VALIDATION OF NUMERICAL CODES TO COMPUTE TSUNAMI RUNUP AND INUNDATION

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INTRODUCTION

FLOW 3D and NAMI DANCE are two numerical codes which can be applied to analysis of flow and motion of long waves. Flow 3D simulates linear and nonlinear propagating surface waves as well as irregular waves including long waves. NAMI DANCE uses finite difference computational method to solve nonlinear shallow water equations (NSWE) in long wave problems, specifically tsunamis. Both codes can be applied to tsunami simulations and visualization of long waves. Both codes are capable of solving flooding problems. However, FLOW 3D is designed mainly to solve flooding problem from land and NAMI DANCE is designed to solve flooding problem from the sea. These numerical codes are applied to some benchmark problems for validation and verification.

OBJECTIVE

One useful benchmark problem is the runup of solitary waves which is investigated analytically and experimentally by Synolakis (1987). Since 1970s, solitary waves have commonly been used to model tsunamis especially in experimental and numerical studies. In this respect, a benchmark problem on runup of solitary waves is a relevant choice to assess the capability and validity of the numerical codes on amplification of tsunamis. In this study both codes have been tested, compared and validated by applying to the analytical benchmark problem of solitary wave runup on a sloping beach. Comparison of the results showed that both codes are in good agreement with the analytical and experimental results and thus can be proposed to be used in inundation of long waves and tsunami hazard analysis.

EXPERIMENTAL MODEL

A detailed analysis of wave run up on shores is a necessity in order to assess the propagation limits of the incoming wave and possible damage on the nearby infrastructures in case of a tsunami or a strong storm surge. Therefore, for tsunami inundation modeling wave runup is one of the key parameters. The benchmark problem consists of analytical and experimental investigations regarding runup of solitary waves on a sloping beach.

A ramp having a slope of 1:19.85 is installed at one end of the wave tank to model the sloping beach of the problem. A representative sketch of the setup is given in Figure 1. The description of experimental apparatus as well as the experimental data are given in the study of Synolakis (1986) in detail.

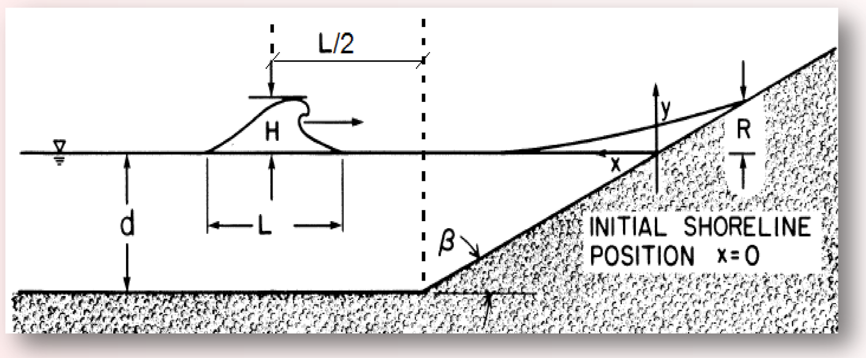

Figure 1. A definition sketch of the problem (Synolakis,1986)

Height to depth ratio, H/d, and undisturbed water depth, d, are the two parameters that are used to define a solitary wave. The wave height values that are used in the experiments are between 6.25 cm and 38.32 cm. The H/d values range from 0.021 to 0.626. Synolakis (1986) emphasizes that there are two different runup regimes for breaking and nonbreaking waves and describes nonbreaking solitary waves as the waves that do not break during runup. He also states that breaking for this particular beach slope occurs first during backwash when H/d value is larger than 0.044.

$$\frac{R}{d} = 2.831\sqrt{\cot\beta}\left(\frac{H}{d}\right)^{5/4} \qquad \text{(Equation 1)}$$

Synolakis (1986) also developed a formula depending on the results of the experiments. Equation 2 gives the maximum runup of breaking solitary waves based on the maximum position of the shoreline for the specific beach slope of 1:19.85.

$$\frac{R}{d} = 1.109\left(\frac{H}{d}\right)^{0.582} \qquad \text{(Equation 2)}$$

where,

H is the height of solitary wave, R is the maximum runup of waves, d is the undisturbed water depth, β is the slope angle of the beach.

