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Modelling of tsunami waves generated by a subaerial landslide

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Introduction

Following on from previous work in modelling tsunami waves generated by underwater landslides (or submarine slides) reported in [1], which made use of a modelling approach described in [2] that is referred to in this document as "Iwasaki's method", it was thought that it might be interesting to see if this modelling approach could be extended further to handle tsunami waves generated by subaerial slides.

In a subaerial slide, the slide material originates from above the water level. An example of a subaerial slide, in which a large mass of soil material has slid down a steep slope into the sea (but which may not necessarily have generated a tsunami), is shown in Fig 1.

Figure 1 Example of subaerial slide

Iwasaki's method applied to subaerial slides

The essential difference in applying Iwasaki's method to the wave generated by a subaerial slide is that the slide material could be regarded as effectively having only one wave generating end, if the slide is assumed to be composed of loose material as in Fig 1, as opposed to the two wave generating ends that occur with a submarine slide. The left end of the slide material effectively remains stuck near the shoreline.

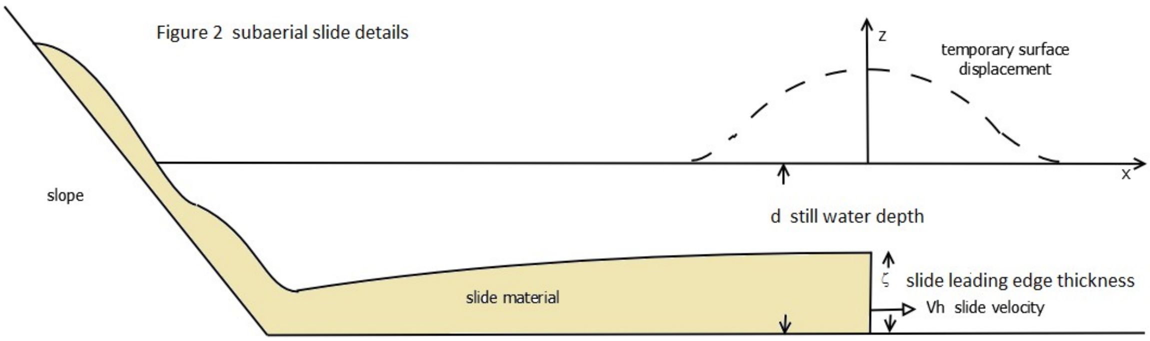

Figure 2 subaerial slide details

For a slide with a single wave generating end, the formula for the temporary surface displacement η generated over a time step Δt given in [1] is modified to:

$$\eta = \frac{V_h \Delta t}{\pi} \tanh^{-1}\left[\frac{\sin(\zeta\pi/2d)}{\cosh(x\pi/2d)}\right]$$

where, as shown in Fig 2, ζ is the thickness of the leading edge of the sliding material, d is the still water depth at the leading edge location, x is the horizontal distance measured from the moving leading edge, and V_h is the horizontal velocity of the leading edge. The numerator term sin(ζπ/2d) is limited to a value of 1 if $\zeta > d$.

Two potential limitations of applying this method to subaerial slides are:

(a) if the mass of material sliding down a steep slope into water reaches a sufficiently high velocity, an air cavity associated with a fast-moving projectile entering and travelling in water can form. The method does not take any account of the formation and subsequent collapse of this air cavity during the slide event.

(b) a substantial thickness of slide material could be deposited on the sea floor, potentially causing significant changes to the bathymetry of the sea floor during the analysis, whereas the method assumes that the bathymetry stays constant during the analysis.

The method is implemented in a slightly modified version of SOLA-3D called SUBSLIDE2.

Wave tank test problem

The wave tank test problem selected for checking whether SUBSLIDE2 works satisfactorily is based on test work described in [3], and the overall test arrangement is shown in Fig 3. The test work was aimed at explaining the extremely high run-up of 524 m observed in the Lituya Bay tsunami event of 1958 in Alaska, USA. The testing assumes that the slide was composed of loose material rather than being a solid block of material, and is based on the simplified 1HD (horizontal dimension) geometry shown in Fig 4. All results and information provided in [3] are given at the real world scale rather than the wave tank scale, so any computer modelling of the test problem would have to be carried out at the real world scale.

