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Validation of TELEMAC for tsunami inundation modelling in compliance with the NOAA-NTHMP benchmark test cases

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Abstract – **This paper presents initial results from an ongoing validation exercise aimed at validating TELEMAC for tsunami inundation modelling in compliance with the National Oceanic and Atmospheric Administration (NOAA) National Tsunami Hazard Mitigation Program (NTHMP) benchmark test cases.**

Keywords: tsunamis, validation, runup, inundation, TELEMAC-2D, TELEMAC-3D

I. INTRODUCTION

Predicting natural disasters and their likely impact on the natural and built environment is a fundamental step towards the development of better-informed global risk management strategies, contributing to worldwide risk reduction and mitigation. In this context, accurate and effective modelling of tsunamis is not only vital for the safety of coastal communities but contributes to the creation of safer and more resilient world.

The capacity of the TELEMAC solvers to qualitatively model tsunamis has already been proven in previous publications and is further discussed in the twin paper [12] presented for the conference. The purpose of this paper is to present initial results from an ongoing validation exercise aimed at validating TELEMAC for tsunami inundation modelling in compliance with the National Oceanic and Atmospheric Administration (NOAA) National Tsunami Hazard Mitigation Program (NTHMP) benchmark test cases. The initiative was discussed at the last TELEMAC Scientific Committee at the EDF R&D Lab in Chatou, Paris, which confirmed the interest of the TELEMAC users' community as this is expected not only to strengthen the confidence in the usability of TELEMAC for this specific task but is now also a requirement introduced by ASCE 7-16 [11] or the use of any modelling tool in assessing tsunami induced inundation.

II. THE NOAA NTHMP BENCHMARK TEST CASES

Held on March 31st to April 2nd, 2011, at Texas A&M University at Galveston under the auspices of the NTHMP Mapping and Modelling Subcommittee (MMS), the Model Benchmarking workshop participants were tasked with developing and implementing a strategy for the validation of tsunami inundation models.

The workshop report is accessible at [5] and includes a list of NTHMP benchmark tests, which is a further evolution of the set of test cases identified in the OAR-PMEL-135 report [6].

The three categories of reference data used for defining benchmark tests for tsunami numerical model validation and verification are: (a) analytical solutions; (b) laboratory experiments; (c) field measurements.

Accordingly, the proposed benchmark test cases include:

- Analytical benchmarking
  - BP01 - Solitary Wave on a Canonical Beach
  - BP02 - Solitary Wave on a Composite Beach
  - BP03 - Subaerial landslide on simple beach
- Laboratory benchmarking
  - BP04 - Solitary Wave on a Canonical Beach
  - BP05 - Solitary Wave on a Composite Beach
  - BP06 - Solitary wave on a conical island
  - BP07 - Tsunami runup onto a complex three-dimensional beach, Monai Valley
  - BP08 - Tsunami generation and runup due to three-dimensional landslide
- Field benchmarking
  - BP09 - Okushiri Tsunami
  - BP10 - Rat Islands Tsunami

Different acceptability criteria apply to each test, which reflects the complexity of the phenomena being represented as well as the uncertainty in the target values. In this paper we present initial results obtained addressing analytical benchmarking only. A full description of each test case included in the full set can be found in [2], technical information needed to generate test cases and check model results can be found at: https://github.com/rjleveque/nthmp-benchmark-problems.

