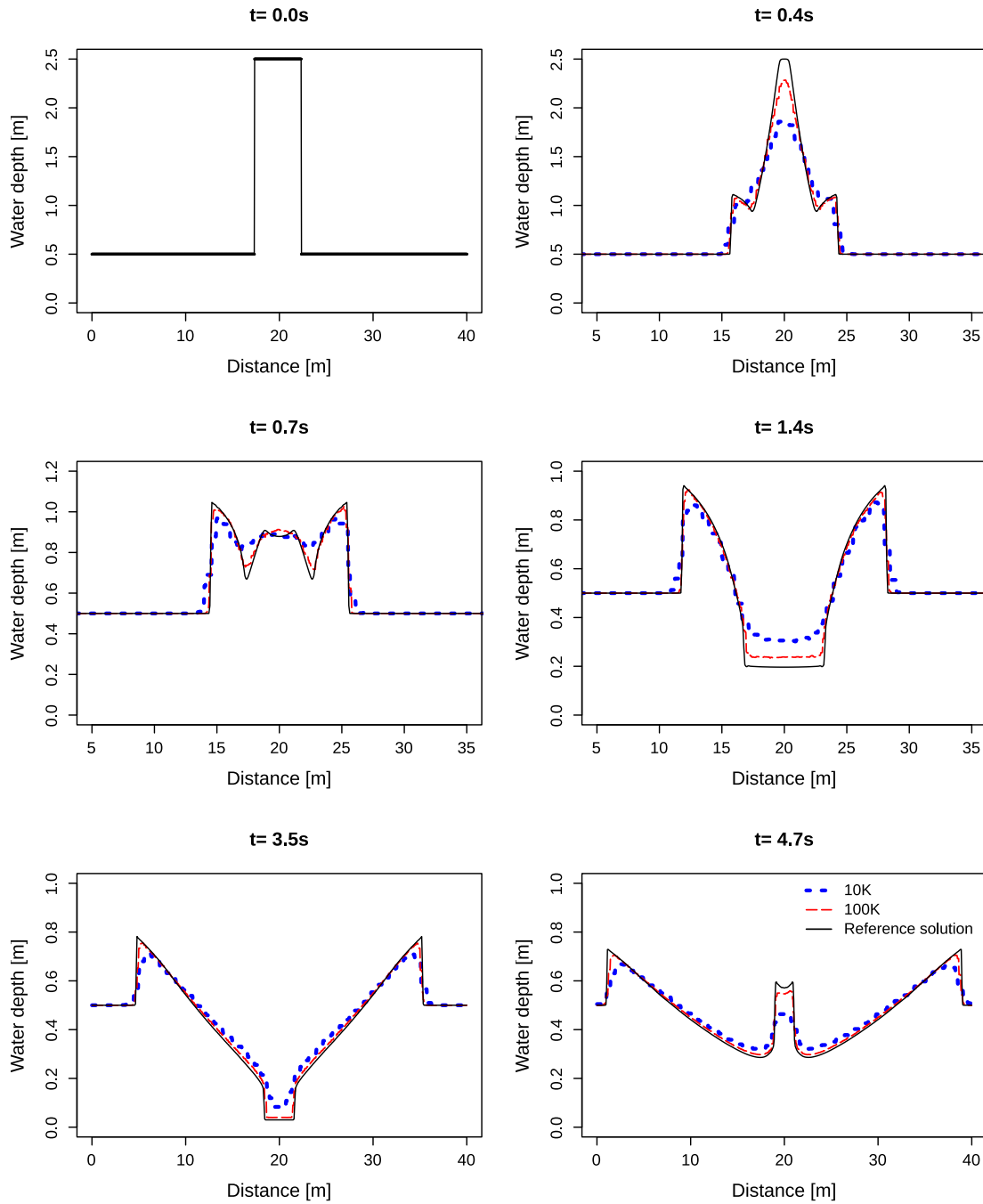


Figure 5.2 Snapshots of the water depth evolution along the reference cross-section. Comparison between BASEMENT simulations with a computational grid of 10k cells, 100k cells and the reference solution of Toro (2001).

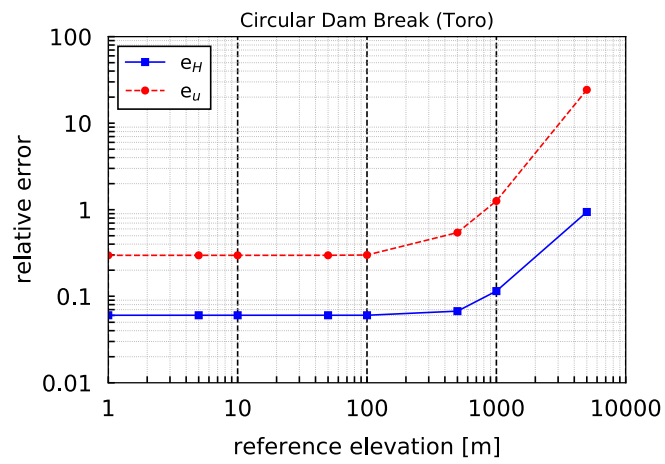


Figure 5.3 Relative error compared to the reference solution of Toro (2001)

5.2.4 Performance

The performance is evaluated in terms of effective computation time and in terms of speedup S . The latter is a measure of parallelization efficiency. The speedup S is calculated as the division of the sequential runtime T_1 (of each mesh size respectively) by the runtime with a certain number of cores T_N or a specific GPU card.

5.2.4.1 Ubuntu

Tables 5.4, 5.5 and 5.6 contain the execution time and speedup of all the simulations performed on different backends under Linux. The backends belong to two categories, either in Central Processor Units (CPU) or Graphics Processor Units (GPU). The CPU run simulations exclusively with double precision, while GPU can perform simulations with single or double precision. More details are explained in Section 5.1.2.

Table 5.3 Computational time (s) and speedup (in parentheses) of the circular dam break simulations for CPU simulations under Ubuntu 16.04 (Intel Xeon Gold 6154, 3.00GHz)

Mesh size	Xeon 1 Double	Xeon 2 Double	Xeon 4 Double	Xeon 8 Double	Xeon 16 Double	Xeon 32 Double
10k	0.16	0.19 (1.49x)	0.11 (2.46x)	0.07 (3.33x)	0.04 (4.18x)	0.03 (5.31x)
50k	1.88	1.08 (1.73x)	0.57 (3.29x)	0.33 (5.70x)	0.20 (9.31x)	0.15 (12.68x)
100k	5.44	3.06 (1.77x)	1.62 (3.35x)	0.89 (6.12x)	0.52 (10.4x)	0.35 (15.47x)
500k	63.63	34.49 (1.85x)	17.71 (3.59x)	9.28 (6.86x)	5.06 (12.57x)	3.07 (20.72x)
1000k	190.39	101.66 (1.87x)	51.83 (3.67x)	26.98 (7.06x)	14.36 (13.26x)	8.75 (21.77x)

Table 5.4 Computational time (s) and speedup (in parentheses) of the circular dam break simulations for CPU simulations under Ubuntu 16.04 (Intel Xeon E5-2667 v3 @ 3.20GHz)

Mesh size	Xeon 1 Double	Xeon 2 Double	Xeon 4 Double	Xeon 8 Double	Xeon 16 Double
10k	0.16	0.19 (1.49x)	0.11 (2.46x)	0.07 (3.33x)	0.04 (4.18x) 0.03 (5.31x)
50k	1.88	1.08 (1.73x)	0.57 (3.29x)	0.33 (5.70x)	0.20 (9.31x) 0.15 (12.68x)

Mesh size	Xeon 1 Double	Xeon 2 Double	Xeon 4 Double	Xeon 8 Double	Xeon 16 Double
100k	5.44	3.06 (1.77x)	1.62 (3.35x)	0.89 (6.12x)	0.52 0.35 (10.4x) (15.47x)
500k	63.63	34.49 (1.85x)	17.71 (3.59x)	9.28 (6.86x)	5.06 3.07 (12.57x) (20.72x)
1000k	190.39	101.66 (1.87x)	51.83 (3.67x)	26.98 (7.06x)	14.36 8.75 (13.26x) (21.77x)