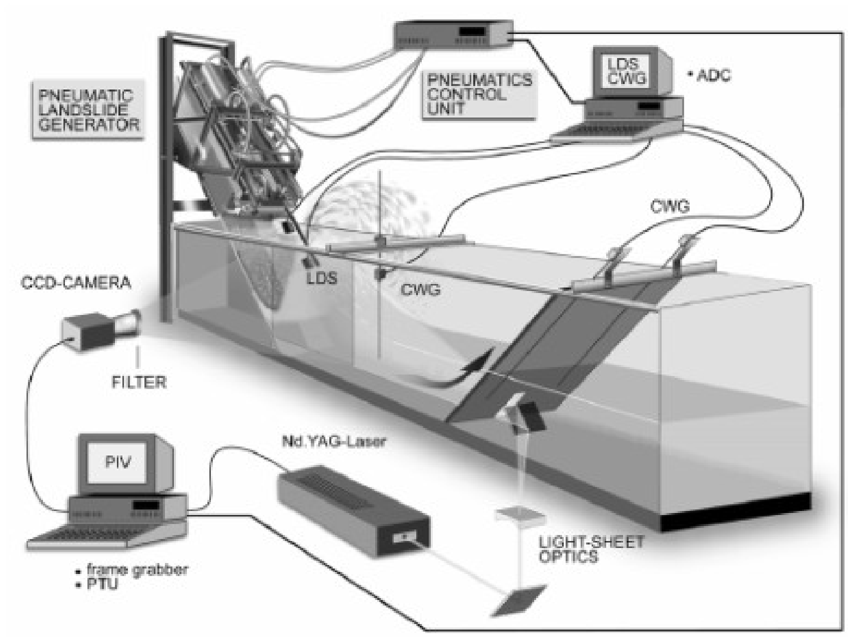

Figure 3 Lituya Bay wave tank test arrangement

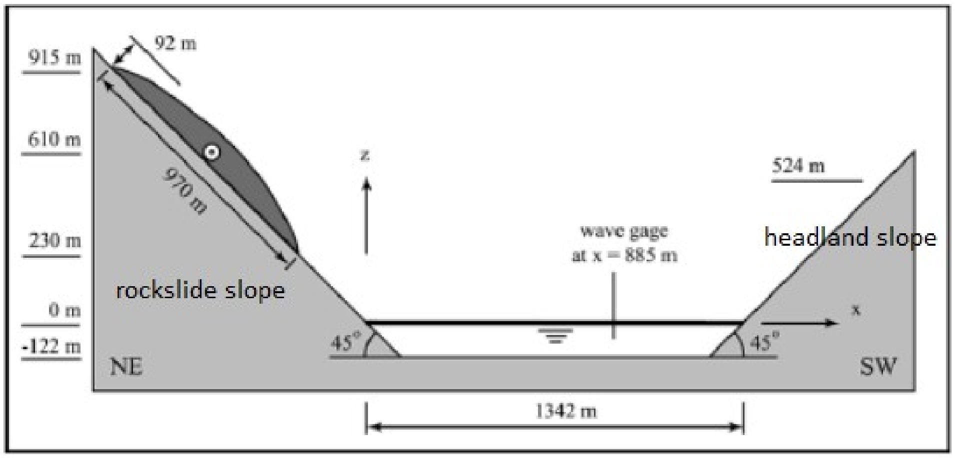

Figure 4 Geometry assumed for Lituya Bay wave tank test

A set of twelve figures is provided in [3] which show the granular sliding material cross-section and wave height profile at various times during the sliding event. A sample of four of these figures is shown in Fig 5a and Fig 5b. The time values quoted in Fig 5a and Fig 5b are measured from the initial impact of the sliding material with the water surface. Formation of an air cavity is evident in Fig 5a, and its subsequent collapse is evident in Fig 5b. The significant change to the bathymetry which occurs as a result of the depositing of slide material on the sea floor is also evident in Fig 5a and Fig 5b.