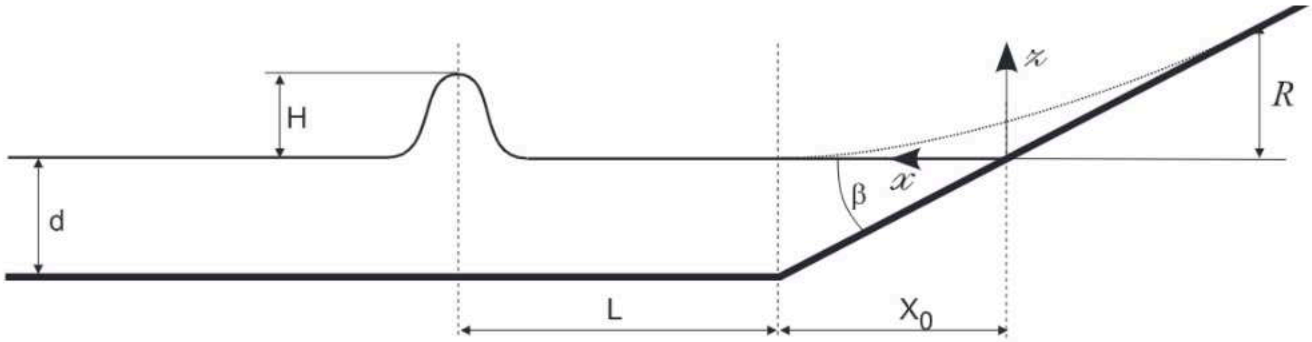
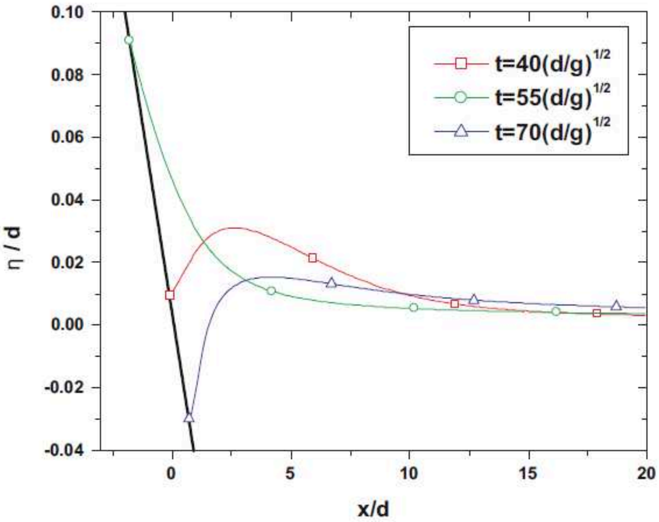


Figure 1. Model setup according to the NOAA NTHMP Benchmark test case "Solitary wave on a slope beach"



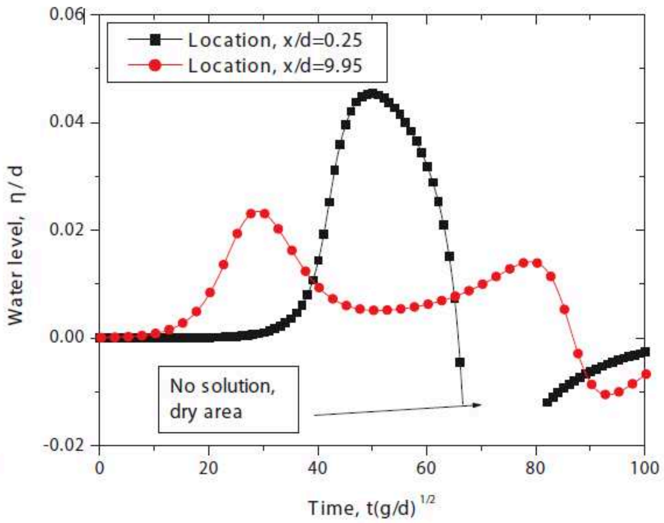


Figure 2. Left: non-dimensional water profile for specific time-steps. Right: non-dimensional water profile at two different probe locations

III. Analytical Benchmarking

A. General overview

The evolution of the tsunami waves from ocean areas to its nearshore targets is modelled in order to calculate tsunami currents, forces, and runup on coastal structures as well as coastal inundation.

For this scope, analytical formulations like the shallow water wave equations are useful for validating numerical models like TELEMAC.

The usefulness of the benchmarking relies on the comparisons of the numerical predictions with analytical solutions for identifying systematic errors, as when using friction factors or dissipative terms to augment the idealized equations of fluids motion.

This document shows only 1+1 (one directional and time) propagation problems.

B. BP01 - Solitary Wave on a Canonical Beach

1) Description of the test case

In this test, the bathymetry consists of a channel of constant depth d, connected to a plane sloping beach of angle β = acot (19.85) = 2.88º. A sketch (with distorted scale) of the canonical beach is displayed in Figure 1. The x coordinate increases monotonically seaward, x = 0 is the initial shore location, and the toe of the beach is located at $x = X_0 = d \cdot \cot(\beta)$.

2) Model setup

The wave of height H is initially centered at $X = X_S$ at t = 0 s. This benchmark test is focused on modeling the runup of an incident non-breaking solitary wave such that H/d = 0.0185, where H/d is the dimensionless wave height.

The initial wave profile η is given by:

$$\eta(x,0) = H\mathrm{sech}^2\left(\gamma(x - X_1)/d\right)$$

The initial water particle velocity u is given by:

$$u(x,0) = -\sqrt{g/d}\ \eta(x,0)$$

3) Results

Results from the model were compared with analytical solution, in terms of:

- water level at specific time-steps,
- water levels at prescribed locations,
- maximum run-up.

For the test to be successfully passed, results from the numerical model must be within 5% of the calculated value from the analytical solution.