Solitary wave length is theoretically infinite. However, for practical purposes it is defined as the distance between the point on the front, x_f, and the point on the tail, x_t, where the local height is 1% of the maximum, i.e. $\eta(x_f, t=0) = \eta(x_t, t=0) = (H/d)/100$. For this study, the local height is taken as 5% of the maximum; therefore, the length of a solitary wave is formulated as:

$$L = \frac{2}{\gamma}\operatorname{arccosh}\left(\sqrt{\frac{1}{0.05}}\right) \qquad \text{(Equation 3)} \qquad \text{where} \qquad \gamma = \sqrt{\frac{3H}{4d^3}}$$

Solitary waves of different heights have different wavelenghts. Each solitary wave is generated L/2 distance away from the toe of the ramp; therefore, the initial location in the analytical consideration changes with different wave heights.

Synolakis (1987) presented the comparison of laboratory and analytical data regarding the maximum runup of solitary waves climbing up the sloping beach.

NUMERICAL MODEL – FLOW 3D

Flow 3D is a computational fluid dynamics (CFD) software that allows highly accurate simulations of free surface flows by using volume of fluid technique (VOF). It is validated over a wide range of water and environmental issues such as large hydroelectric power projects, dam break cases, avalanches, fish passages and small municipal wastewater treatment systems. It also has the capability to simulate regular linear and nonlinear propagating surface waves as well as irregular waves. Linear wave theory is used to simulate small amplitude gravity waves. Fifth-order Stokes' wave theory and Fenton's fourier series method are used to simulate Stokes and cnoidal waves. Solitary waves are simulated using the theory of McCowan (1891) which is recommended by Munk (1949) after several investigations.

Flow 3D is yet to be validated for different cases of wave mechanics. The benchmark problem presented in this study is selected and modeled using Flow 3D to make a contribution to this issue and to assess whether the code is suitable for tsunami inundation modeling in real cases or not.

The dimensions of the experimental apparatus are kept intact in the model. The code gives initial solitary wave at t=0 with a wave celerity, C, which is formulated as:

$$C = \sqrt{g(d+H)} \qquad \text{(Equation 4)}$$

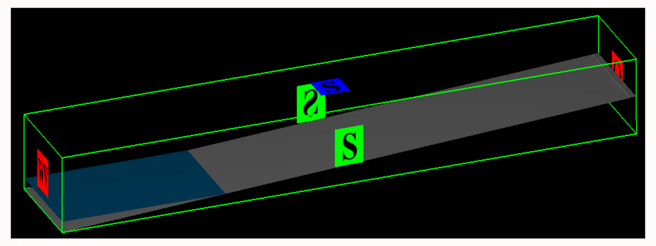

Figure 2. Flow 3D Model

For x-min and x-max boundaries, wave and symmetry boundary conditions are applied, respectively. Wave boundary condition applies a velocity field associated with the selected wave type. Specifically, solitary wave boundary condition is used for this study. The height of the solitary wave and the undisturbed water depth are the inputs to this model. Symmetry boundary condition applies a zero-gradient and a zero velocity condition normal to the boundary and it is also used for y-min, y-max and z-max boundaries. For z-min, wall boundary condition is used. Wall boundary condition applies no slip condition between the fluid and solid surfaces as well as zero velocity condition normal to the boundary. Pressure is zero on the free surface. Pressure distribution is accepted as hydrostatic throughout the computational domain. Duration of simulations is selected as 270 sec.

NUMERICAL MODEL – NAMI DANCE

NAMI DANCE is developed in collaboration with METU, Turkey and Special Bureau of Automation of Research Russian Academy of Sciences, Russia. NAMI DANCE uses finite difference computational method to solve non-Linear Shallow Water Equations (NSWE) to model long wave problems, specifically tsunamis (NAMI DANCE, 2010). It provides direct simulation and efficient visualization of tsunamis to the user as well as the assessment, understanding and investigation of tsunami generation and propagation mechanisms. It is developed by C++ programming language by following leap frog scheme numerical solution procedures. In addition to necessary tsunami parameters, NAMI DANCE also computes the distributions of current velocities and their directions at selected time intervals, relative damage levels according to drag and impact forces, and it also prepares 3D plots of sea state at selected time intervals from different camera and light positions, and animates the tsunami propagation from source to target. NAMI DANCE is able to perform calculations by using all processors of the executed computer and thus increases the simulation speed considerably.

