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Modelling of tsunami waves generated by an underwater landslide

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Introduction

Following on from earlier work in developing a capability to model tsunami waves generated by an earthquake, the next step would be to develop a capability to model tsunami waves generated by an underwater landslide. It was thought that the best approach for doing this, which enables programs supplied with the book [1] to be utilised, would be to implement a method described in [2], which is referred to as "Iwasaki's method" in this document. The tsunami waves generated by an underwater landslide are expected to involve a much greater amount of frequency dispersion (where water waves with different frequencies travel at different speeds) than occurs with an earthquake-induced tsunami, so the incompressible Navier-Stokes program SOLA-3D supplied with [1] was adopted as the basis for a program which can model underwater landslides.

Modifications to SOLA-3D

The main modifications made to the version of SOLA-3D that is supplied with [1] were:

(a) Problem-specific coding in subroutines sola, betacal, surfset and lprt was removed in favour of having a fixed version of the program where data is entered from outside the program. The new input data consists of: (i) a set of grid locations where surface time history responses are to be output, (ii) a separate input file giving details of the arrangement of columns of obstacle grid cells which represent the bathymetry for the problem, (iii) a separate input file which gives details of an initial vertical surface displacement pattern to be applied for the problem, and (iv) location of a 2D cross-section in the 3D grid where grid cell responses such as pressure and velocity are output at a requested time interval.

(b) Double precision was implemented. In the case of SOLA-3D, implementing double precision is not as straightforward as it is for a typical Fortran program. It required taking the integer arrays kt, itwx and isort out of the existing main common blocks and removing these arrays from equivalence statements. The definition of subscript variables used in the kt array also needed to be modified in subroutine sthpln to make the storage for the kt array more compact.

(c) In testing the program, it was found that the automatic time step selection scheme used in the program does not guarantee accurate results or even stable results for a tsunami wave problem, so a feature was introduced where the automatically selected time step cannot exceed a specified maximum allowed time step.

One limitation of SOLA-3D observed in testing the program is that it does not model run-up over dry land. If obstacle grid cells representing dry land are included in the computational grid, water does not flow on to the dry land region, and the dry land is treated as though it is a reflecting boundary or vertical cliff. It would be desirable to modify the program to be able to model run-up over dry land, but the modification was regarded as being too difficult to implement, and it should be possible to carry out a separate run-up analysis using another program that does have the capability to model run-up over dry land.

Iwasaki's method

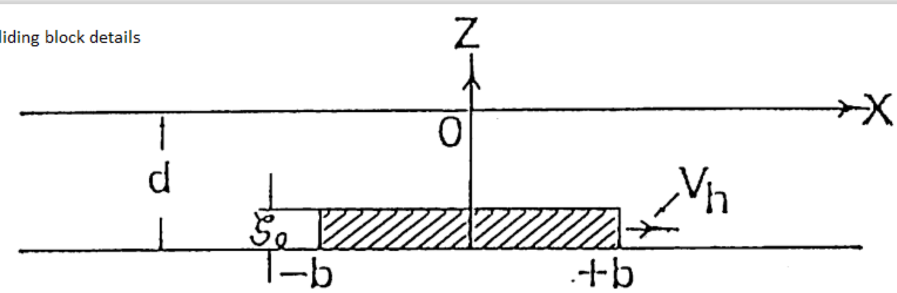
The temporary surface displacement η generated over a time step Δt for the sliding block shown in Fig 1, which has a rectangular cross-section of length 2b and thickness ζ, and is sliding along the seabed with a horizontal velocity V_h in a still water depth d is given by the expression:

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

Note that there is a major typographical error in [2], repeated in a subsequent paper [3], where the above formula is quoted with the x-b and x+b terms given as x-d and x+d. x is the horizontal distance measured from the centre of the moving block.

The temporary surface displacement is then added to the current surface height of the fluid in a program which is able to model propagation of surface waves.

Figure 1 sliding block details



Using the approximations $\tanh^{-1}(z) \approx z$ if z is small, and $\sin(\zeta\pi/2d) \approx \zeta\pi/2d$ if $\zeta\pi/2d$ is small, which can be regarded as applying for an ζ/d ratio up to about 0.1, the above expression for η takes the simpler form:

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

The 1/cosh terms have a peak value of 1 at x = b and x = -b, so the peak vertical surface displacement generated by the right end of the sliding block is $(\zeta/2d)V_h\Delta t$ at x = b and $(-\zeta/2d)V_h\Delta t$ by the left end of the sliding block at x = -b for the small ζ/d ratio case.