NTHMP suggests specific guidelines to validate the numerical model against the analytical solution. For accomplishing this benchmark, TELEMAC3D water level results need to be compared at different timesteps:

- $t = 40 \cdot (d/g)^{1/2}$,
- $t = 55 \cdot (d/g)^{1/2}$,
- $t = 70 \cdot (d/g)^{1/2}$.

Further comparisons should be computed to present water level dynamics at different locations during both the propagation and the reflection phases:

- x/d = 0.25,
- x/d = 9.95.

Computation of the maximum runup, according to the formulation provided by Synolakis (1986, 1987, 2017), must be provided for comparison with the maximum runup modelled with TELEMAC-3D.

Water levels at specific timesteps are compared with the analytical solution in Figure 3. The model appears to be able to represent well the evolution of the relevant process in space, both within the wet and dry regions.

Water levels at specific locations are compared with the analytical solution in Figure 4. The model appears to be able to represent well the evolution of the relevant process in space, both within the wet and dry regions.

Maximum run-up R/d predicted by the model compare well with that calculated according to the analytical solution, respectively equals to 0.073 and 0.089.

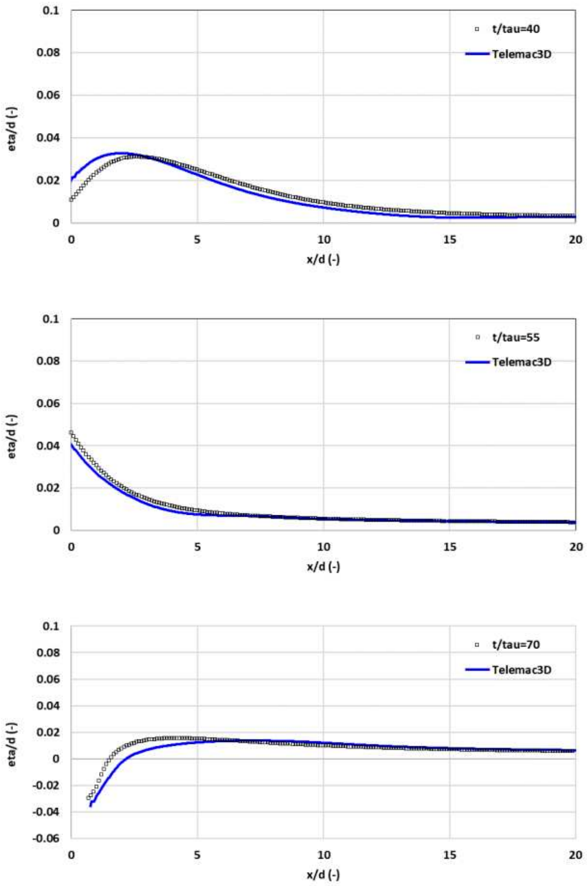


Figure 3. Solitary waves water level horizontal profile at different time-steps: during the propagation phase, the run-up of the wave along the slope and the run-down step