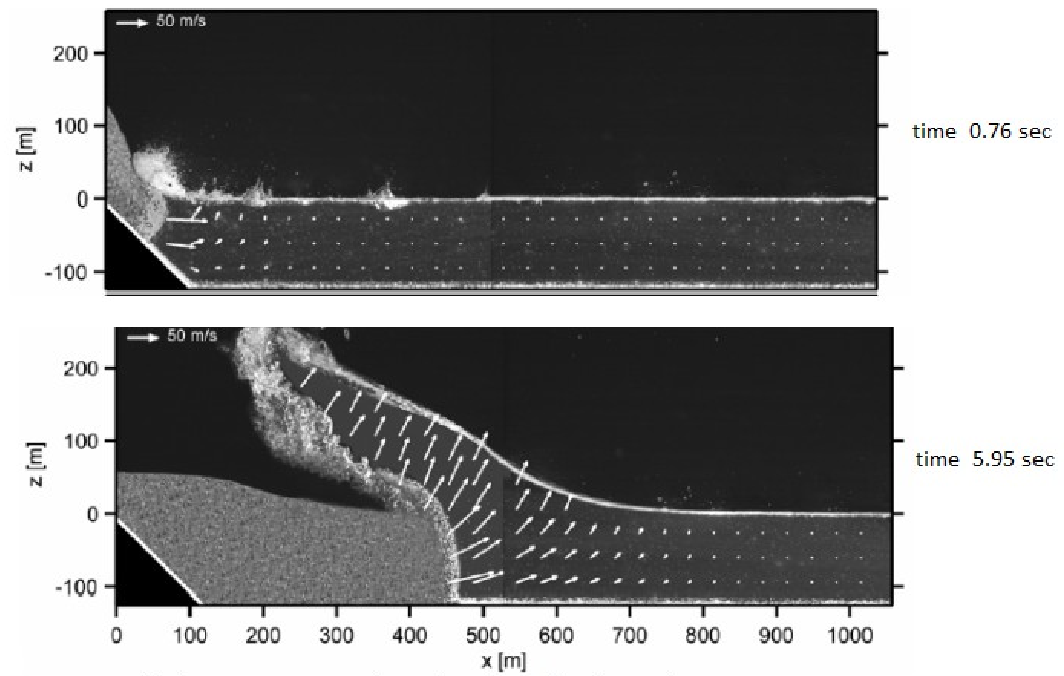

Figure 5a Landslide cross-section and wave height profile observed in test

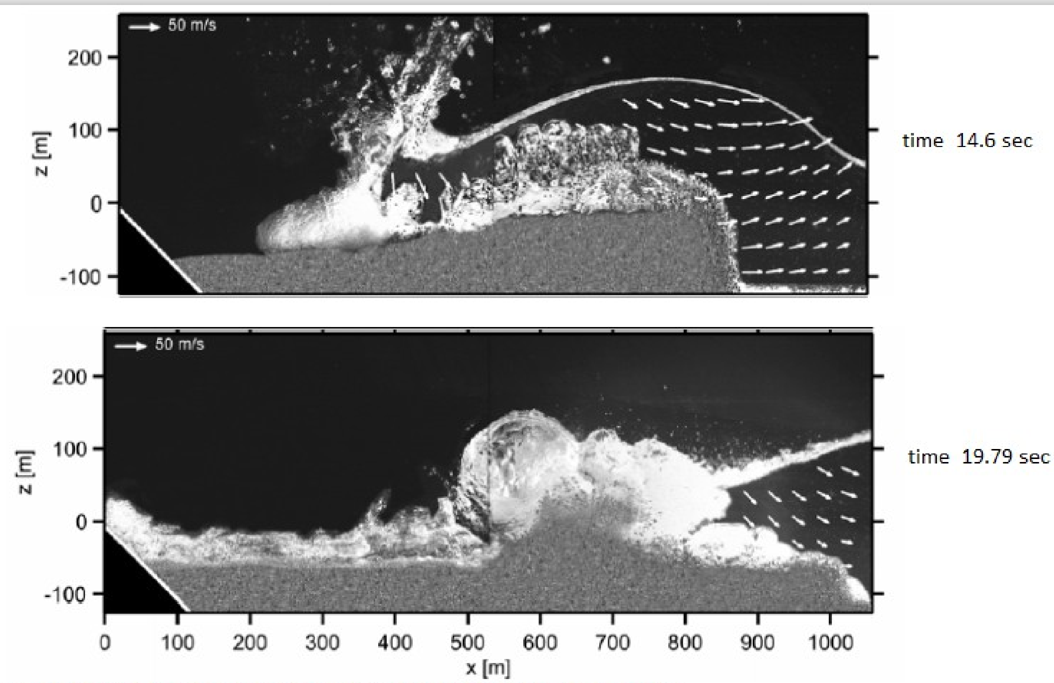

Figure 5b Landslide cross-section and wave height profile observed in test

A horizontal velocity time history for the leading edge of the sliding material is not available in [3], but the velocity time history can be approximately constructed from determining sliding displacements from the set of figures provided in [3] for the variation of the landslide cross-section with time. The estimated