Table 5.5 Computational time (s) and speedup (in parentheses) of the circular dam break simulations for GPU simulations

Mesh size	Xeon 1 Double	RTX 2080Ti Single	RTX 2080Ti Double	Tesla K20 Single	Tesla K20 Double	Tesla P100 Single	Tesla P100 Double
10k	0.16	0.04 (4.41x)	0.04 (4.10x)	0.06 (2.86x)	0.05 (2.99x)	0.04 (3.85x)	0.04 (4.04x)
50k	1.88	0.15 (12.18x)	0.19 (9.74x)	0.24 (7.90x)	0.27 (7.01x)	0.18 (10.5x)	0.18 (10.53x)
100k	5.44	0.30 (18.01x)	0.37 (14.65x)	0.51 (10.61x)	0.59 (9.23x)	0.36 (15.28x)	0.37 (14.67x)
500k	63.63	1.66 (38.37x)	2.57 (24.72x)	3.42 (18.61x)	4.67 (13.61x)	2.13 (29.84x)	2.52 (25.28x)
1000k	190.39	3.63 (52.48x)	6.45 (29.54x)	8.63 (22.05x)	12.45 (15.29x)	5.03 (37.87x)	6.28 (30.33x)

Table 5.6 Computational time (s) and speedup (in parentheses) of the circular dam break simulations for GPU simulations

Mesh size	Xeon 1 Double	GTX 1050Ti Single	GTX 1050Ti Double	GTX 1070Ti Single	GTX 1070Ti Double	GTX 1080Ti Single	GTX 1080Ti Double
10k	0.16	0.04 (3.98x)	0.05 (2.93x)	0.03 (4.42x)	0.04 (4.00x)	0.04 (4.26x)	0.04 (4.05x)
50k	1.88	0.20 (9.28x)	0.34 (5.53x)	0.13 (11.1x)	0.21 (8.78x)	0.16 (11.81x)	0.19 (9.68x)

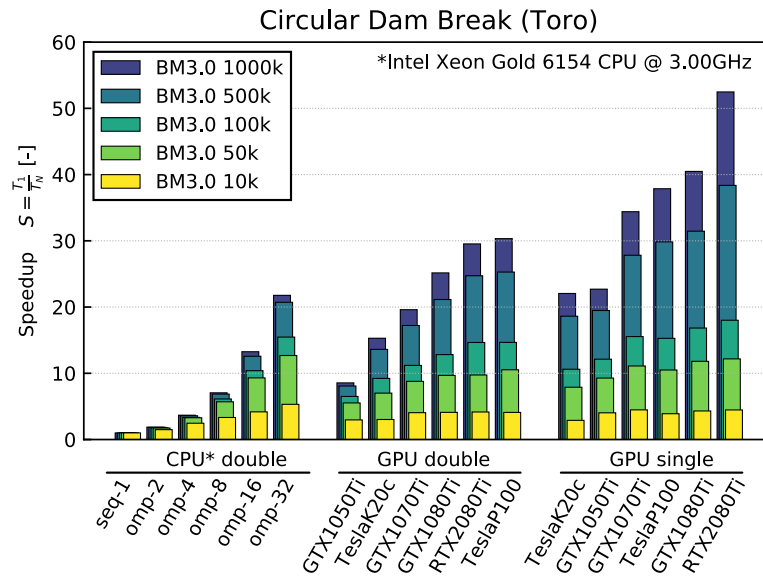


Figure 5.4 Speedup for CPU (double precision) and GPU (single and double precision) backends for the circular dam break test case.

Mesh size	Xeon 1 Double	GTX	GTX	GTX	GTX	GTX	GTX
		1050Ti Single	1050Ti Double	1070Ti Single	1070Ti Double	1080Ti Single	1080Ti Double
100k	5.44	0.45 (12.13x)	0.84 (6.5x)	0.30 (15.54x)	0.49 (11.19x)	0.21 (16.83x)	0.42 (12.82x)
500k	63.63	3.27 (19.48x)	7.88 (8.08x)	1.96 (27.82x)	3.70 (17.21x)	2.02 (31.45x)	3.01 (21.14x)
1000k	190.39	8.55 (22.70x)	22.26 (8.55x)	5.53 (34.40x)	9.71 (19.61x)	4.70 (40.48x)	7.57 (25.16x)

Figure 5.4 shows the speedup achieved by the different backends. The sequential and OpenMP backends were run on processors of type Intel Xeon Gold 6154 (3.00GHz) with two sockets and with 18 cores per socket. The largest speedups are obtained for certain GPU cards using single precision. But also by using the GPU backend with double precision, the simulation time can be reduced significantly compared to sequential computation. It should be noted that the results of simulations with single and double precision can vary greatly depending on the problem. Further, it can be observed that the speedup greatly depends on the problem size. For smaller mesh, the speedup obtained by increasing the number of cores or by using GPU cards can be limited. The speedup increases particularly for meshes with a fine resolution (500K and 1000K) using GPU.

Figure 5.5 compares the speedup with the number of threads (CPU) between the different mesh resolutions. The simulations were performed using the CPU backend with Intel Xeon

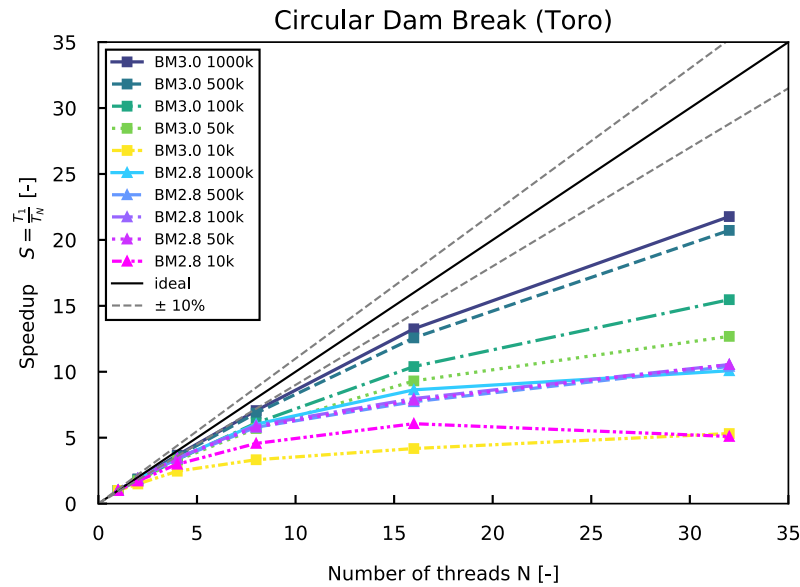


Figure 5.5 Speedup of the computational time $[T_N]$ using different number of threads (CPU) compared to the time of the sequential backend Xeon1 $[T_1]$ for the circular dam break

Gold 6154 (3.00GHz) processors. The speedup is more effective for meshes with a fine resolution than for those of coarse resolution, where the increase in number of cores leads to a plateau.

5.2.4.2 Windows

Tables 5.7 contains the execution time and speedup of all the simulations performed on different backends under Windows. The simulations were run on Prozessor Intel Xeon E-2174G (3.80GHz) processors with 4 cores and 2 threads per core (8 logical cores using HyperThreading). The performance scales adequately up to 4 cores. The use of 8 logical usings (HyperThreading) does not results in a significant improvement of performance compared to using 4 physical cores.