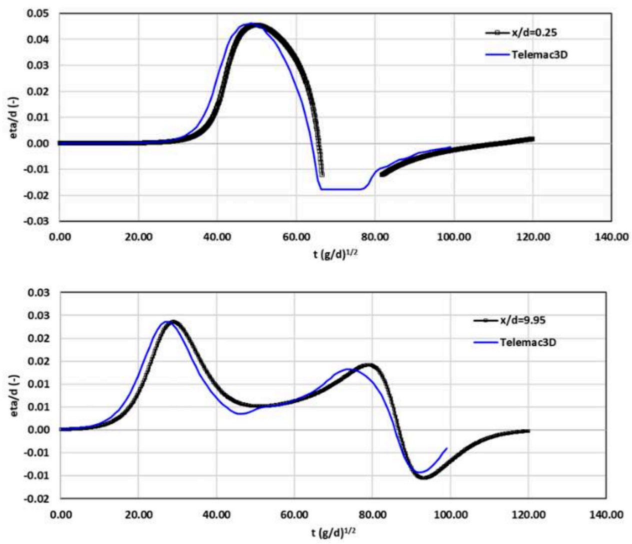


Figure 4. Non-dimensional water profile at two different probe locations

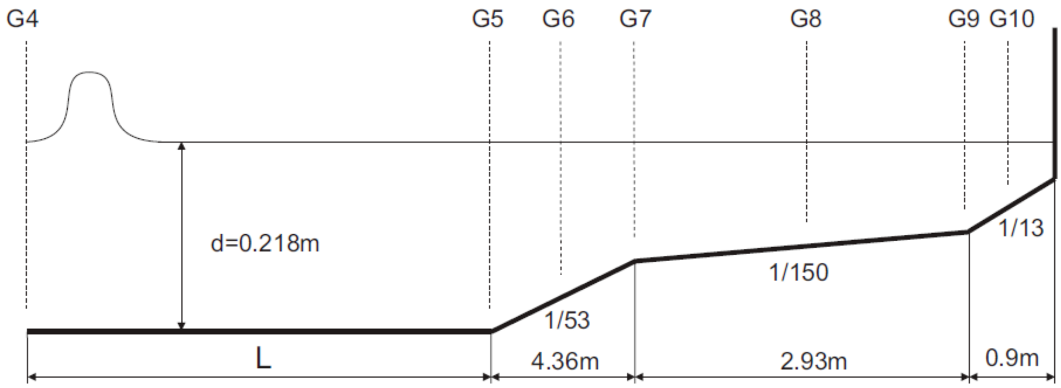


Figure 5. Model setup according to the NOAA NTHMP Benchmark test case “Solitary wave on a composite beach”

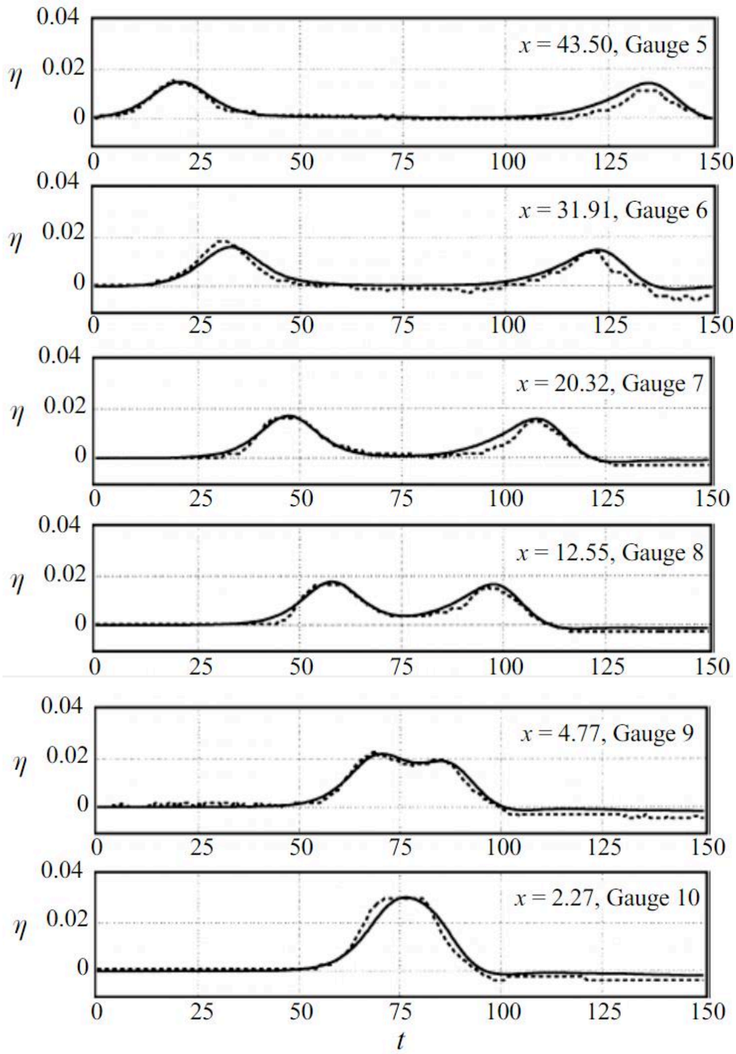


Figure 6. Dimensional water profiles at different probe locations

C. BP02 - Solitary Wave on a Composite Beach

1) Description of the test case

This benchmark has been based on a set of physical model tests performed in a water tank by the U.S. Army Corps of Engineers at the Coastal Engineering Research Center in Vicksburg, Mississippi. The numerical domain represents a composite beach simulating geometrical dimension of the Revere Beach.

Kânoĝlu and Synolakis (1998) developed an exact analytical solution to the linear shallow water equations to predict propagation and run-up of an incident solitary wave over the piece-wise linear bathymetry.

This analytical solution was proposed to be used as a benchmark problem by Synolakis et al. (2007).

2) Model setup

The model of the numerical flume presents an initial part having a constant depth and a length which is function of the wavelength. Furthermore, three different slopes follow the constant depth channel equal to 1/53, 1/150 and 1/13, respectively.