horizontal velocity time history input for the SUBSLIDE2 analysis is shown in Fig 6.

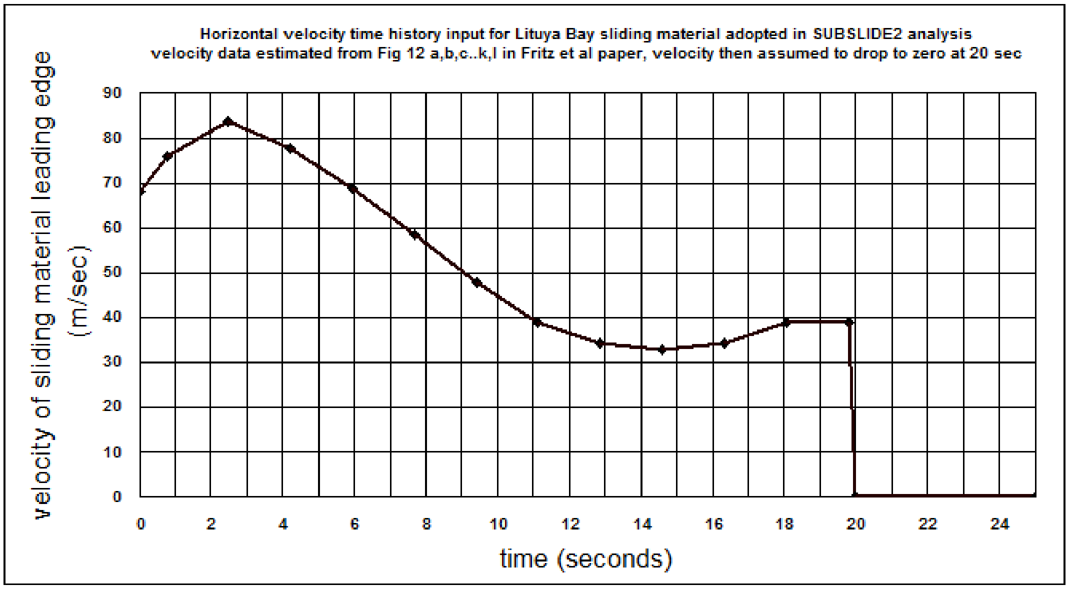

Figure 6

The horizontal grid spacing used in the SUBSLIDE2 analysis was 5 m (in the longitudinal direction of the tank) and the vertical grid spacing was also 5 m. The value for the thickness of the leading edge of the sliding material in the analysis was taken as being 100 m (a thickness of at least 100 m through nearly the whole sliding event can be justified from inspection of the landslide cross-section figures in [3]).