Table 5.7 Computational time (s) and speedup (in parentheses) of the circular dam break simulations for CPU simulations under Windows 10 (Intel Xeon E-2174G, 3.80GHz)

Mesh size	Xeon 1 Double	Xeon 2 Double	Xeon 4 Double	Xeon 8 Double
10k	0.23	0.14 (1.67x)	0.08 (3.0x)	0.09 (2.49x)
50k	2.80	1.58 (1.77x)	0.98 (2.84x)	0.81 (3.44x)
100k	8.08	4.73 (1.71x)	3.16 (2.56x)	2.58 (3.13x)

Mesh size	Xeon 1 Double	Xeon 2 Double	Xeon 4 Double	Xeon 8 Double
500k	95.01	51.78 (1.83x)	30.55 (3.11x)	23.62 (4.02x)
1000k	275.02	149.84 (1.84x)	90.00 (3.06x)	67.25 (4.09x)

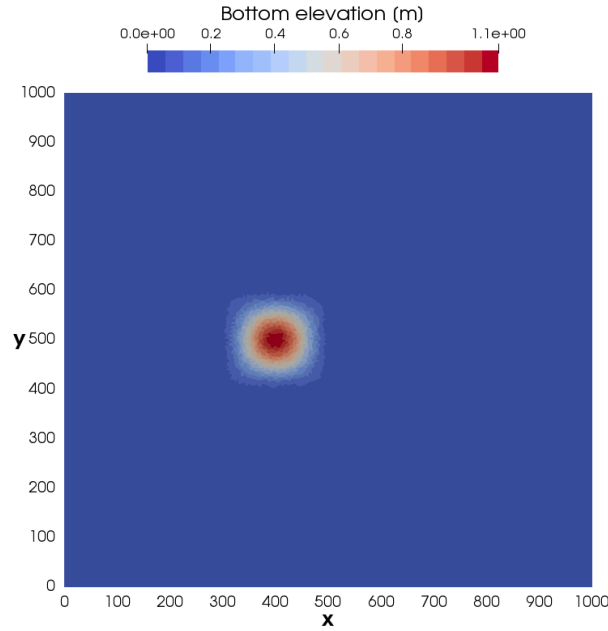


Figure 5.6 Initial bottom elevation of the conical dune, maximum elevation of 1.1 m at $[x=400, y=500]$.

5.3 Conical Dune

5.3.1 Description

The conical dune test proposed by Hudson and Sweby (2005) is used to assess the accuracy of two dimensional morphodynamic models under sub-critical flow and without friction. The simulation describes the evolution of an initial conical dune of sediments that evolves in a star shaped pattern characterized by a spread angle α_s . Numerical results are compared with the approximate analytical solution for the spread angle of the disturbance front proposed by de Vriend (1987).

5.3.2 Geometry and Initial Conditions

The computational mesh is a squared area of size 1000 x 1000 m with an initial bottom elevation $z_{B,initial}$ (see Figure 5.6):

$$z_{B,initial} = \begin{cases} 0.1 + \sin^2\left(\frac{\pi(x-300)}{200}\right) \sin^2\left(\frac{\pi(y-400)}{200}\right) & \text{for } x \in [300, 500] \\ & \text{and } y \in [400, 600] \\ 0.1 & \text{otherwise} \end{cases} \quad (5.3)$$

An inflow boundary condition of Froude type is defined along the y-axis at $x=0$ setting a constant unit discharge of 10 m/s. At $x=1000$ m, a h-Q relation is defined as outflow boundary condition. The initial water depth is 10 m and the water surface elevation is kept constant at the boundaries. The Strickler coefficient is set to $K_s = 10^7 [m^{1/3}/s]$ in order to obtain an almost frictionless simulation. The CFL number is set to 0.8, the

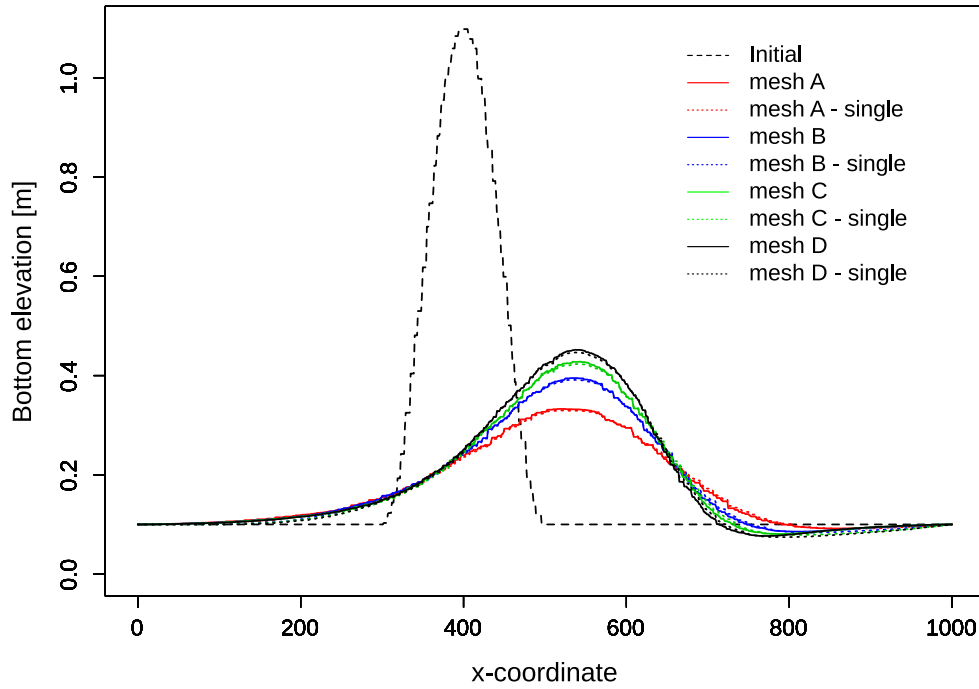


Figure 5.7 Longitudinal bottom elevation profile at $y=500$ m for initial conditions and after 100h of simulation for the meshes A, B, C and D with double and single precision

porosity to 0.4 and the morphodynamic boundary conditions are at equilibrium. Bed load transport is computed using the Grass formula with the parameters $A_G = 0.001002$ and $m_G = 3$ assuming a slow interaction between the sediment layer and the water flow. The analytical solution for the spread angle (eq. 5.4) proposed by de Vriend (1987) gives a value of $\alpha_{s,ref} = 21.787^\circ$.

$$\alpha_s = \arctan\left(\frac{3\sqrt{3}(m_G - 1)}{9m_G - 1}\right) \quad (5.4)$$

The tests were performed with different computational mesh resolution, mesh A has 30160 cells (30k), mesh B 61201 cells (60k), mesh C 91083 cells (90k) and mesh D 126020 cells (120k). The simulation results were analyzed after 100 hours and each test was performed using different backends.

5.3.3 Results

Figure 5.7 shows the bed elevation profile at $y = 500$ m along the x -coordinates at the beginning and after 100 h of the simulation for the four different meshes (A, B, C and D) performed with double and single precision. The results are exactly the same for all processor types, except for the simulation performed with CUDA-single, where the values are slightly different due to the reduced precision.

Table 5.8 summarizes the results obtained from the numerical simulations at $t=100$ h for

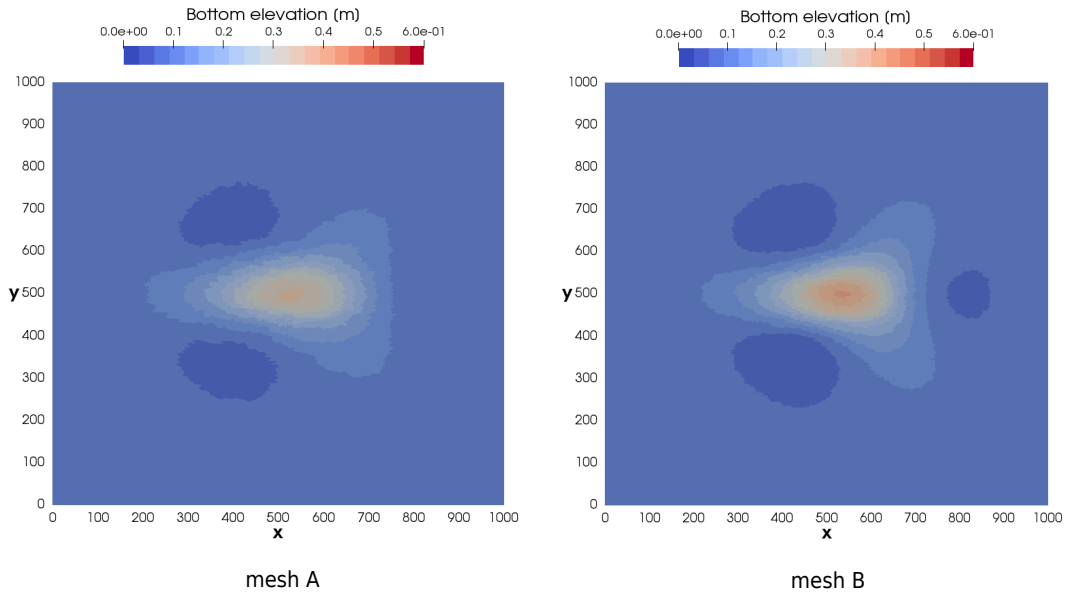


Figure 5.8 Planar view of the bottom elevation after 100 hours of simulation for the meshes A and B.

the different meshes using the backend types CPU and GPU-double. The spread angle α_s is measured between $y = 500$ m and the line passing through the initial conical dune center point and the farthest point in the x -direction where the conical dune spread for a similar bottom elevation (Figure 5.8 and Figure 5.9). The spread angle was measured at time $t=25h$, $50h$, $75h$ and $100h$ for each mesh size and the mean value is reported in Table 5.8. The accuracy of the simulations is assessed by the relative deviation between the measure spread angle α_s and the spread angle defined by de Vriend (1987) $\alpha_{s,ref}$.