Probes are located at different distances from the reflecting wall at the right end of the channel:

- **G10** - 0.43 m distant from the wall,
- **G09** - 0.90 m distant from the wall,
- **G08** - 2.37 m distant from the wall,
- **G07** - 3.83 m distant from the wall,
- **G06** - 6.01 m distant from the wall,
- **G05** - 8.19 m distant from the wall,
- **G04** - 10.59 m distant from the wall.

3) Results

Results from the model were compared with analytical solution, in terms of:

- water levels at probes locations,
- water levels at the wall.

For the test to be successfully passed, results from the numerical model must be within 5% of the calculated value from the analytical solution.

Water levels at probes locations are compared with the analytical solution at location of probes locations in the next figures. The model appears to be able to represent well the evolution of the relevant process in time at the instrumented locations: reflection of the incident wave is qualitatively good represented by TELEMAC-3D.

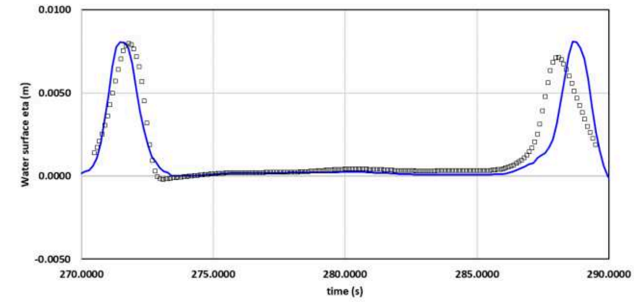


Figure 7. Solitary waves water level horizontal profile at G4 location. Black squared dot lines represent the analytical data. Blue lines are numerical results

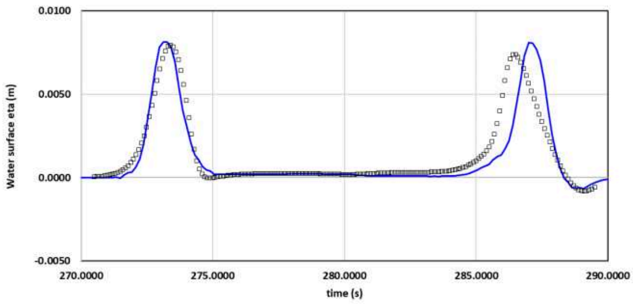


Figure 8. Solitary waves water level horizontal profile at G5 location. Black squared dot lines represent the analytical data. Blue lines are numerical results

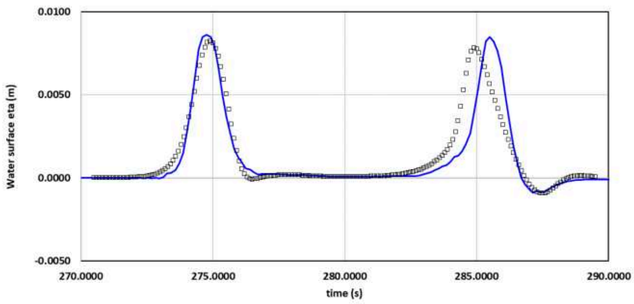


Figure 9. Solitary waves water level horizontal profile at G6 location. Black squared dot lines represent the analytical data. Blue lines are numerical results

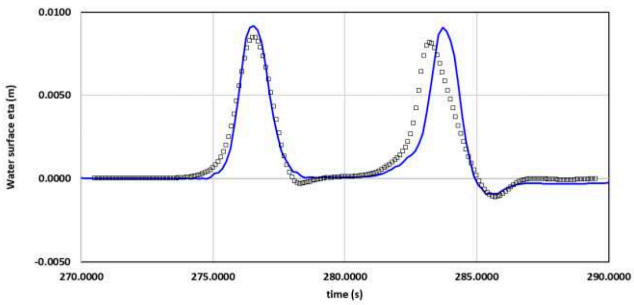


Figure 10. Solitary waves water level horizontal profile at G7 location. Black squared dot lines represent the analytical data. Blue lines are numerical results

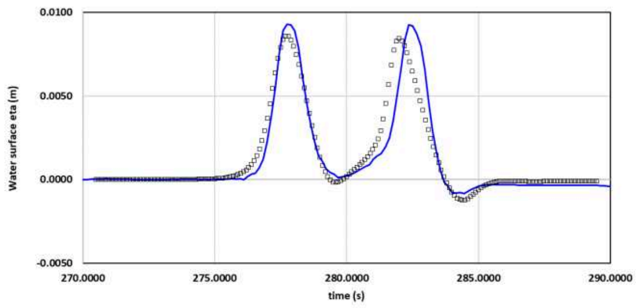


Figure 11. Solitary waves water level horizontal profile at G8 location. Black squared dot lines represent the analytical data. Blue lines are numerical results