Figs 2a shows the distribution of temporary surface displacement in relation to the two ends of the sliding block for the case where the still water depth is one tenth of the block length. The displacement is limited to a small surface region around each end of the block. Fig 2b shows the distribution of temporary surface displacement for the case where the still water depth is the same as the block length. In this case, the surface region affected by each end of the block is significantly broader, and the left end of the block has an influence on the peak displacement seen at the right end of the block and vice-versa.

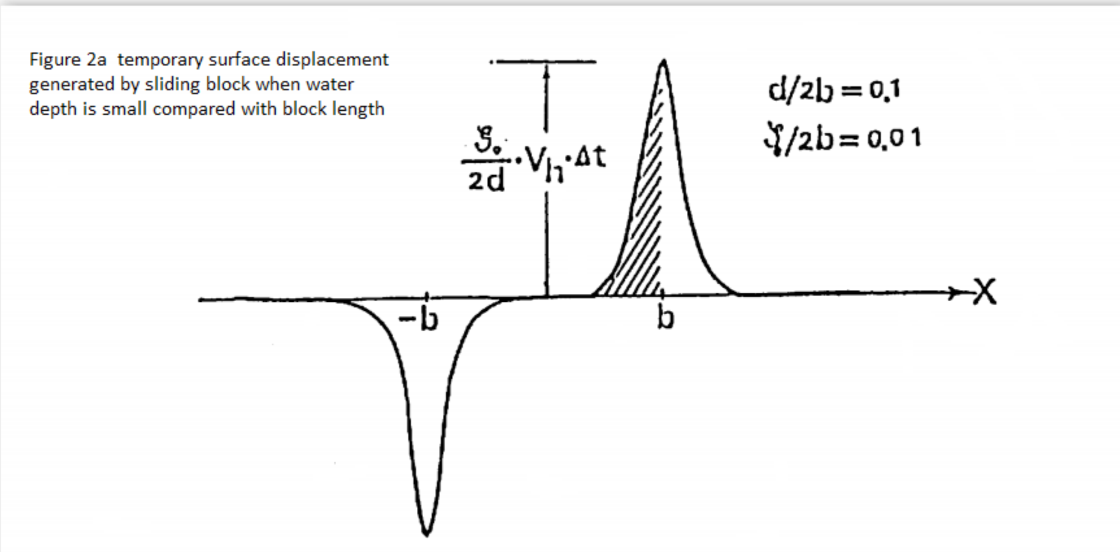


Figure 2a temporary surface displacement generated by sliding block when water depth is small compared with block length

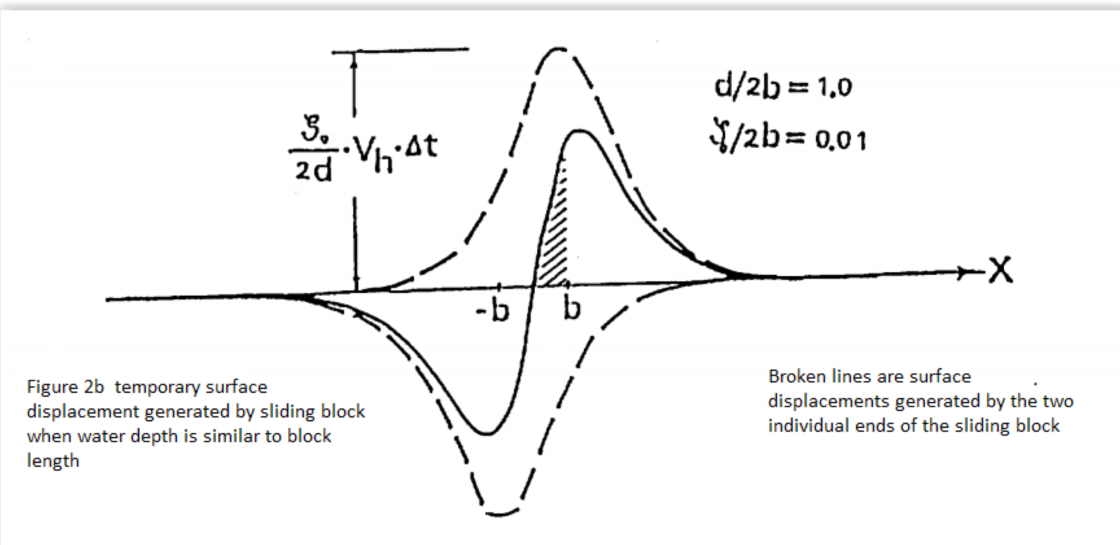


Figure 2b temporary surface displacement generated by sliding block when water depth is similar to block length

Broken lines are surface displacements generated by the two individual ends of the sliding block

SUBSLIDE1 program

Iwasaki's method is implemented in a slightly modified version of SOLA-3D called SUBSLIDE1, which includes a new subroutine called 'slide' which calculates the temporary vertical surface displacement η caused by a horizontal movement of the sliding block, and adds it to the hn fluid surface height array at a given time point in subroutine sola.