Table 5.8 Summary of the simulation results performed with CPU and GPU double at $t=100h$ for different computational meshes

Mesh	Number of cells [-]	Max. cone elevation [m]	α_s [°]	Relative deviation [%]
A	30160	0.3327	25.57	16.0
B	61201	0.3950	25.12	14.2
C	91083	0.4279	23.94	9.4
D	126020	0.4518	23.35	6.9

The maximum bottom elevation after 100h increases with the mesh resolution while the spread angle decreases (Table 5.8). The results are more accurate for finer meshes (mesh C and mesh D, Figure 5.7), where less diffusive sediment transport is observed and thus the maximum bottom elevation after 100h is higher than for coarser meshes. This increase in accuracy for finer meshes is also observed in Figure 5.8 and Figure 5.9 by a well defined star shaped sediment transport and a spread angle that becomes closer to the value proposed by de Vriend (1987).

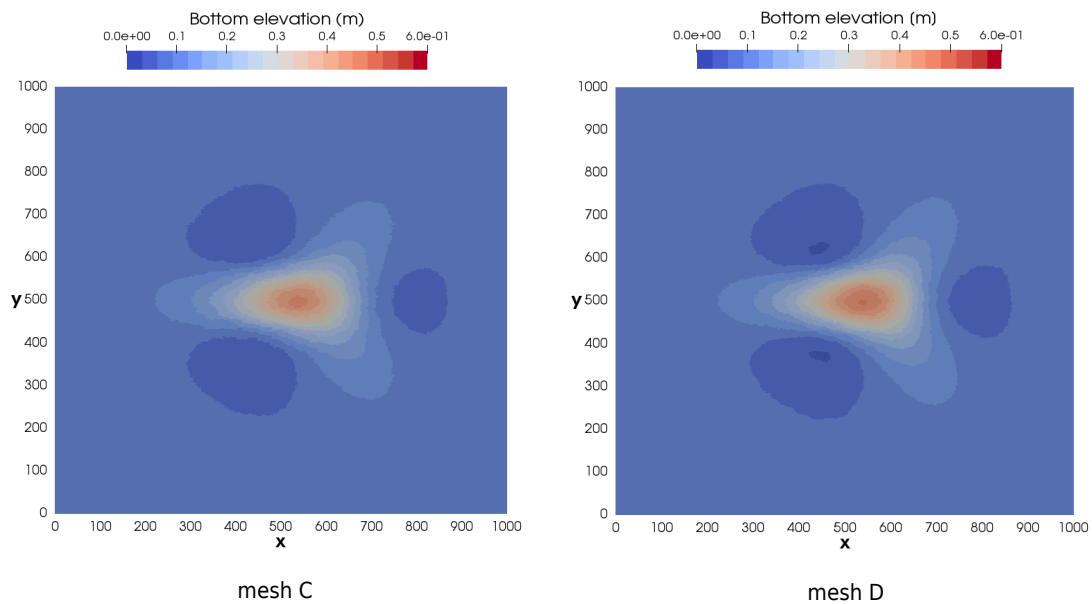


Figure 5.9 Planar view of the bottom elevation after 100 hours of simulation for the meshes C and D.

5.4 Dam-break flow in a L-shaped channel with a mobile-bed

5.4.1 Description

This test case is based on the experiments described in Palumbo et al. (2008) and is a frequently used benchmark test case in literature (e.g. Siviglia et al. (2013), Soares-Frazão and Zech (2011)).

5.4.2 Geometry and initial conditions

This test case consist of a domain with a non-symmetrical sudden enlargement. The dimensions of the domain as illustrated in Figure 5.10. The sediment bed is composed of coarse uniform sand with grain size diameter of $d_s = 1.82$ mm. The sediment porosity is $p = 0.47$ and the sediment density $\rho_s = 2680$ kg/m³. The Manning friction coefficient is set to $n = 0.0167$ s/m^{1/3}. The initial bed level is at an elevation of 0.1 m over the whole domain. The initial water depth upstream (left) of the dam is set to 0.25 m. The dam at is located at $x = 3.0$ m. At time $t = 0$ seconds, he dam is removed instantaneously, resulting in wave propagation and sediment transport.

The computational domain is discretised by unstructured triangular cells. Four different sized computational grids were generated, resulting in grids with 27,000 cells (27k), 54,000 cells (54k), 108,000 cells (108k), 216,000 cells (216k). Wall boundary conditions are applied at the domain side walls. At the outflow boundary (right), a free-outflow boundary condition was applied. The sediment transport is calculated using the MPM_like formula with a pre-factor of 3.97 and an exponent of 1.5. The simulation lasts 12 seconds.

5.4.3 Results

The simulated bed elevations at $t = 12$ s are compared to the experimental results from Palumbo et al. (2008) in Figure 5.11. Overall, the simulated bed elevations are in acceptable agreement with experimental data. The scour in cross section CS1 ($x = 4.1$ m) is matched well, while the deposition around $y = 0.3$ m is underestimated. At cross-section CS2, the numerical results correspond well with the experimental data. In particular at location CS1, the observed deviations may be attributed to distinct 3D flow effects that are not captured by the 2D depth-averaged model (Siviglia et al. 2013, Xia et al. 2010).

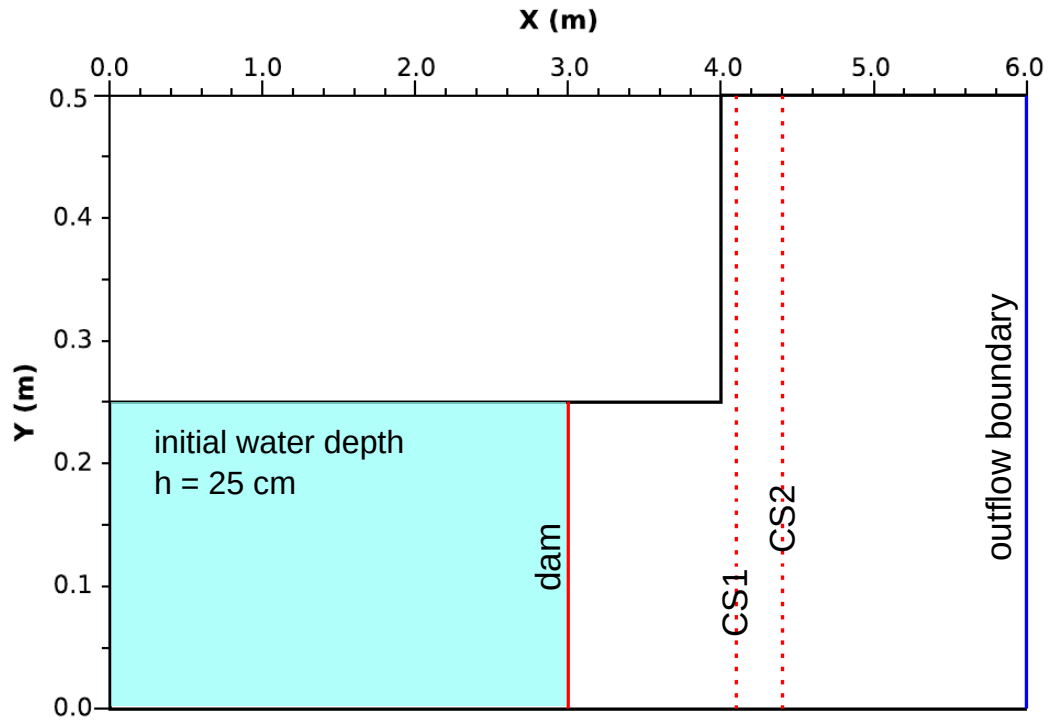


Figure 5.10 The numerical test setup for the dam-break flow in a L-shaped channel with a mobile-bed. Experimental and numerical bed elevations are compared along cross-sections CS1 and CS2. Modified from Siviglia et al. (2013).