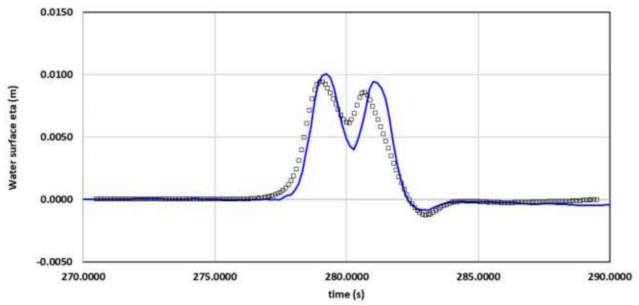


Figure 12. Solitary waves water level horizontal profile at G9 location. Black squared dot lines represent the analytical data. Blue lines are numerical results

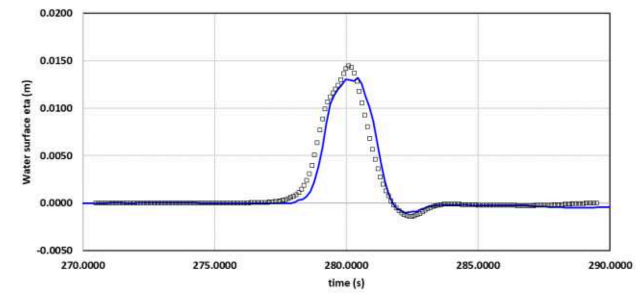


Figure 13. Solitary waves water level horizontal profile at G10 location. Black squared dot lines represent the analytical data. Blue lines are numerical results

IV. LABORATORY BENCHMARKING

A. General overview

Long before the spread availability of numerical codes as well as their increasing reliability and the advancement in computational power of the machines, physical modelling in laboratory at small scale have been used to analyse wave related processes for assessing specific hydraulic performances of the structures and eventually scale results to the prototype.

Nevertheless, nowadays physical models are still used in technical practice to confirm performances of non-standard design configurations, to study specific flow details in the fluid structure interactions and to validate numerical models to be used in the analysis and in the design process of maritime and coastal defences.

For the purpose of validating TELEMAC-3D, the scale differences are not believed to be significantly important. NTHMP reports a significant series of diverse benchmarks of numerical codes developed in the last decade that consistently produced predictions in excellent agreement with measurements from small-scale laboratory experiments. It has been shown that these were able to model geophysical-scale tsunamis well. Furthermore, it has been shown that bottom friction tends to be less important than the inertia of the motion of such long waves like tsunamis.

B. BP04 - SOLITARY WAVE ON A CANONICAL BEACH (Laboratory)

1) Description of the test case

The experiments were conducted in a 31.73 m-long, 60.96 cm-deep, and 39.97 cm-wide flume located at the California Institute of Technology, Pasadena, California wave tank.

The bottom of the tank consisted of painted stainless-steel plates. A ramp was installed at one end of the tank to model the bathymetry of the canonical problem of a constant-depth region adjoining a sloping beach.

Several tests have been carried out (more than 40 experiments) with solitary waves running up the sloping beach (water depths ranging from 6.25 cm to 38.32 cm). The test case problem has been parametrized as follows: 3 parameters can be used to describe the different tests combinations - the offshore depth d; the height of the solitary wave H, and the beach slope β.

2) Model setup

The model of the numerical flume has been setup according to what already presented within the BP01 benchmark (Figure 1): an initial constant depth flume has been setup and the wave height imposed for satisfying the $H/d = 0.0185$ criteria. The wave height has been used as input to parametrize the initial water profile for perturbating the model with.

The beach presents a constant slope (cotβ = 19.85).

3) Results

Results from the model were compared with laboratory measurements, in terms of:

- water level at specific time-steps,
- maximum run-up.

NTHMP suggests specific guidelines to validate the numerical model against the analytical solution.

For accomplishing this benchmark, TELEMAC3D water level results need to be compared at different timesteps:

- t = 30 s - 40 s - 50 s - 60 s - 70 s.

Numerical results in terms of water profiles are provided in Figure 14 to Figure 18: numerical model (blue lines) is compared with the experiments and a good agreement is achieved.

The maximum run-up was measured during the experiments, and it is reported in non-dimensional form, R/d = 0.077. Run-up result from the numerical modelling is R/d = 0.07.