To test SUBSLIDE1, it was thought necessary to check the program against published results for a wave tank test that considers a submarine slide. Slope angles used in submarine slide wave tank tests tend to be at least 15° in order to produce a reasonably high velocity for the sliding block under the action of gravity, and this is several times higher than the angles of 3° to 4° for typical submarine slopes quoted in [2]. For a slope angle as high as 15°, the still water depth d used in the expression to calculate η could vary significantly over the length of the block. To take account of this situation, subroutine slide has been set up to check the value of d at the two ends of the block at each time point, and then use the lower value of d as this should give a more conservative value for η.

Another issue in regard to submarine slide wave tank tests is that they do not tend to use the rectangular cross-section shape for the sliding block that is specifically considered by Iwasaki. No guidance is provided in [2] on how to treat a non-rectangular cross-section using the method. The policy adopted in developing SUBSLIDE1 has been to assume that a non-rectangular section can be represented by an equivalent area rectangular section, with the equivalent rectangular section having the same length as the non-rectangular section in the direction of sliding, and the thickness ζ is assigned a value that gives the same cross-sectional area as the non-rectangular section.

Wave tank test problem

The wave tank test problem selected for checking whether SUBSLIDE1 works satisfactorily is based on test work reported in [4], and the overall test arrangement is shown in Fig 3. The test work in [4] includes some features which possibly make it superior to previous test work on submarine slides. It uses a streamlined semi-elliptical cross-section shape for the sliding block, and the sliding track is designed with a curved transition region to allow the sliding block to come gently to rest on the horizontal bottom of the wave tank. Test work prior to [4] has often used a wedge shaped (triangular cross-section) sliding block, and the sliding block is often brought to a fairly abrupt stop near the bottom of the slope (as there is no transition region), and the adoption of these test practices might be regarded as unrepresentative of a real underwater landslide. The slope angle of 15° used in [4] is also lower than in previous test work.

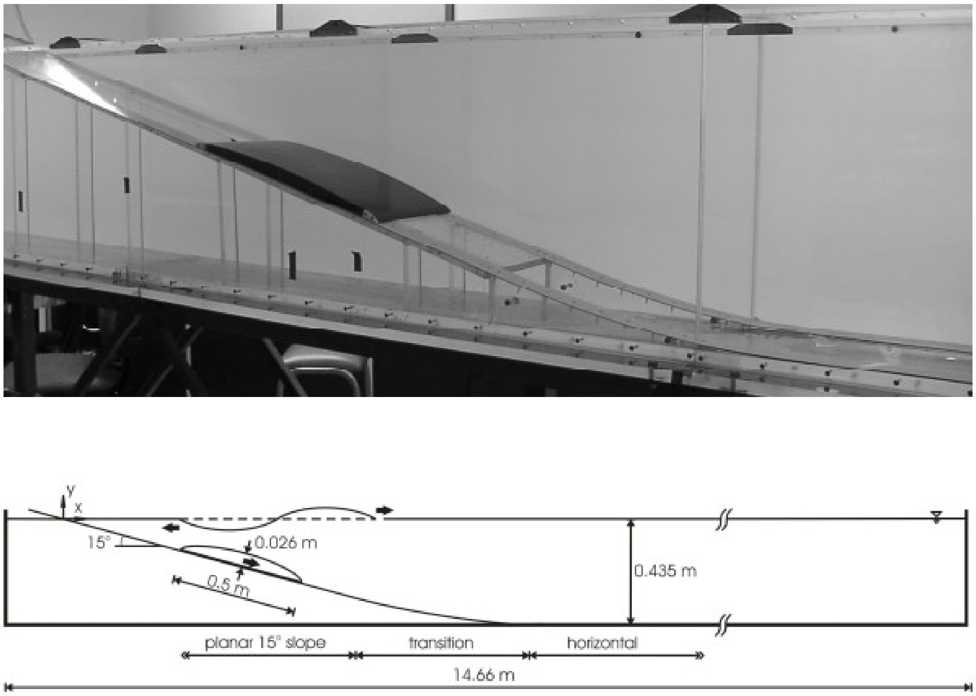


Figure 3 LP Sue wave tank test details

The test configuration selected for modelling by SUBSLIDE1 is described by the identifier SG5_IS3, where SG5 denotes the specific gravity case for the sliding block and IS3 denotes the initial submergence case for the block. The IS3 case was interpreted as having a starting position where the depth of water (to the surface of the slope) is 15 cm at the midpoint of the block, and the depths are 8.5295 cm and 21.4705 cm for the left and right ends of the block respectively, with the left end of the block starting at a horizontal distance of 31.8326 cm from the initial shoreline.