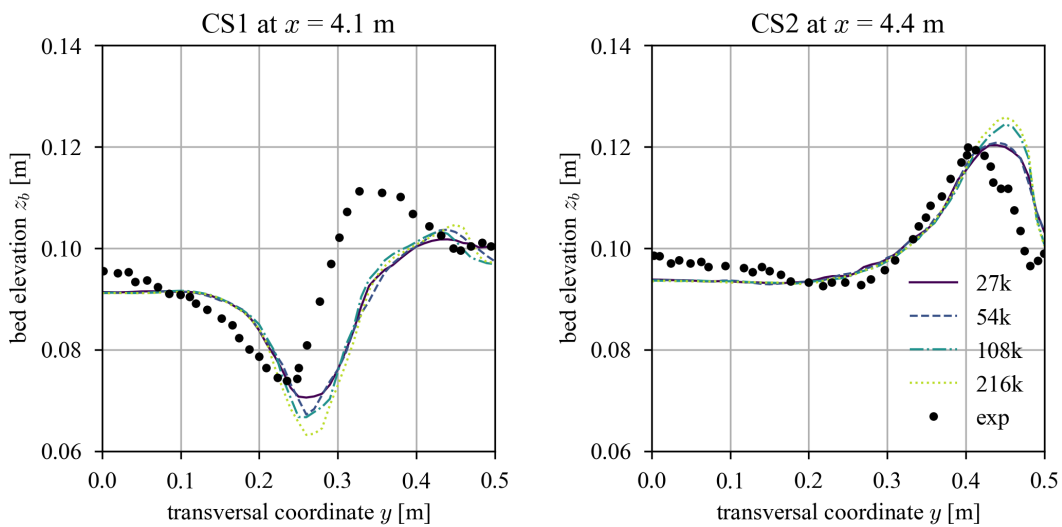


Figure 5.11 Experimental and numerical bed elevation are compared at cross-sections CS1 and CS2.

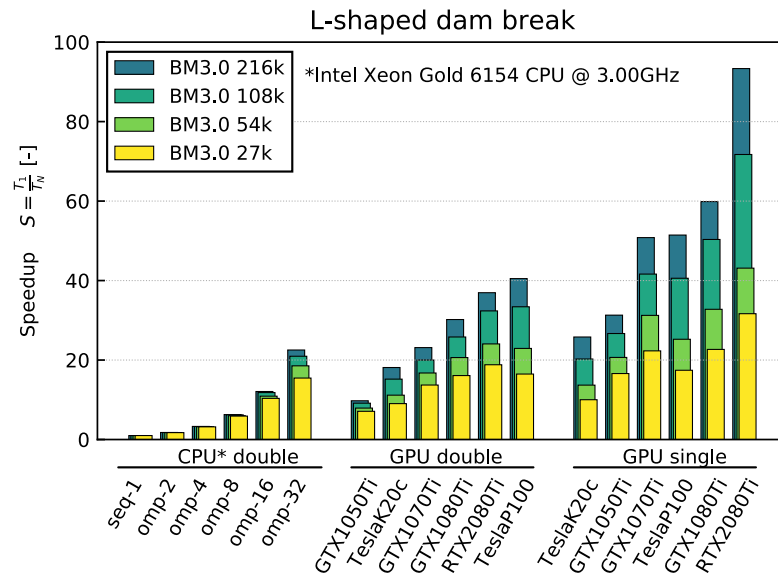


Figure 5.12 Speedup of the computational time $[T_N]$ for CPU (double) and GPU (single and double) compared to the time of the sequential backend Xeon1 $[T_1]$ for the L-shaped dam break test case.

5.4.4 Performance

5.4.4.1 Ubuntu

Simulations of this test case were performed on CPU- and GPU-backends. The largest execution times are obtained by using the sequential backend. By using the OpenMP-backend, the computation time can be reduced almost linearly with the number of cores. Also by using GPU-backends the computation time can be reduced in comparison to sequential computation, whereas the increase in performance depends on the GPU-card and the precision (single or double). The best performance using double precision is obtained with the card Tesla P100, while the RTX 2080Ti outperformed other cards when using single precision (see Tables 5.9, 5.10 and 5.11 or Figure 5.12). It should be noted that the results of simulations with single and double precision can vary greatly depending on the problem.

Table 5.9 Computational time (s) and speedup S (inside brackets) of the L-shaped dam break simulations for CPU simulations (Intel Xeon Gold 6154, 3.00GHz)

Mesh size	Xeon 1 Double	Xeon 2 Double	Xeon 4 Double	Xeon 8 Double	Xeon 16 Double	Xeon 32 Double
30k	43.8	25.2 (1.7x)	13.7 (3.2x)	7.4 (5.9x)	4.2 (10.4x)	2.8 (15.5x)
60k	97.7	56.1 (1.7x)	30.4 (3.2x)	16.3 (6.0x)	9.0 (10.9x)	5.3 (18.5x)

Mesh size	Xeon 1 Double	Xeon 2 Double	Xeon 4 Double	Xeon 8 Double	Xeon 16 Double	Xeon 32 Double
90k	357.3	202.7 (1.8x)	109.3 (3.3x)	57.5 (6.2x)	3.2 (11.8x)	17.0 (21.0x)
120k	1096.3	618.5 (1.8x)	332.6 (3.3x)	174.9 (6.3x)	90.7 (12.1x)	48.7 (22.5x)

Table 5.10 Computational time (s) and speedup S (inside brackets) of the L-shaped dam break simulations for GPU simulations

Mesh size	Xeon 1 Double	RTX 2080Ti Single	RTX 2080Ti Double	Tesla K20 Single	Tesla K20 Double	Tesla P100 Single	Tesla P100 Double
30k	43.8	1.4 (31.7x)	2.3 (18.8x)	4.4 (10.0x)	4.8 (9.0x)	2.5 (17.4x)	2.7 (16.5x)
60k	97.7	2.3 (43.1x)	4.1 (24.1)	7.1 (13.7x)	8.8 (11.2x)	3.9 (25.2x)	4.3 (22.9x)
90k	357.3	5.0 (71.7x)	11.0 (32.4x)	17.6 (20.3x)	23.5 (15.2x)	8.8 (40.6x)	10.7 (33.4x)
120k	1096.3	11.7 (93.3x)	29.7 (37.0x)	42.5 (25.8x)	60.5 (18.1x)	21.3 (51.4x)	27.1 (40.5x)

Table 5.11 Computational time (s) and speedup S (inside brackets) of the L-shaped dam break simulations for GPU simulations

Mesh size	Xeon 1 Double	GTX 1050 Single	GTX 1050 Double	GTX 1070 Single	GTX 1070 Double	GTX 1080 Single	GTX 1080 Double
30k	43.8	2.6 (16.6x)	6.2 (7.1x)	2.0 (22.3x)	3.2 (13.7x)	1.9 (22.7x)	2.7 (16.1x)
60k	97.7	4.7 (20.7x)	12.4 (7.9x)	3.1 (31.2x)	5.8 (16.7x)	3.0 (32.8x)	4.7 (20.69x)
90k	357.3	13.4 (26.7x)	39.1 (9.1x)	8.6 (41.6x)	17.9 (20.0x)	7.1 (50.3x)	13.8 (25.8x)
120k	1096.3	35.0 (31.3x)	112.4 (9.8x)	21.6 (50.8x)	47.4 (23.1x)	18.3 (59.9x)	36.3 (30.2x)