COMPARISON OF RESULTS

The maximum runup of solitary waves climbing up to a beach having a slope of 1:19.85 are compared analytically and numerically for nonbreaking runup regime. For breaking runup regime, the runup values that are obtained from numerical modeling are compared with experimental values.

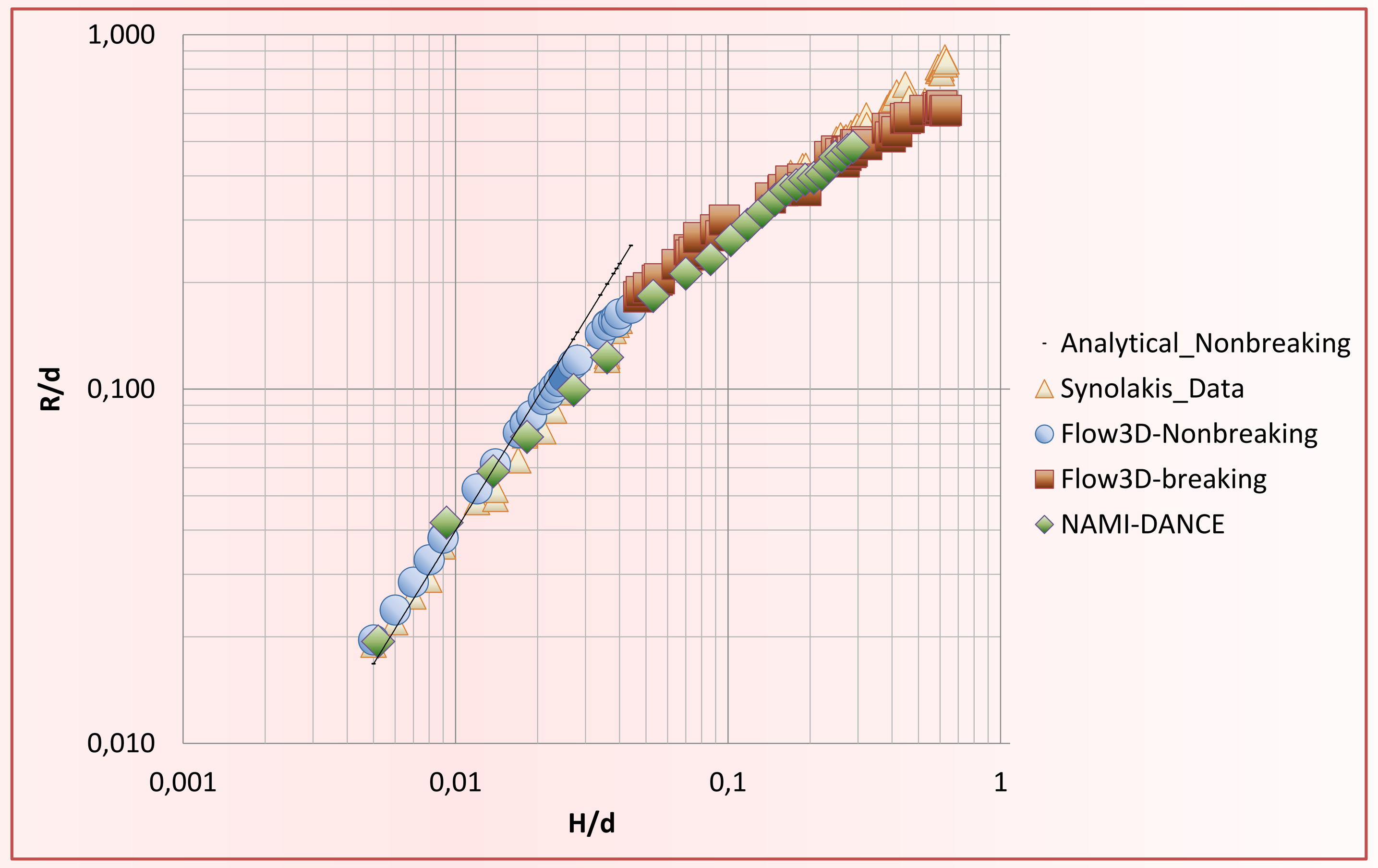

Figure 3. Numerical, experimental and analytical comparison of maximum runup values