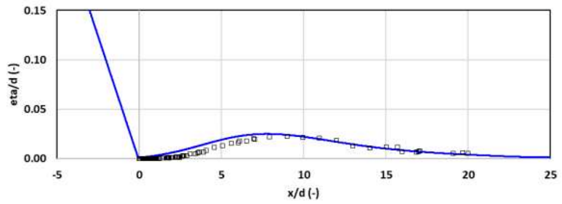


Figure 14. Solitary waves water level horizontal profile at t = 30 s time-step: laboratory measurements (black squared dots) against numerical model results (blue line)

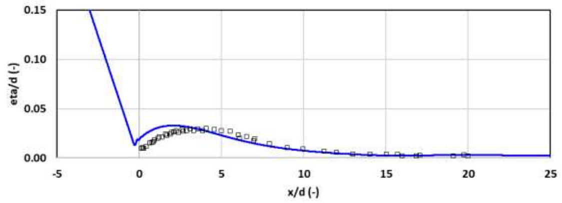


Figure 15. Solitary waves water level horizontal profile at t = 40 s time-step: laboratory measurements (black squared dots) against numerical model results (blue line)

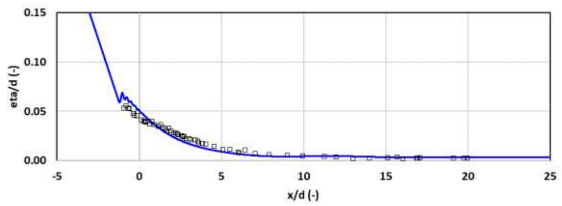


Figure 16. Solitary waves water level horizontal profile at t = 50 s time-step: laboratory measurements (black squared dots) against numerical model results (blue line)

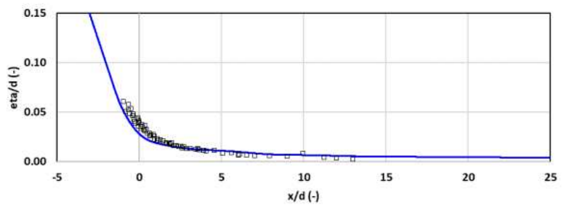


Figure 17. Solitary waves water level horizontal profile at t = 60 s time-step: laboratory measurements (black squared dots) against numerical model results (blue line)

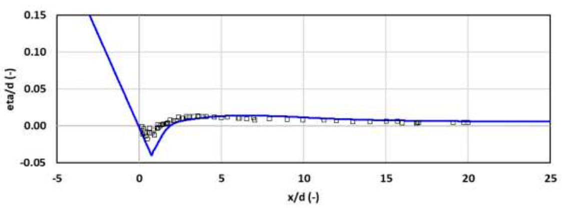


Figure 18. Solitary waves water level horizontal profile at t = 70 s time-step: laboratory measurements (black squared dots) against numerical model results (blue line)

C. BP05 - Solitary Wave On A Composite Beach (Laboratory)

1) Description of the test case

The original laboratory experiments which are presented in the BP05 benchmark were conducted in the Coastal & Hydraulics Laboratory of US Army Corps of Engineers. The set of the original tests to be used as reference are the same ones used for deriving the analytical solution in BP02.

The basin for the experiments was a long narrow flume with reflecting side walls (glass), as shown in Figure 5. The depth variation and all the wave motion occurred strictly in the direction along the flume, and all the measurements were taken on the flume's centreline. Thus a 1D approach seems reasonable to describe the case.

The wavemaker was used to generate solitary waves of the form:

$$\eta(x,0) = d_0 H sech^2(\sqrt{0.75H}x/d_0)$$

The velocities are complemented with corresponding elevation values:

$$v = \eta\sqrt{9.81/(d_0+\eta)}$$

2) Model setup

The model of the numerical flume has been setup according to what already presented within the BP02 benchmark (Figure 5): an initial constant depth of 0.218 m has been adopted as well as three different slopes equal to 1/53, 1/150 and 1/13, respectively. The wave height must satisfy the criteria H/d = 0.30 and it has been used as input to parametrize the initial water profile for perturbating the model with.

3) Results

Results from the model were compared with the laboratory data measurements, in terms of:

- water levels at probes locations,
- run-up at the wall.

The comparison of the water profiles at specific gauges are shown in Figure 19 to Figure 24: the images present the measurements (black squared dots) against the numerical results in TELEMAC-3D (blue lines) and a good agreement is achieved.

The maximum run-up was measured during the experiments, and it is reported in both dimensional and non-dimensional forms, R = 0.45 m and R/d = 2.10 respectively.

Run-up results from the numerical modelling are: R = 0.15 m and R/d = 0.69 respectively. This specific benchmark needs more investigations in order to get better agreement with the physical modelling measurements.