Velocity time histories for the sliding block were measured in the test work, and the velocity time history for the SG5_IS3 configuration is shown in Fig 4. This was interpreted as being a horizontal velocity time history. In SUBSLIDE1 the time history is simplified to being represented as a piecewise linear time history with fourteen straight line segments.

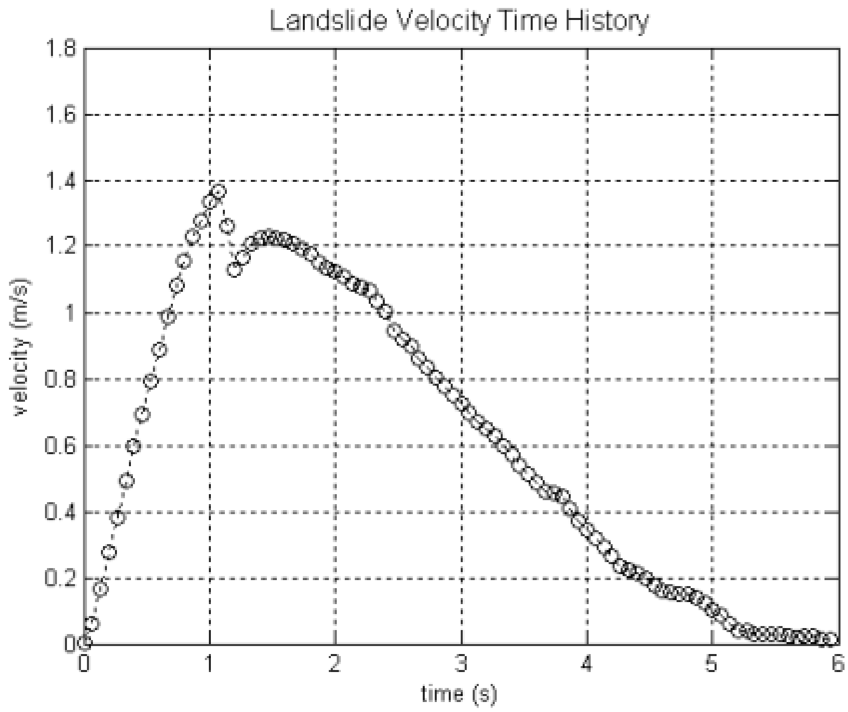


Figure 4 velocity time history for SG5_IS3 configuration

The wave tank test slope arrangement, which consists of a planar 15° slope region and a curved slope transition region, was simplified to a uniform 1 in 4 slope (which corresponds to a slope angle of 14.0362°) in the SUBSLIDE1 analysis, as it was preferred to use a uniform grid spacing in the vertical direction. The horizontal grid spacing used in the analysis was 2.5 cm (in the longitudinal direction of the tank) and the vertical grid spacing was 1.25 cm.

The semi-elliptical cross-section sliding block has a length of 50 cm and a maximum thickness of 2.6 cm at its midpoint. In the SUBSLIDE1 analysis, this was represented as a rectangular section of 50 cm length and thickness 2.042 cm, which has the same cross-sectional area as the semi-elliptical section.

Comparison of SUBSLIDE1 results with test results

SUBSLIDE1 results are compared with test results for surface elevation time histories in Figs 5a to 5e, which correspond to a set of horizontal distances 1.5, 2.5, 3.5, 4.5 and 5.5m from the initial shoreline. The test results were digitised from figures provided in [4]. A surface elevation time history plot is also provided in [4] for the smaller distance of 0.5 m from the shoreline, but the amplitude levels in the plot were regarded as too small to achieve a satisfactory digitisation. The comparison of surface elevation time histories is good, and SUBSLIDE1 gives conservative results for the maximum and minimum surface elevation.

