Development of tsunami modelling analysis route

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Introduction

Following the Great East Japan earthquake of March 11th, 2011, in which the associated tsunami event gave rise to the Fukushima nuclear accident, it was decided to investigate the idea of developing a tsunami modelling capability. The starting point in this activity was to acquire the book and associated software in [1], which includes a 2HD (two horizontal dimensions) non-linear shallow water modelling program MC/SWAN (referred to in this document as "MC/SWAN", to avoid confusion with other programs called SWAN). The overall objective is to produce a program, or a set of programs, which can model the Great East Japan earthquake from its initial seafloor displacement source up to the calculation of run-up at the Fukushima nuclear plants.

Modified version of MC/SWAN program

The modified program, written in Fortran 77, is called TSUNWAVE. The main modifications from MC/SWAN are:

(a) The single precision coding was converted to double precision for TSUNWAVE as the amount of available RAM is much less of a constraint on modern personal computers.

(b) The original program was designed to be used in conjunction with the MCGRAPH graphics program, which is included with the software provided in [1]. For TSUNWAVE it was preferred to carry out wave height time history plotting using spreadsheet programs, and contour plotting of finite difference grid data using the R statistical analysis program [2], which incorporates an extensive graphics capability.

(c) A feature was introduced to search for the maximum wave height versus time seen in the entire grid, the water region of the entire grid, or within a specified rectangular land area. This feature allows maximum run-up in a land area to be determined without having to plot graphs.

(d) The strategy in the original program was to specify a simplified vertical seafloor displacement pattern, which can potentially vary with time, by modifying the program coding for a specific problem. In TSUNWAVE, the program coding is not modified for the specific problem, and has been set up to handle four types of general vertical seafloor displacement input: (i) specification of individual grid cells and their displacements, which can also vary with time, (ii) a set of grid cells given a uniform displacement within a specified polygon shape, (iii) as (ii) but using multiple polygon shapes to build up a more complex non-uniform displacement pattern, and (iv) specification of individual grid cells and their displacements with the input data generated by a separate program called OKADA. In the case of inputs (ii) and (iii), only the grid cells at the vertices of the polygons have to be specified. Input types (ii), (iii) and (iv) assume the seafloor displacement pattern is applied instantaneously.

(e) In addition to the sine wave input capability that is available at the rectangular grid boundaries in the original program, options to apply a solitary wave input and a general time history input were introduced at one of the boundaries to test TSUNWAVE's run-up analysis capability.

(f) A feature was introduced to re-set zero values in the input bathymetric and topographic data to a specified small non-zero value. The uvh subroutine interprets zero depth values at grid cells as being a reflective boundary condition, which was observed to cause some spurious results.

Tsunami generation phase

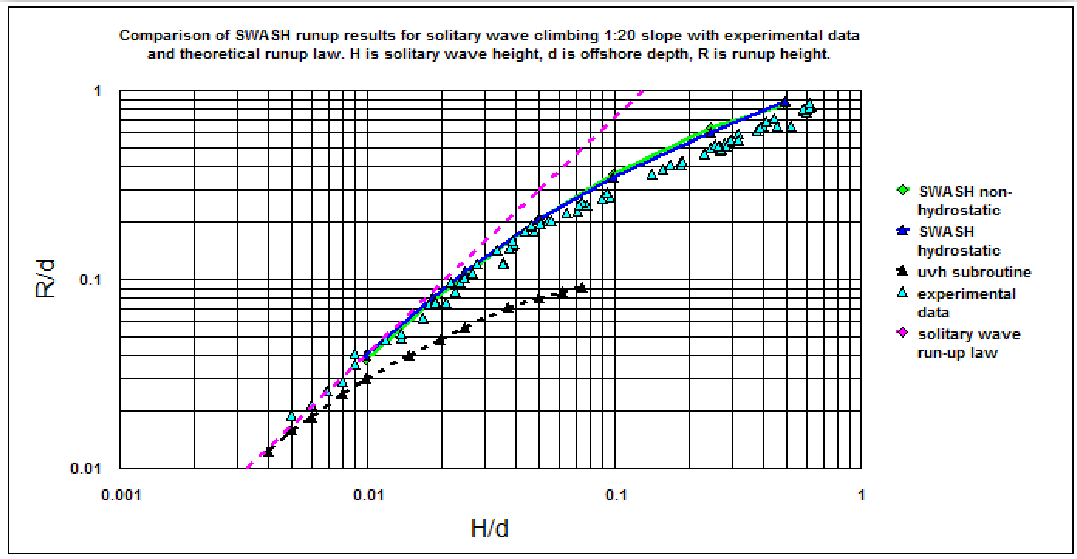
The most accurate way to define a seafloor displacement pattern for a tsunami event is to calculate the displacement pattern from geological fault information for the offshore earthquake. An approach for doing this, which is widely used in the contemporary tsunami modelling literature, is the Okada method given in [3]. The Okada method provides an analytical solution for the surface displacements generated by the slip of a rectangular fault source at an arbitrary orientation angle buried in a uniform half space. A Fortran 77 program called OKADA was written that is based on this method. The program can also handle an overall non-uniform distribution of slip over a fault surface by superposing the responses due to the slip of a number of individual rectangular sub-faults.