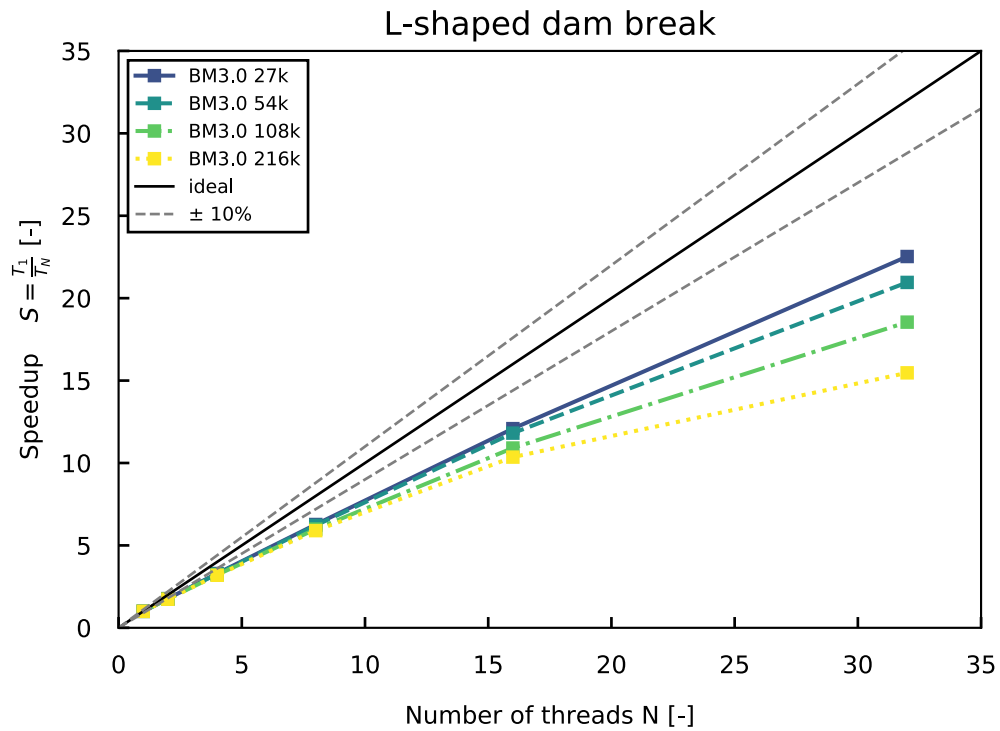


Figure 5.13 Speedup of the L-shaped dam break test case performed on CPU for an increasing number of threads and different mesh sizes

In Figure 5.13, the speedup of the OpenMP-backend is illustrated for different mesh sizes on an Intel Xeon Gold 6154 (3.00GHz) processor on an Ubuntu system with 36 cores. The speedup of scales almost linearly up to 32 cores for this test case, indicating a good scaling behaviour.

5.4.4.2 Windows

Tables 5.12 contains the execution time and speedup of the simulations performed on different backends under Windows. The simulations were run on Prozessor Intel Xeon E-2174G (3.80GHz) processors with 4 cores and 2 threads per core (8 logical cores using HyperThreading). The performance scales adequately up to 4 cores. The use of 8 logical usings (HyperThreading) does not results in a significant improvement of performance compared to using 4 physical cores.

Table 5.12 Computational time (s) and speedup (in parentheses) for CPU simulations of L-shaped dam break with a mobile bed under Windows 10 (Intel Xeon E-2174G, 3.80GHz)

Mesh size	Xeon 1 Double	Xeon 2 Double	Xeon 4 Double	Xeon 8 Double
27k	70.0	38.3 (1.83x)	25.6 (2.73x)	16.8 (4.18x)

Mesh size	Xeon 1 Double	Xeon 2 Double	Xeon 4 Double	Xeon 8 Double
54k	158.8	87.3 (1.82x)	58.1 (2.73x)	37.5 (4.23x)
108k	578.5	319.6 (1.81x)	212.3 (2.72x)	137.7 (4.20x)
216k	1770.6	986.0 (1.80x)	680.9 (2.60x)	427.8 (4.14x)

6

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**BASIC SIMULATION ENVIRONMENT
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APPENDIX

**VERSION 4.1.0
JUNE 2024**



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Julian Seward, jseward@acm.org
bzip2/libbzip2 version 1.0.8 of 13 July 2019

Curl

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Mesa 3-D graphics library
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File: aclocal.m4 (only for ICU4C)
Section: pkg.m4 - Macros to locate and utilise pkg-config.

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```

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=====

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=====

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However, linking a "work that uses the Library" with the Library creates an executable that is a derivative of the Library (because it contains portions of the Library), rather than a "work that uses the library". The executable is therefore covered by this License. Section 6 states terms for distribution of such executables.

When a "work that uses the Library" uses material from a header file that is part of the Library, the object code for the work may be a derivative work of the Library even though the source code is not. Whether this is true is especially significant if the work can be linked without the Library, or if the work is itself a library. The threshold for this to be true is not precisely defined by law.

If such an object file uses only numerical parameters, data structure layouts and accessors, and small macros and small inline functions (ten lines or less in length), then the use of the object file is unrestricted, regardless of whether it is legally a derivative work. (Executables containing this object code plus portions of the Library will still fall under Section 6.)

Otherwise, if the work is a derivative of the Library, you may distribute the object code for the work under the terms of Section 6. Any executables containing that work also fall under Section 6, whether or not they are linked directly with the Library itself.

6. As an exception to the Sections above, you may also combine or link a "work that uses the Library" with the Library to produce a work containing portions of the Library, and distribute that work under terms of your choice, provided that the terms permit modification of the work for the customer's own use and reverse engineering for debugging such modifications.

You must give prominent notice with each copy of the work that the Library is used in it and that the Library and its use are covered by this License. You must supply a copy of this License. If the work during execution displays copyright notices, you must include the copyright notice for the Library among them, as well as a reference directing the user to the copy of this License. Also, you must do one of these things:

a) Accompany the work with the complete corresponding machine-readable source code for the Library including whatever changes were used in the work (which must be distributed under Sections 1 and 2 above); and, if the work is an executable linked with the Library, with the complete machine-readable "work that uses the Library", as object code and/or source code, so that the user can modify the Library and then relink to produce a modified executable containing the modified Library. (It is understood that the user who changes the contents of definitions files in the Library will not necessarily be able to recompile the application to use the modified definitions.)

b) Use a suitable shared library mechanism for linking with the Library. A suitable mechanism is one that (1) uses at run time a copy of the library already present on the user's computer system, rather than copying library functions into the executable, and (2) will operate properly with a modified version of the library, if

the user installs one, as long as the modified version is interface-compatible with the version that the work was made with.

- c) Accompany the work with a written offer, valid for at least three years, to give the same user the materials specified in Subsection 6a, above, for a charge no more than the cost of performing this distribution.
- d) If distribution of the work is made by offering access to copy from a designated place, offer equivalent access to copy the above specified materials from the same place.
- e) Verify that the user has already received a copy of these materials or that you have already sent this user a copy.

For an executable, the required form of the "work that uses the Library" must include any data and utility programs needed for reproducing the executable from it. However, as a special exception, the materials to be distributed need not include anything that is normally distributed (in either source or binary form) with the major components (compiler, kernel, and so on) of the operating system on which the executable runs, unless that component itself accompanies the executable.

It may happen that this requirement contradicts the license restrictions of other proprietary libraries that do not normally accompany the operating system. Such a contradiction means you cannot use both them and the Library together in an executable that you distribute.

7. You may place library facilities that are a work based on the Library side-by-side in a single library together with other library facilities not covered by this License, and distribute such a combined library, provided that the separate distribution of the work based on the Library and of the other library facilities is otherwise permitted, and provided that you do these two things:

- a) Accompany the combined library with a copy of the same work based on the Library, uncombined with any other library facilities. This must be distributed under the terms of the Sections above.
- b) Give prominent notice with the combined library of the fact that part of it is a work based on the Library, and explaining where to find the accompanying uncombined form of the same work.

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If any portion of this section is held invalid or unenforceable under any particular circumstance, the balance of the section is intended to apply, and the section as a whole is intended to apply in other circumstances.