In addition to this study, another analytical benchmark problem regarding runup of long waves on a plane beach is studied using NAMI DANCE code. The problem is solved theoretically by Kânoglu (2007). Beach slope is extended to infinite and fixed at 1/10. The 2D channel cross-section and the initial free surface elevation as a certain wave with specific shape are given in Figures 4 and 5. The numerical and analytical results of the water level at certain time steps are compared at a certain distance from shore line.

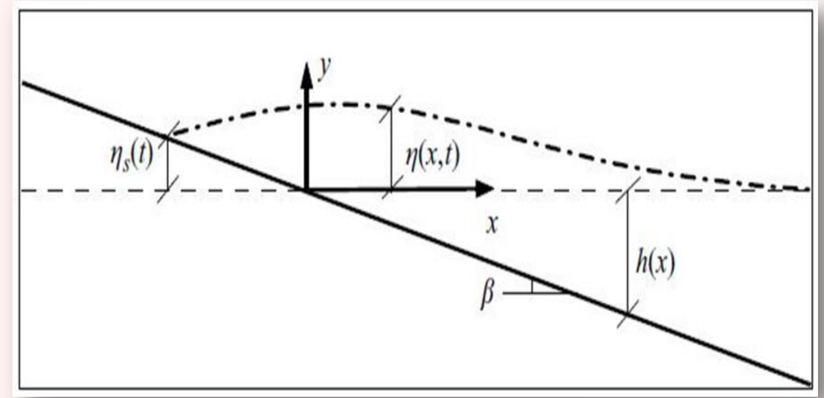

Figure 4. Definition sketch of sloping beach which is used in analytical benchmarking

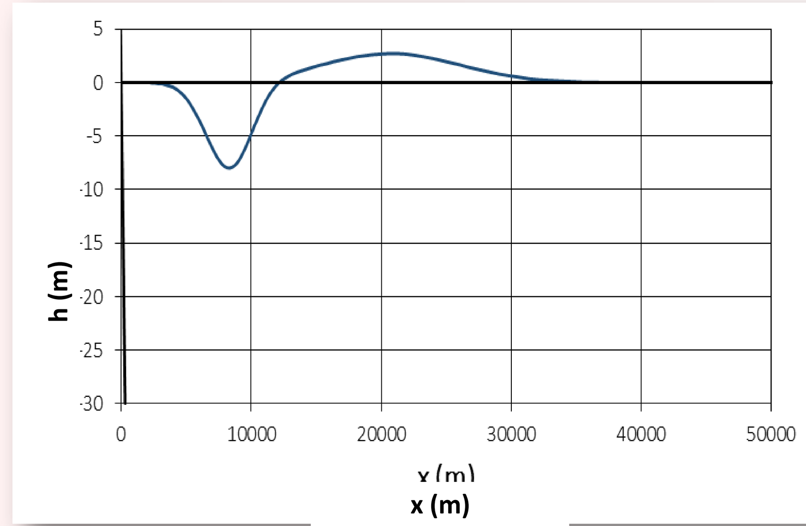

Figure 5. Problem of runup on a 1/10 sloping beach
(distorted cross section of the 2D channel - thick black line, and the initial wave - blue line)