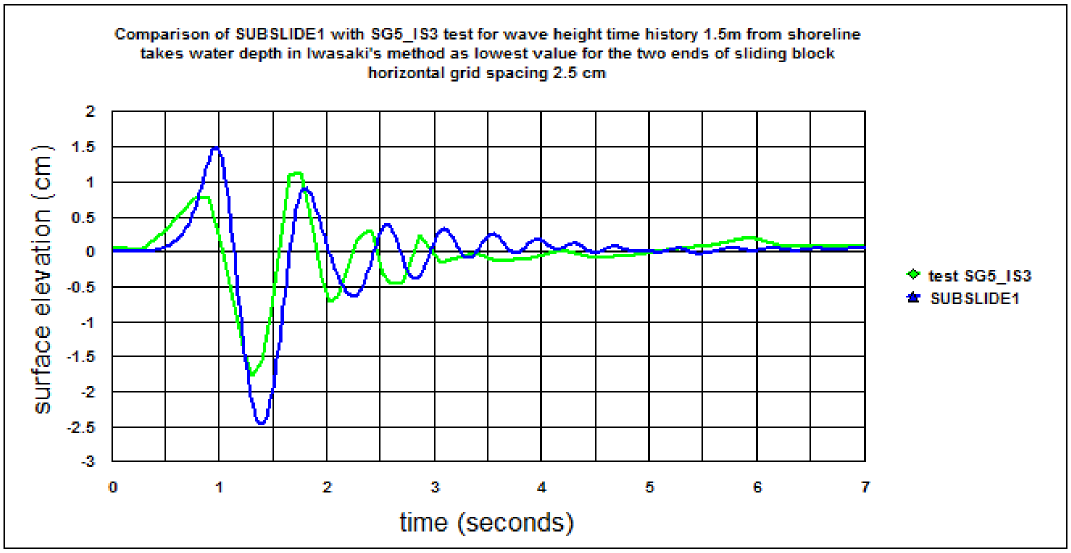


Figure 5a

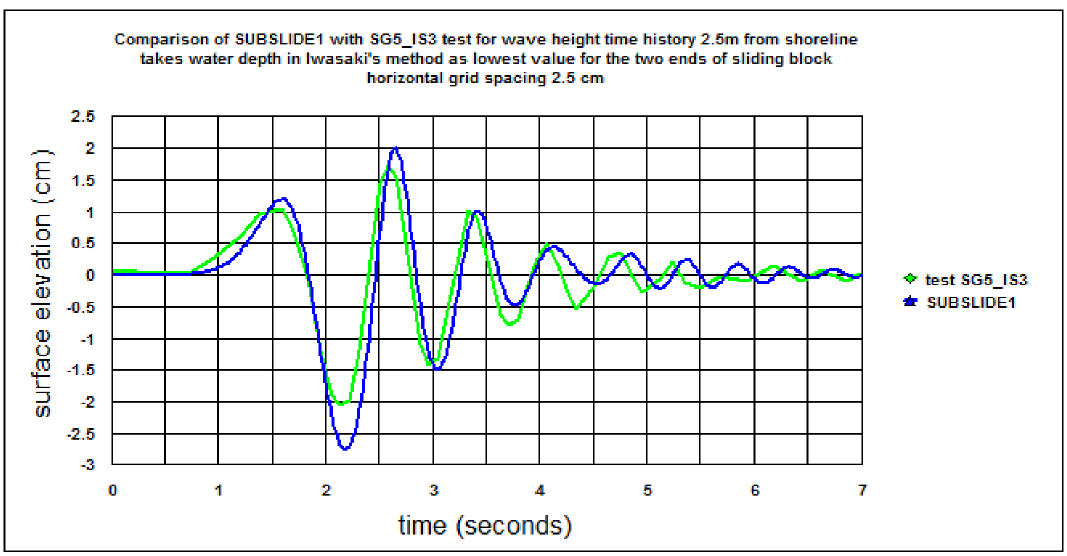


Figure 5b

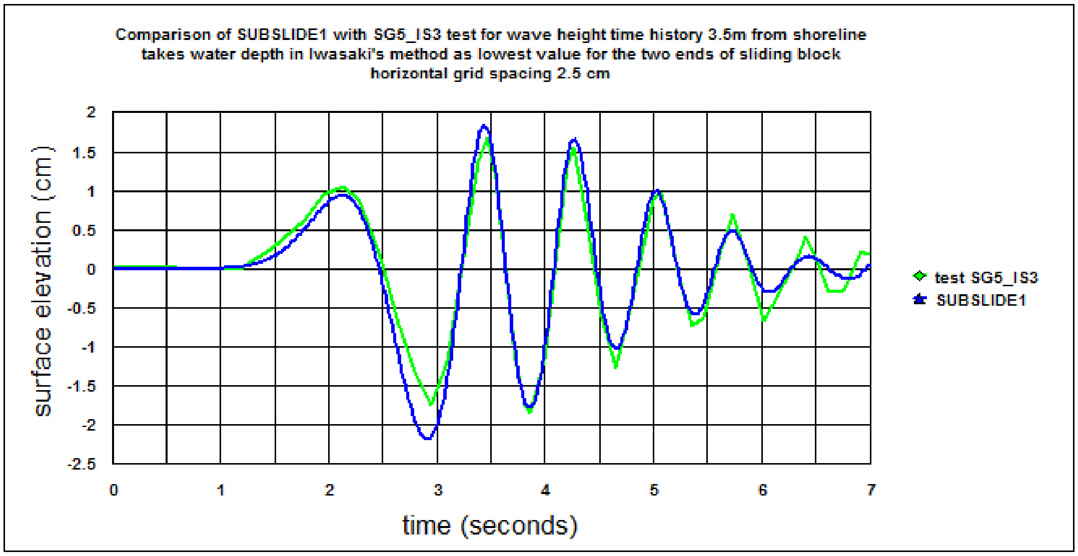


Figure 5c

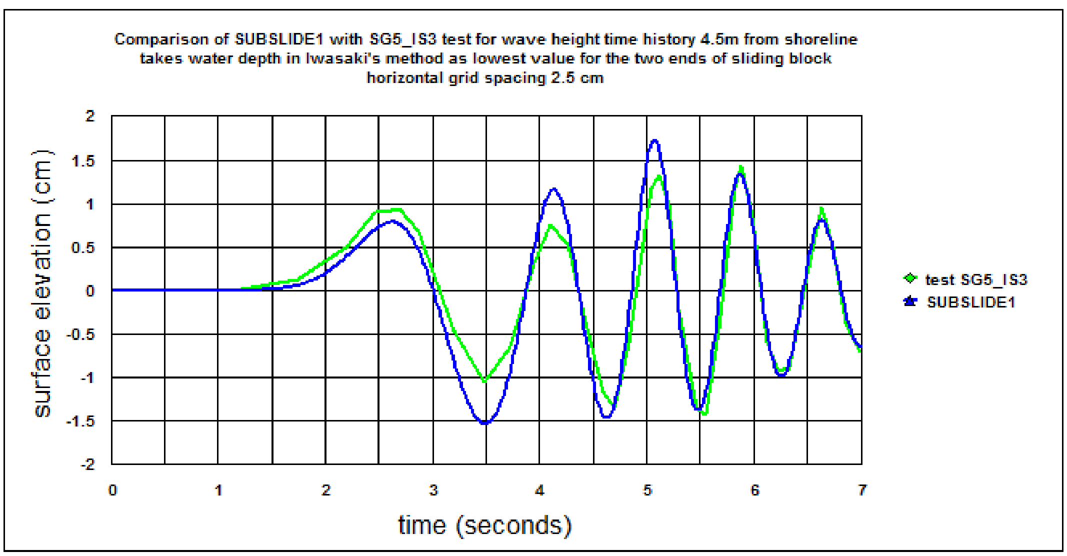


Figure 5d

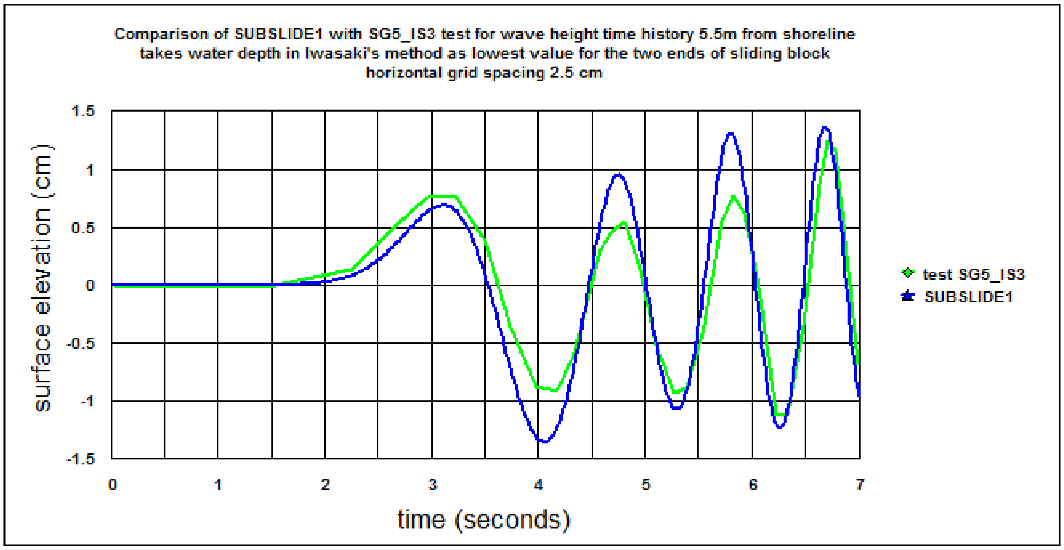


Figure 5e

A run-up time history for the test is also provided in [4]. As previously mentioned, SOLA-3D (the program SUBSLIDE1 