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END OF TERMS AND CONDITIONS

How to Apply These Terms to Your New Libraries

If you develop a new library, and you want it to be of the greatest possible use to the public, we recommend making it free software that everyone can redistribute and change. You can do so by permitting redistribution under these terms (or, alternatively, under the terms of the ordinary General Public License).

To apply these terms, attach the following notices to the library. It is safest to attach them to the start of each source file to most effectively convey the exclusion of warranty; and each file should have at least the "copyright" line and a pointer to where the full notice is found.

```
<one line to give the library's name and a brief idea of what it does.>
Copyright (C) <year> <name of author>
```

```
This library is free software; you can redistribute it and/or
modify it under the terms of the GNU Lesser General Public
License as published by the Free Software Foundation; either
version 2.1 of the License, or (at your option) any later version.
```

```
This library is distributed in the hope that it will be useful,
but WITHOUT ANY WARRANTY; without even the implied warranty of
MERCHANTABILITY or FITNESS FOR A PARTICULAR PURPOSE. See the GNU
Lesser General Public License for more details.
```

```
You should have received a copy of the GNU Lesser General Public
License along with this library; if not, write to the Free Software
Foundation, Inc., 59 Temple Place, Suite 330, Boston, MA 02111-1307 USA
```

Also add information on how to contact you by electronic and paper mail.

You should also get your employer (if you work as a programmer) or your school, if any, to sign a "copyright disclaimer" for the library, if necessary. Here is a sample; alter the names:

```
Yoyodyne, Inc., hereby disclaims all copyright interest in the
library `Frob' (a library for tweaking knobs) written by James Random Hacker.
```

```
<signature of Ty Coon>, 1 April 1990
Ty Coon, President of Vice
```

That's all there is to it!

Shapelib

GNU LIBRARY GENERAL PUBLIC LICENSE
Version 2, June 1991

```
Copyright (C) 1991 Free Software Foundation, Inc.
675 Mass Ave, Cambridge, MA 02139, USA
Everyone is permitted to copy and distribute verbatim copies
```

of this license document, but changing it is not allowed.

[This is the first released version of the library GPL. It is numbered 2 because it goes with version 2 of the ordinary GPL.]

Preamble

The licenses for most software are designed to take away your freedom to share and change it. By contrast, the GNU General Public Licenses are intended to guarantee your freedom to share and change free software--to make sure the software is free for all its users.

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When we speak of free software, we are referring to freedom, not price. Our General Public Licenses are designed to make sure that you have the freedom to distribute copies of free software (and charge for this service if you wish), that you receive source code or can get it if you want it, that you can change the software or use pieces of it in new free programs; and that you know you can do these things.

To protect your rights, we need to make restrictions that forbid anyone to deny you these rights or to ask you to surrender the rights. These restrictions translate to certain responsibilities for you if you distribute copies of the library, or if you modify it.

For example, if you distribute copies of the library, whether gratis or for a fee, you must give the recipients all the rights that we gave you. You must make sure that they, too, receive or can get the source code. If you link a program with the library, you must provide complete object files to the recipients so that they can relink them with the library, after making changes to the library and recompiling it. And you must show them these terms so they know their rights.

Our method of protecting your rights has two steps: (1) copyright the library, and (2) offer you this license which gives you legal permission to copy, distribute and/or modify the library.

Also, for each distributor's protection, we want to make certain that everyone understands that there is no warranty for this free library. If the library is modified by someone else and passed on, we want its recipients to know that what they have is not the original version, so that any problems introduced by others will not reflect on the original authors' reputations.

Finally, any free program is threatened constantly by software patents. We wish to avoid the danger that companies distributing free software will individually obtain patent licenses, thus in effect transforming the program into proprietary software. To prevent this, we have made it clear that any patent must be licensed for everyone's free use or not licensed at all.

Most GNU software, including some libraries, is covered by the ordinary GNU General Public License, which was designed for utility programs. This license, the GNU Library General Public License, applies to certain designated libraries. This license is quite different from the ordinary one; be sure to read it in full, and don't assume that anything in it is the same as in the ordinary license.

The reason we have a separate public license for some libraries is that they blur the distinction we usually make between modifying or adding to a program and simply using it. Linking a program with a library, without changing the library, is in some sense simply using the library, and is analogous to running a utility program or application program. However, in a textual and legal sense, the linked executable is a combined work, a derivative of the original library, and the ordinary General Public License treats it as such.

Because of this blurred distinction, using the ordinary General Public License for libraries did not effectively promote software sharing, because most developers did not use the libraries. We concluded that weaker conditions might promote sharing better.

However, unrestricted linking of non-free programs would deprive the users of those programs of all benefit from the free status of the libraries themselves. This Library General Public License is intended to permit developers of non-free programs to use free libraries, while preserving your freedom as a user of such programs to change the free libraries that are incorporated in them. (We have not seen how to achieve this as regards changes in header files, but we have achieved it as regards changes in the actual functions of the Library.) The hope is that this will lead to faster development of free libraries.

The precise terms and conditions for copying, distribution and modification follow. Pay close attention to the difference between a "work based on the library" and a "work that uses the library". The former contains code derived from the library, while the latter only works together with the library.

Note that it is possible for a library to be covered by the ordinary General Public License rather than by this special one.

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A "library" means a collection of software functions and/or data prepared so as to be conveniently linked with application programs (which use some of those functions and data) to form executables.

The "Library", below, refers to any such software library or work which has been distributed under these terms. A "work based on the Library" means either the Library or any derivative work under copyright law: that is to say, a work containing the Library or a portion of it, either verbatim or with modifications and/or translated straightforwardly into another language. (Hereinafter, translation is included without limitation in the term "modification".)

"Source code" for a work means the preferred form of the work for making modifications to it. For a library, complete source code means all the source code for all modules it contains, plus any associated interface definition files, plus the scripts used to control compilation and installation of the library.

Activities other than copying, distribution and modification are not covered by this License; they are outside its scope. The act of running a program using the Library is not restricted, and output from such a program is covered only if its contents constitute a work based on the Library (independent of the use of the Library in a tool for writing it). Whether that is true depends on what the Library does and what the program that uses the Library does.

1. You may copy and distribute verbatim copies of the Library's complete source code as you receive it, in any medium, provided that you conspicuously and appropriately publish on each copy an appropriate copyright notice and disclaimer of warranty; keep intact all the notices that refer to this License and to the absence of any warranty; and distribute a copy of this License along with the Library.

You may charge a fee for the physical act of transferring a copy, and you may at your option offer warranty protection in exchange for a

fee.

2. You may modify your copy or copies of the Library or any portion of it, thus forming a work based on the Library, and copy and distribute such modifications or work under the terms of Section 1 above, provided that you also meet all of these conditions:

- a) The modified work must itself be a software library.
- b) You must cause the files modified to carry prominent notices stating that you changed the files and the date of any change.
- c) You must cause the whole of the work to be licensed at no charge to all third parties under the terms of this License.
- d) If a facility in the modified Library refers to a function or a table of data to be supplied by an application program that uses the facility, other than as an argument passed when the facility is invoked, then you must make a good faith effort to ensure that, in the event an application does not supply such function or table, the facility still operates, and performs whatever part of its purpose remains meaningful.

(For example, a function in a library to compute square roots has a purpose that is entirely well-defined independent of the application. Therefore, Subsection 2d requires that any application-supplied function or table used by this function must be optional: if the application does not supply it, the square root function must still compute square roots.)

These requirements apply to the modified work as a whole. If identifiable sections of that work are not derived from the Library, and can be reasonably considered independent and separate works in themselves, then this License, and its terms, do not apply to those sections when you distribute them as separate works. But when you distribute the same sections as part of a whole which is a work based on the Library, the distribution of the whole must be on the terms of this License, whose permissions for other licensees extend to the entire whole, and thus to each and every part regardless of who wrote it.

Thus, it is not the intent of this section to claim rights or contest your rights to work written entirely by you; rather, the intent is to exercise the right to control the distribution of derivative or collective works based on the Library.

In addition, mere aggregation of another work not based on the Library with the Library (or with a work based on the Library) on a volume of a storage or distribution medium does not bring the other work under the scope of this License.

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Once this change is made in a given copy, it is irreversible for that copy, so the ordinary GNU General Public License applies to all subsequent copies and derivative works made from that copy.