Comparison of SUBSLIDE2 results with test results

Test results are provided in [3] for a surface elevation time history at a distance of 885 m from the rockslide slope shoreline, and for a run-up time history for the headland slope.

The comparison between SUBSLIDE2 and the test result at the 885 m location is shown in Fig 7a. The first peak in the time history is represented fairly well by SUBSLIDE2. The agreement is worse for the second peak, which corresponds to a wave reflected from the headland slope. A major factor in the worse agreement might be that SUBSLIDE2 ignores the significant change in bathymetry that occurs at the 885 m location as a result of the slide event (Fig 5b shows that slide material was deposited for slightly over 1000 m from the rockslide slope shoreline). The modelling method in SUBSLIDE2 does not take any account of the formation and collapse of an air cavity during the slide event, but this issue does not appear to be important for the response at a distance as far as 885 m from the rockslide slope shoreline.

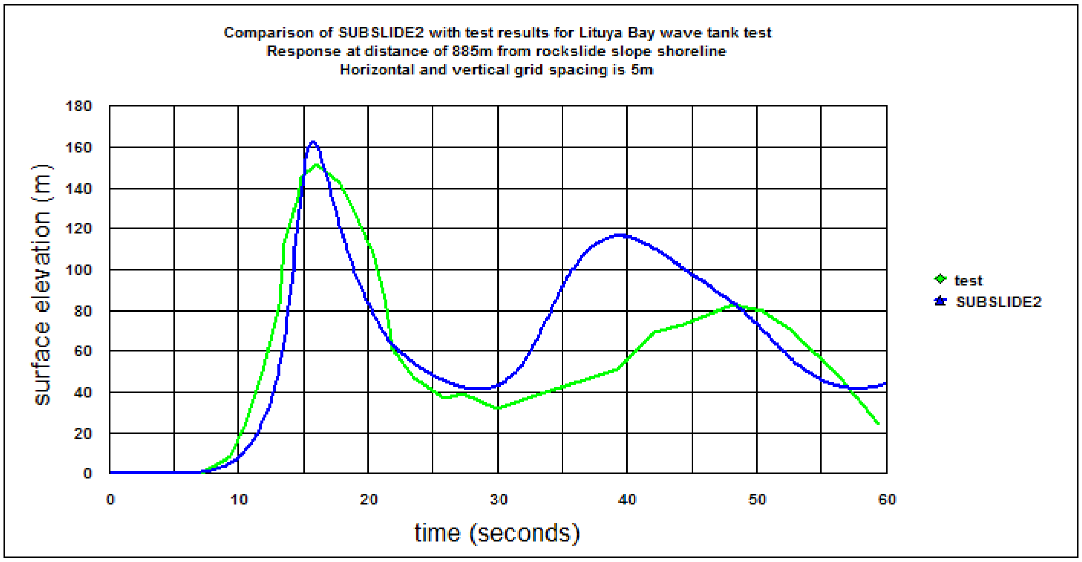

Figure 7a

The comparison between SUBSLIDE2 and the test result for run-up on the headland slope is shown in Fig 7b. As discussed in [1], SOLA-3D (the program SUBSLIDE2 is based on) does not model run-up over dry land, and the closest equivalent of a run-up time history available is the surface elevation time history for the grid cell next to the shoreline, where the shoreline is treated as a reflecting boundary. SUBSLIDE2 gives a peak run-up value of 983 m, 87% higher than the test value of 526 m.