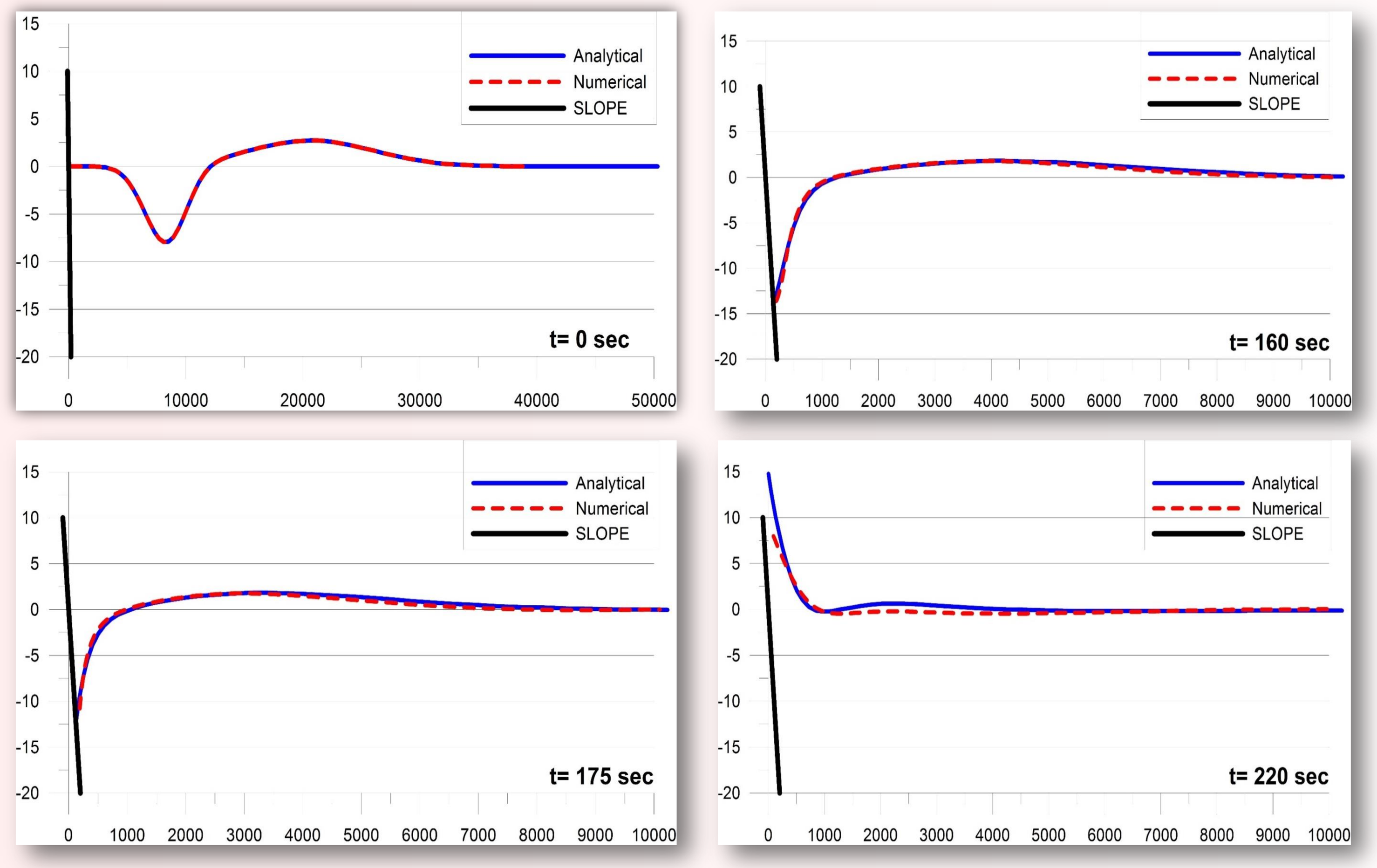

Figure 6. Water surface elevations along the axis perpendicular to shoreline at t=0 sec, t=160 sec, t=175 sec and t=220 sec
(Units are in meters)

CONCLUSION

The results obtained from both codes are in agreement with the analytical data as well as the experimental data. The maximum runup values obtained from the codes are close to the experimental results. For the second benchmark problem, the wave profiles obtained using NAMI DANCE show very close similarity with the theoretical solution. Flow 3D and NAMI DANCE give satisfactory results regarding wave runup phenomenon. For future work, both models will be applied to a case study in order to investigate the possible inundation of long waves in Turkey.

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