This option is useful when you wish to copy part of the code of the Library into a program that is not a library.

4. You may copy and distribute the Library (or a portion or derivative of it, under Section 2) in object code or executable form under the terms of Sections 1 and 2 above provided that you accompany

it with the complete corresponding machine-readable source code, which must be distributed under the terms of Sections 1 and 2 above on a medium customarily used for software interchange.

If distribution of object code is made by offering access to copy from a designated place, then offering equivalent access to copy the source code from the same place satisfies the requirement to distribute the source code, even though third parties are not compelled to copy the source along with the object code.

5. A program that contains no derivative of any portion of the Library, but is designed to work with the Library by being compiled or linked with it, is called a "work that uses the Library". Such a work, in isolation, is not a derivative work of the Library, and therefore falls outside the scope of this License.

However, linking a "work that uses the Library" with the Library creates an executable that is a derivative of the Library (because it contains portions of the Library), rather than a "work that uses the library". The executable is therefore covered by this License. Section 6 states terms for distribution of such executables.

When a "work that uses the Library" uses material from a header file that is part of the Library, the object code for the work may be a derivative work of the Library even though the source code is not. Whether this is true is especially significant if the work can be linked without the Library, or if the work is itself a library. The threshold for this to be true is not precisely defined by law.

If such an object file uses only numerical parameters, data structure layouts and accessors, and small macros and small inline functions (ten lines or less in length), then the use of the object file is unrestricted, regardless of whether it is legally a derivative work. (Executables containing this object code plus portions of the Library will still fall under Section 6.)

Otherwise, if the work is a derivative of the Library, you may distribute the object code for the work under the terms of Section 6. Any executables containing that work also fall under Section 6, whether or not they are linked directly with the Library itself.

6. As an exception to the Sections above, you may also compile or link a "work that uses the Library" with the Library to produce a work containing portions of the Library, and distribute that work under terms of your choice, provided that the terms permit modification of the work for the customer's own use and reverse engineering for debugging such modifications.

You must give prominent notice with each copy of the work that the Library is used in it and that the Library and its use are covered by this License. You must supply a copy of this License. If the work during execution displays copyright notices, you must include the copyright notice for the Library among them, as well as a reference directing the user to the copy of this License. Also, you must do one of these things:

- a) Accompany the work with the complete corresponding machine-readable source code for the Library including whatever changes were used in the work (which must be distributed under Sections 1 and 2 above); and, if the work is an executable linked with the Library, with the complete machine-readable "work that uses the Library", as object code and/or source code, so that the user can modify the Library and then relink to produce a modified executable containing the modified Library. (It is understood that the user who changes the contents of definitions files in the Library will not necessarily be able to recompile the application to use the modified definitions.)
- b) Accompany the work with a written offer, valid for at least three years, to give the same user the materials

specified in Subsection 6a, above, for a charge no more than the cost of performing this distribution.

c) If distribution of the work is made by offering access to copy from a designated place, offer equivalent access to copy the above specified materials from the same place.

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It may happen that this requirement contradicts the license restrictions of other proprietary libraries that do not normally accompany the operating system. Such a contradiction means you cannot use both them and the Library together in an executable that you distribute.

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END OF TERMS AND CONDITIONS

Appendix: How to Apply These Terms to Your New Libraries

If you develop a new library, and you want it to be of the greatest possible use to the public, we recommend making it free software that everyone can redistribute and change. You can do so by permitting redistribution under these terms (or, alternatively, under the terms of the ordinary General Public License).

To apply these terms, attach the following notices to the library. It is safest to attach them to the start of each source file to most effectively convey the exclusion of warranty; and each file should have at least the "copyright" line and a pointer to where the full notice is found.

```
<one line to give the library's name and a brief idea of what it does.>
Copyright (C) <year> <name of author>
```

```
This library is free software; you can redistribute it and/or
modify it under the terms of the GNU Library General Public
License as published by the Free Software Foundation; either
version 2 of the License, or (at your option) any later version.
```

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```

```
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License along with this library; if not, write to the Free
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```

Also add information on how to contact you by electronic and paper mail.

You should also get your employer (if you work as a programmer) or your school, if any, to sign a "copyright disclaimer" for the library, if necessary. Here is a sample; alter the names:

```
Yoyodyne, Inc., hereby disclaims all copyright interest in the
library `Frob' (a library for tweaking knobs) written by James Random Hacker.
```

```
<signature of Ty Coon>, 1 April 1990
Ty Coon, President of Vice
```

That's all there is to it!

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Tecio

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Utfcpp

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Vtk

/*****

Program: Visualization Toolkit
Module: Copyright.txt

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Zlib

ZLIB DATA COMPRESSION LIBRARY

zlib 1.2.12 is a general purpose data compression library. All the code is thread safe. The data format used by the zlib library is described by RFCs (Request for Comments) 1950 to 1952 in the files <http://tools.ietf.org/html/rfc1950> (zlib format), [rfc1951](http://tools.ietf.org/html/rfc1951) (deflate format) and [rfc1952](http://tools.ietf.org/html/rfc1952) (gzip format).

All functions of the compression library are documented in the file `zlib.h` (volunteer to write man pages welcome, contact zlib@gzip.org). A usage example of the library is given in the file `test/example.c` which also tests that the library is working correctly. Another example is given in the file `test/minigzip.c`. The compression library itself is composed of all source files in the root directory.

To compile all files and run the test program, follow the instructions given at the top of `Makefile.in`. In short `./configure; make test`, and if that goes well, `make install` should work for most flavors of Unix. For Windows, use

one of the special makefiles in win32/ or contrib/vstudio/ . For VMS, use make_vms.com.

Questions about zlib should be sent to <zlib@zip.org>, or to Gilles Vollant <info@winimage.com> for the Windows DLL version. The zlib home page is <http://zlib.net/> . Before reporting a problem, please check this site to verify that you have the latest version of zlib; otherwise get the latest version and check whether the problem still exists or not.

PLEASE read the zlib FAQ http://zlib.net/zlib_faq.html before asking for help.

Mark Nelson <markn@ieee.org> wrote an article about zlib for the Jan. 1997 issue of Dr. Dobbs's Journal; a copy of the article is available at <http://marknelson.us/1997/01/01/zlib-engine/> .

The changes made in version 1.2.12 are documented in the file ChangeLog.

Unsupported third party contributions are provided in directory contrib/ .

zlib is available in Java using the java.util.zip package, documented at <http://java.sun.com/developer/technicalArticles/Programming/compression/> .

A Perl interface to zlib written by Paul Marquess <pmqs@cpan.org> is available at CPAN (Comprehensive Perl Archive Network) sites, including <http://search.cpan.org/~pmqs/IO-Compress-Zlib/> .

A Python interface to zlib written by A.M. Kuchling <amk@amk.ca> is available in Python 1.5 and later versions, see <http://docs.python.org/library/zlib.html> .

zlib is built into tcl: <http://wiki.tcl.tk/4610> .

An experimental package to read and write files in .zip format, written on top of zlib by Gilles Vollant <info@winimage.com>, is available in the contrib/minizip directory of zlib.

Notes for some targets:

- For Windows DLL versions, please see win32/DLL_FAQ.txt
- For 64-bit Irix, deflate.c must be compiled without any optimization. With -O, one libpng test fails. The test works in 32 bit mode (with the -n32 compiler flag). The compiler bug has been reported to SGI.
- zlib doesn't work with gcc 2.6.3 on a DEC 3000/300LX under OSF/1 2.1 it works when compiled with cc.
- On Digital Unix 4.0D (formerly OSF/1) on AlphaServer, the cc option -std1 is necessary to get gzprintf working correctly. This is done by configure.
- zlib doesn't work on HP-UX 9.05 with some versions of /bin/cc. It works with other compilers. Use "make test" to check your compiler.
- gzdopen is not supported on RISCOS or BEOS.
- For PalmOs, see <http://palmzlib.sourceforge.net/>

Acknowledgments:

The deflate format used by zlib was defined by Phil Katz. The deflate and zlib specifications were written by L. Peter Deutsch. Thanks to all the people who reported problems and suggested various improvements in zlib; they are too numerous to cite here.

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