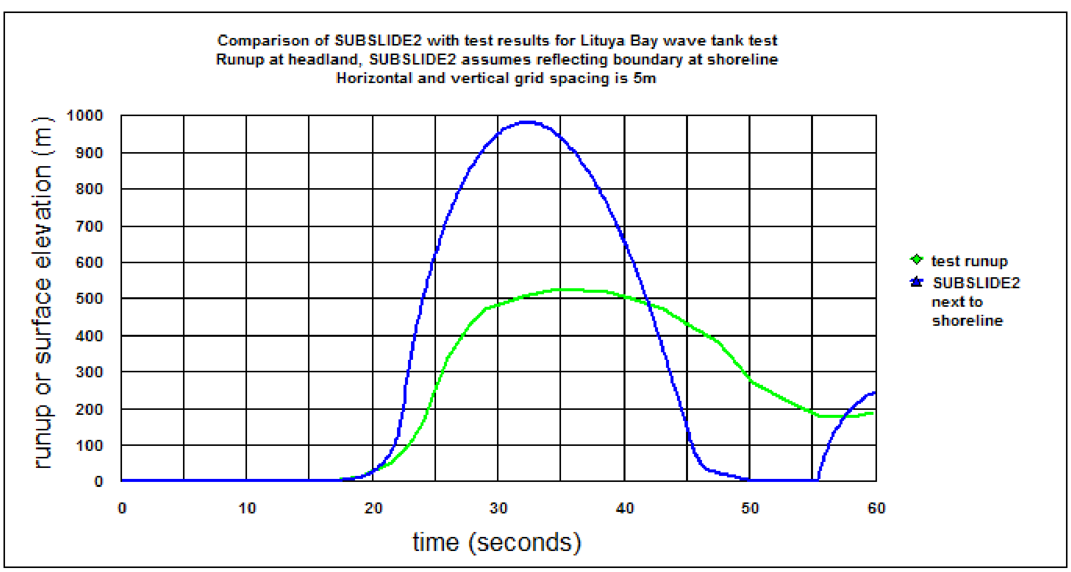

Figure 7b

As the run-up value obtained with SUBSLIDE2 is substantially higher than the test value, an attempt was made to see if closer agreement with the test could be achieved by carrying out a separate run-up analysis using the program SWASH [4]. This program has been used in previous tsunami modelling work for tsunamis generated by offshore earthquakes. SWASH is able to model run-up over dry land, but significant difficulties were encountered in using the program for run-up involving a slope as steep as 45° and in using multiple vertical layers (which were thought to be necessary for the modelling of a very high amplitude wave), and the attempt to use SWASH was not pursued further.

The Lituya Bay wave tank test has been modelled by a number of groups according to the tsunami modelling literature. The closest agreement with the test run-up value seems to be 518 m obtained with the program iSALE in [5], and the highest run-up reported in the literature seems to be a range of values up to about 845 m obtained with the program FLOW-3D in [6].

SOLA-3D run-up study for solitary waves on a 45° slope

To investigate the high run-up value calculated by SUBSLIDE2 further, it was thought advisable to check whether the program can satisfactorily model run-up of solitary waves on a 45° slope in comparison with published run-up formulae. The study was carried out on SOLA-3D as a solitary wave input has to be applied as an initial vertical surface displacement pattern, and this initial surface displacement input feature was taken out for the SUBSLIDE1 and SUBSLIDE2 programs, which are slightly modified versions of SOLA-3D.

The solitary wave displacement input is applied in SOLA-3D as a large single solitary wave varying from 25 m to 400 m in height with its centreline at a distance of at least 700 m from the shoreline, which then splits into two smaller solitary-like waves of height H travelling in left and right directions. The study uses a 5 m horizontal and a 5 m vertical grid spacing, along with a 122 m depth of water, to be consistent with the modelling of the Lituya Bay wave tank test.

The published run-up formulae for solitary waves used in the comparison are:

(a) Hall & Watts 1953 formula for a 45° slope [7]: $R/d = 3.1\ (H/d)^{1.15}$

(b) Synolakis run-up law [8]: $R/d = 2.831\ \sqrt{\cot\beta}\ (H/d)^{5/4}$

(c) Li version of run-up law [9], which consists of the Synolakis run-up law multiplied by a correction factor: $R/d = 2.831\ \sqrt{\cot\beta}\ (H/d)^{5/4}\ (1 + 0.104\ \cot\beta\ (H/d))$

For the above formulae, R is the run-up height, H is the incident solitary wave height, d is the still water depth away from the slope region, and β is the slope angle (45° for this slope). The range of validity of the above formulae is at least up to $H/d = 0.504$ for the Hall & Watts formula, and at least up to the point where wave breaking occurs for the two run-up laws. Wave breaking occurs at a value of $H/d = 0.818\ (\cot\beta)^{-10/9}$ according to

[8], which corresponds to H/d = 0.818 for β=45°. The Hall & Watts formula is experimentally based whereas the two run-up laws are theoretically based.