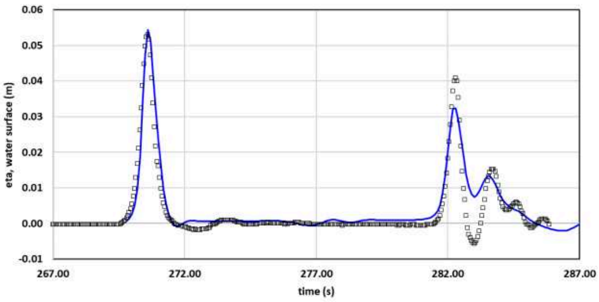


Figure 19. Solitary waves water level horizontal profile at G05 location. Black squared dot lines represent the laboratory data. Blue lines represent numerical results

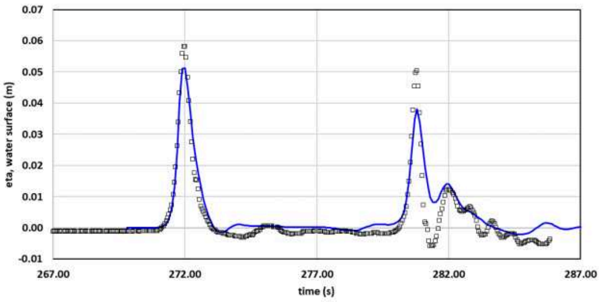


Figure 20. Solitary waves water level horizontal profile at G06 location. Black squared dot lines represent the laboratory data. Blue lines represent numerical results

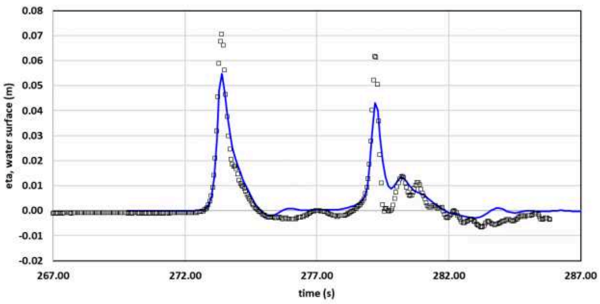


Figure 21. Solitary waves water level horizontal profile at G07 location. Black squared dot lines represent the laboratory data. Blue lines represent numerical results

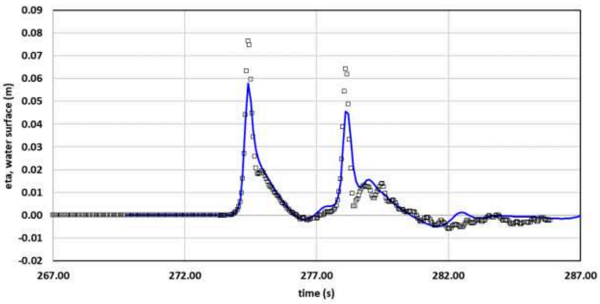


Figure 22. Solitary waves water level horizontal profile at G08 location. Black squared dot lines represent the laboratory data. Blue lines represent numerical results

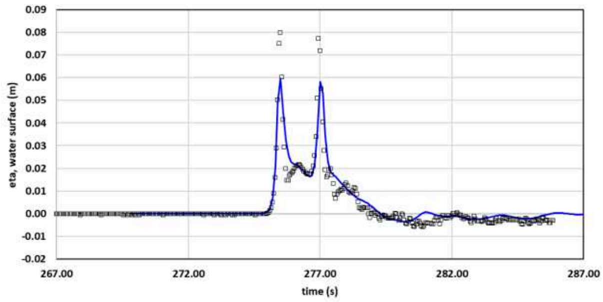


Figure 23. Solitary waves water level horizontal profile at G09 location. Black squared dot lines represent the laboratory data. Blue lines represent numerical results

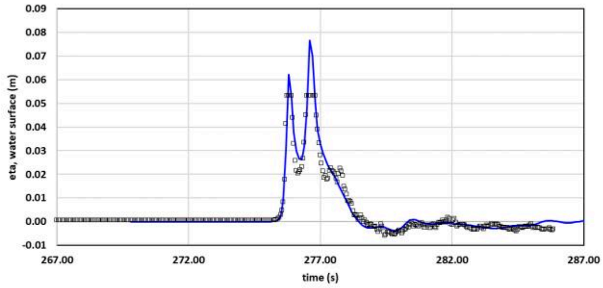


Figure 24. Solitary waves water level horizontal profile at G10 location. Black squared dot lines represent the laboratory data. Blue lines represent numerical results

FURTHER WORK

Work is ongoing to progress testing of TELEMAC with the whole set of benchmark tests. More investigations are needed to obtain better agreement with the reference results.

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