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. The comparison is shown in Fig 6. The peak run-up observed in the test is 0.38 cm and the peak for the SUBSLIDE1 time history next to the shoreline is 0.33 cm, 13% lower than the test value. The peak run-up for the test is several times lower than the peak positive surface elevation seen in the constant depth region of the wave tank (the constant depth region starts at a horizontal distance of 1.807 m from the initial shoreline).

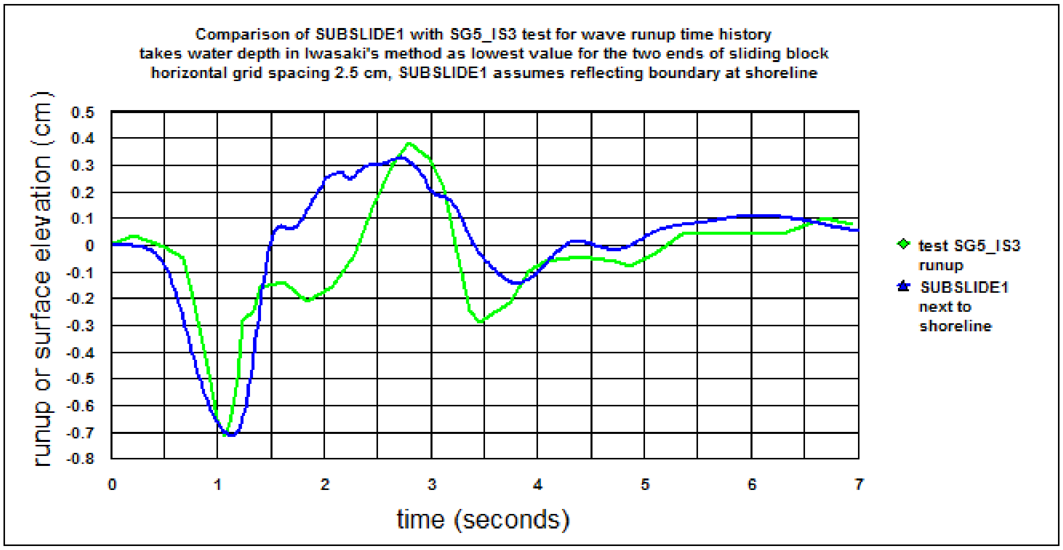


Figure 6

Wave height profiles for the test at a few specific times are also provided in [4], so some SUBSLIDE1 runs were carried out to produce wave height profile output at 3.6 sec and 5.6 sec. The comparison is shown in Fig 7a and 7b, and is reasonably good.