The comparison of SOLA-3D run-up results with the three published run-up formulae for solitary waves is shown in Fig 8a. A comparison between SOLA-3D run-up results, the Hall & Watts 45° slope formula, and the 32 data points measured by Hall & Watts for run-up tests on a 45° slope (which are included in [7]) is shown in Fig 8b.

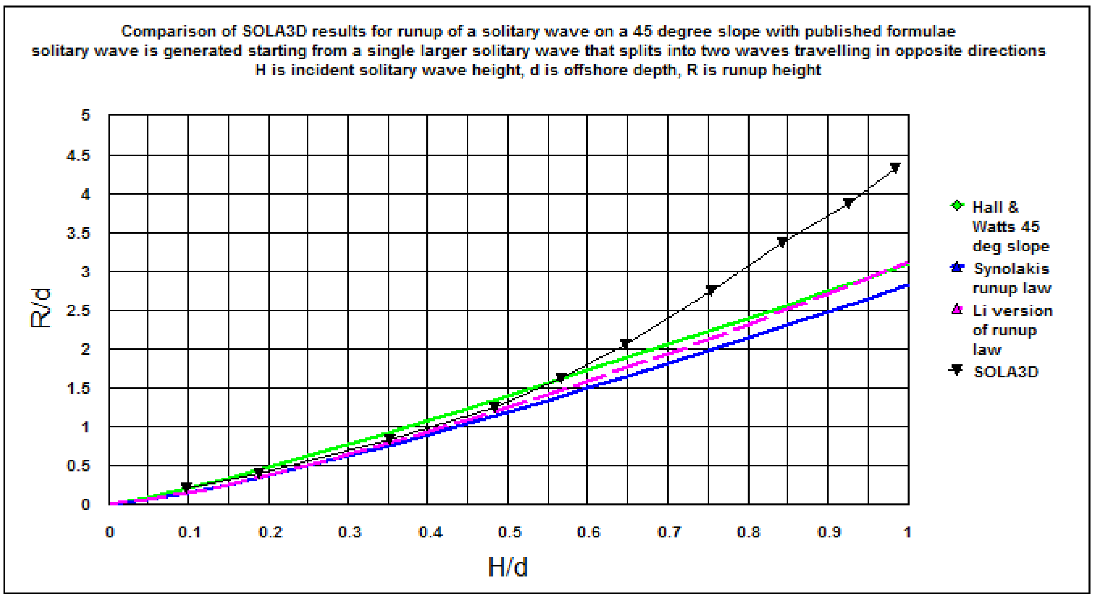

Figure 8a

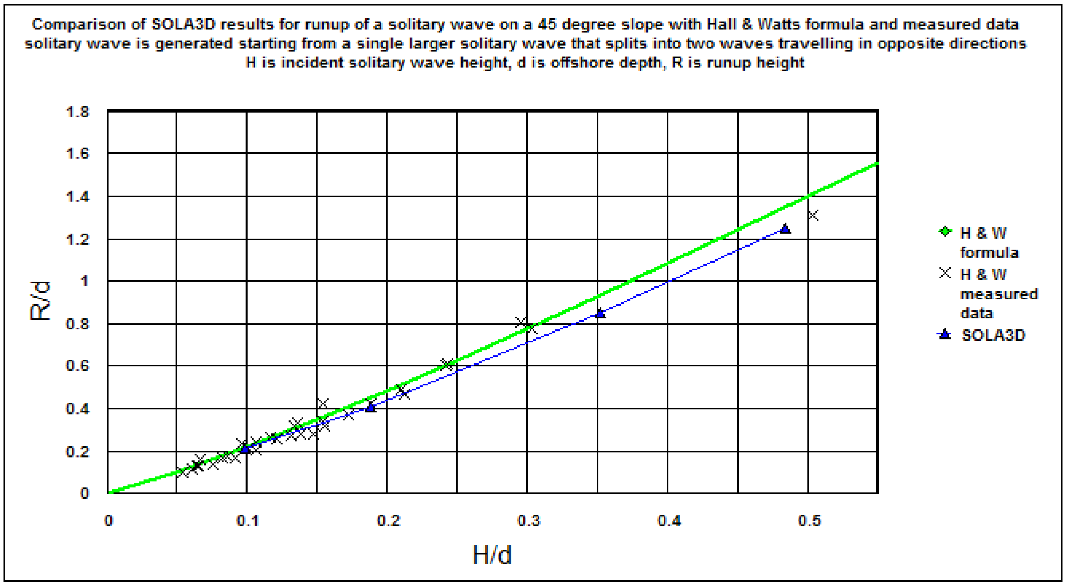

Figure 8b

The SOLA-3D results show good agreement with the Hall & Watts formula at an H/d value of 0.1, the results are about half way between the Hall & Watts formula and the Synolakis run-up law for the H/d range 0.2 to 0.5, and then the results exceed the Hall & Watts formula for H/d > 0.55, with substantial exceedance at H/d =1. SOLA-3D predicts that the observed Lituya Bay wave tank test run-up of 526 m could be achieved with an incident solitary-like wave of height 120 m in a water depth of 122 m.

In the SUBSLIDE2 analysis of the Lituya Bay wave tank test, the peak height of the incident solitary-like wave was 174 m just in front of the toe of the headland slope, which would correspond to an H/d ratio of 1.43. The SUBSLIDE2 run-up value of 983 m is reasonably consistent with the SOLA-3D run-up results shown in Fig 8a if the results in Fig 8a are extrapolated to an H/d value of 1.43.

In [3] it is argued that the Hall & Watts 45° slope run-up formula is still valid for solitary-like waves with H/d ratios as high as 1.33.

One way of reconciling the SOLA-3D run-up results with the Lituya Bay wave tank test would be to assume that the reflecting boundary (or vertical cliff) representation for dry land used in SUBSLIDE2 and SOLA-3D must be introducing a significant conservatism at high H/d values, but the effect is not present for some reason at H/d values up to 0.5.