Inundation analysis phase

The inundation or run-up analysis capability of MC/SWAN appears to be satisfactory according to [4]. However testing of the program indicated that it was using a questionable assumption, that the dry land that is being inundated is in effect highly permeable, with water filling up each dry land cell from the still water level before advancing in-shore to adjacent dry land cells. The opposite assumption, that the dry ground is impermeable, would be more conservative and probably more realistic. It was thought advisable to check that TSUNWAVE gave satisfactory results using any modern benchmark problems for run-up analysis that might have appeared in more recent years.

A set of benchmark problems for tsunami analysis, which concentrate on modelling of near-shore wave propagation and run-up over dry land, are provided in NOAA's PMEL-135 document [5]. A 1HD (one horizontal dimension) test problem was adopted for the uvh subroutine which consists of a solitary wave of initial height H propagating along a constant depth region that is 2 km long and has a depth d of 200 m, before climbing a 1 in 20 slope which continues on to dry land, and produces a run-up height R above the initial shoreline position. As shown in the figure below, the uvh subroutine results for the solitary wave run-up test problem are quite poor in comparison with both the theoretical "run-up law" and experimental results for this slope ratio (actually for a very similar slope ratio of 1 in 19.85) available in [6]. The experimental results deviate from the run-up law due to wave breaking, and the run-up law may be substantially conservative at H/d ratios where wave breaking occurs.

An alternative option to using TSUNWAVE for run-up analysis, regarded as much simpler than attempting to carry out an extensive modification of the uvh subroutine, would be to adopt the program SWASH [7] instead. SWASH, which is specifically designed to model near-shore wave propagation and run-up, produces slightly conservative agreement with the experimental results in [6] for the solitary wave test problem. A computational grid with 10 m spacing was used in the SWASH analysis. The less satisfactory results observed with the uvh subroutine are not connected with its use of non-linear shallow water (NLSW) theory, despite NLSW not being ideal for the propagation of solitary waves. SWASH can also be run in a hydrostatic mode (equivalent to NLSW) rather than the preferred non-hydrostatic mode. The SWASH run-up curves show little difference between hydrostatic and non-hydrostatic analysis for this specific test problem.



It was concluded that it would be best to limit use of TSUNWAVE to propagation analysis from the seafloor displacement source up to near-shore locations, and then use a program potentially capable of passing the PMEL-135 benchmarks like SWASH for the inundation or run-up analysis of coastal land areas.

One of the PMEL-135 benchmark problems, a 1HD problem described as "solitary wave on composite beach", consists of a solitary wave which starts in a constant depth region and then climbs three underwater slope regions of different slope angles before being reflected from a partly submerged vertical wall. As this problem does not involve run-up over dry land, the uvh subroutine might give a better performance. It was found that the uvh subroutine does give satisfactory results in comparison with experimental results for "Case A" of the benchmark problem, which has an H/d ratio for the solitary wave of 0.0378, but gave unsatisfactory results for "Case B", which has a substantially higher H/d ratio of 0.2587, implying that non-hydrostatic analysis would be needed to model Case B.

Generation of detailed coastal grid

Inundation analysis generally requires a detailed coastal grid to be used. The coastal grid is composed of detailed bathymetric and topographic data available from various sources, and will usually have a finer spacing than a grid used for propagation analysis. The detailed bathymetric and topographic data will tend to be irregularly spaced when initially combined, and needs to be interpolated to form a regularly spaced coastal grid, which may have one or two horizontal dimensions. The 'akima package' available in the R program is to used to carry out the interpolation and generate the regularly spaced detailed coastal grid.

Bathymetric and topographic data normally has its positional information defined in a geographical co-ordinate system as latitude and longitude co-ordinates. The direction of the input tsunami wave or direction for a worst case input tsunami wave for an inundation analysis may not in general be lined up with the major geographical axes. A program called Grotate has been written which sets up bathymetric and topographic data in a specified rectangular area that is oriented at an oblique angle to the major geographical axes. The R akima package is then used to interpolate the data in this specified rectangular area to produce a regularly spaced detailed coastal grid.

Conclusions

1 The proposed overall analysis route is to use a set of three programs for the three general phases of tsunami modelling: OKADA to generate the initial detailed seafloor displacement boundary condition due to an offshore earthquake, TSUNWAVE to model the wave propagation from the deformed seafloor to near-shore locations, and finally SWASH to model inundation of a coastal land area using a wave height time history output by TSUNWAVE. It is proposed to use the R program for contour plotting and also to generate regularly spaced detailed coastal grids.

2 It is not recommended that the MC/SWAN program, supplied in a basic form in [1], is used for run-up analysis work. It is anticipated that it would produce unconservative run-up results even under the conditions given in [1] for the model being valid (wave period greater than 10 or 15 minutes, and slope greater than 2%).

References

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