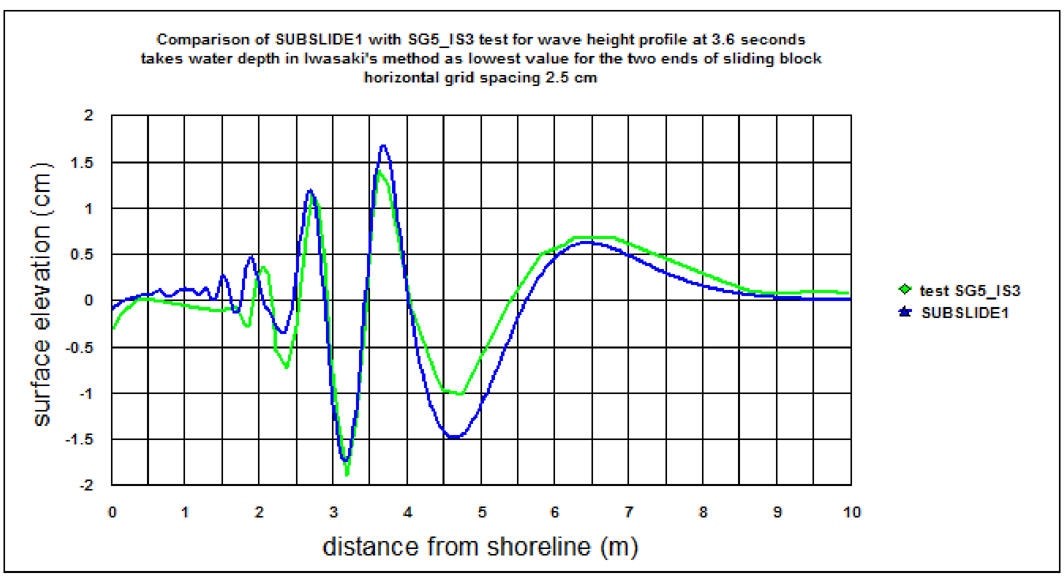


Figure 7a

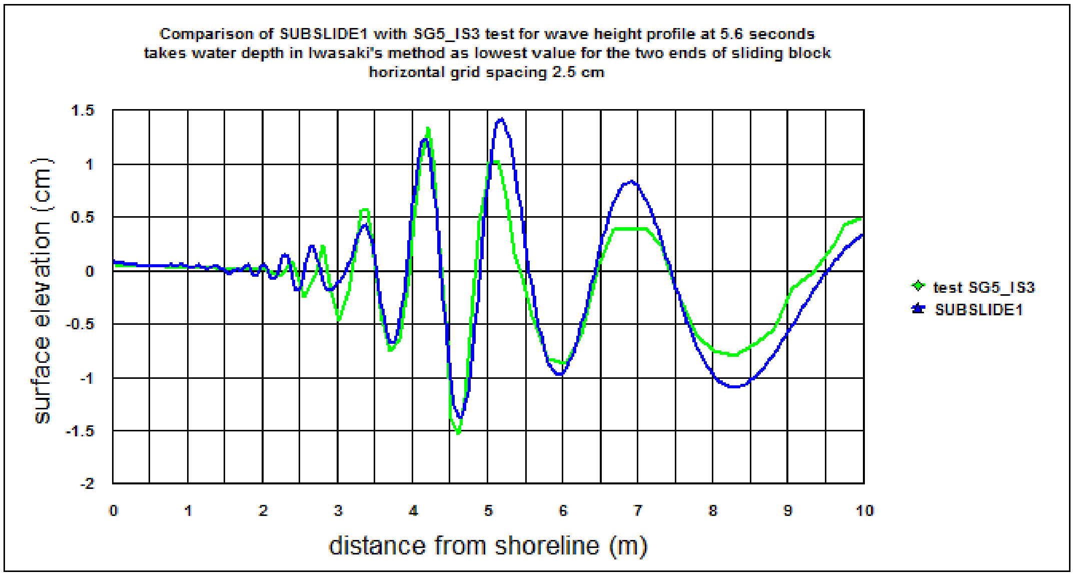


Figure 7b

Conclusions

1. Iwasaki's method for modelling underwater landslides [2] has been implemented in a slightly modified version of the incompressible Navier-Stokes program SOLA-3D called SUBSLIDE1. The SUBSLIDE1 program has been compared with wave tank test results reported in [4] and shows satisfactory agreement.

2. The semi-elliptical cross-section used for the sliding block in the wave tank test was modelled as a rectangular section block of the same length and cross-sectional area. This modelling practice, along with the idea of taking the applicable water depth for the sliding block in Iwasaki's method as being the lowest depth value for the two ends of the block, appears to give satisfactory results.

3. SUBSLIDE1 does not model run-up over dry land, and so the run-up time history was represented by a surface elevation time history at the grid cell next to the shoreline, where the shoreline is treated as a reflecting boundary. This approximation performed better than expected, and the peak run-up estimated using the surface elevation time history was only 13% lower than the test value.

References

[1] Mader C L, "Numerical modeling of water waves", 2nd edition, CRC Press, 2004

[2] Iwasaki S I, Furumoto A S, Honza E, "Can a submarine landslide be considered as a tsunami source?", Science of Tsunami Hazards 14 (2), 1996, pp 89-94

[3] Iwasaki S I, "The wave forms and directivity of a tsunami generated by an earthquake and a landslide", Science of Tsunami Hazards 15 (1), 1997, pp 23-40

[4] Sue L P, "Modelling of tsunami generated by submarine landslides", PhD thesis, University of Canterbury, New Zealand, 2007