Conclusions

1. Iwasaki's method for modelling underwater landslides [2] has been extended to handle subaerial slides that are composed of loose material. The method has been

implemented in a slightly modified version of the incompressible Navier-Stokes program SOLA-3D called SUBSLIDE2.

2. The SUBSLIDE2 program has been compared with wave tank test results reported in [3] and shows satisfactory agreement for the incident solitary-like wave developed in front of the toe of the headland slope, but significantly over-predicts run-up for the headland slope compared with the test.

3. The wave tank test [3] indicates that a sizeable air cavity forms and collapses during the sliding event, and this feature is not modelled in the SUBSLIDE2 analysis. However the inability to consider this feature does not appear to be important at the locations where time history test results are provided.

4. It was also investigated whether SOLA-3D can satisfactorily model run-up of solitary waves on a 45° slope in comparison with the empirical Hall & Watts run-up formula [7]. It was found that SOLA-3D gives fairly good agreement with the formula in its intended application range of H/d up to about 0.5, but then diverges to produce significantly higher run-up values than the formula as H/d is increased. By contrast [3] argues that the Hall & Watts formula is still valid at H/d values as high as 1.33. It should be noted that SOLA-3D does not model run-up over dry land, and the peak run-up has to be estimated by taking the peak surface elevation at the grid cell next to the shoreline, where the shoreline is treated as a reflecting boundary.

References

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