NUMERICAL STUDY OF SUBMARINE LANDSLIDE GENERATED TSUNAMI USING SMOOTHED PARTICLE HYDRODYNAMICS METHOD

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ABSTRACT

Submarine slide is the most serious threat on both local and regional scales. Tsunami phenomenon induced by submarine slide has put us on the challenge in understanding from generation mechanism to propagation and coastal inundation and mitigating the risk from submarine slide generated tsunami. This research presents the numerical simulation methodology by using Smooth Particle Hydrodynamics (SPH) to investigate all stages of tsunami waves with the aid of physical modeling. Results of tsunami generation, propagation, run-up, impact in experimental test are compared with the results from the numerical simulation. The comparisons of results have a slight difference. The conclusions may potentially be taken as guideline of mitigate the risk from tsunami wave.

Keywords: Tsunami; submarine slide; smoothed particles hydrodynamics; SPHysics code.

1. Introduction

Tsunami is the Japanese word meaning "harbor wave" or "seismic sea waves", and has been given worldwide attention over the last decade because of the hydraulic power associated with the water flow and the fact that they affect long shorelines. They can occur for several reasons which include an earthquake-initiated seabed displacement, a volcanic eruption, landslides including submarine slides, or the impact of large objects into the open ocean, i.e. a meteor. Thus, tsunamis become a serious natural hazard for the environment and populations in exposed areas. Consequences of the 1998 Papua New Guinea (PNG) which killed more than 2000 people and destroyed completely three villages (Tappin et al, 2001). The December 2004 Indian Ocean tsunami which causing over 200,000 fatalities and widespread destruction in countries bordering the Indian Ocean (Kawata et.al, 2005) and the 2011 Great Tohoku Japan Earthquake and Tsunami, resulted in 15,000 deaths and an estimated US $300B in damage (Arikawa, 2012), are recent examples. Therefore, tsunami phenomenon has put us on the challenge in understanding and mitigating the risk from it.

The submarine slide is now recognized as an important source of tsunami wave generation, since it is the second most frequent tsunami source after earthquakes responsible for about 10% of all tsunami waves (Gusiakov, 2009). Tsunami waves due to submarine slides are sophisticated phenomena that may be divided into four parts: tsunami generation, propagation, run-up and impact. The understanding and the forecasting of submarine slide generated tsunami waves is very important both for the safety of human and properties which are close to the shoreline.

Increased computer processing power and increased sophistication of programming code have led to drastic improvements in numerical simulation of tsunami waves. A number of applicable models for simulating tsunami generation, propagation, run-up and impact have been developed. Some applications were based on nonlinear shallow water (NSW) model due to its simplicity while the other application was based on Boussinesq-type model (BM). Generally, Boussinesq-type is more efficient and accuracy than model developed based on NSW particularly for waves generated in intermediate and deep water. Furthermore, Lynett et al. (2003) have made a comparison between BM and NSW models in order to quantify the effect of frequency dispersion on the slide-generated tsunami. The numerical comparisons indicated that the NSW model was a poor estimator of offshore wave heights. Besides, the NSW model is not suitable for modeling the entire process of submarine-landslide-generated tsunami whereas the BM is able to simulate separated stage of generation, propagation, and run-up. Despite of using widely the depth-integrated models (including nonlinear shallow water and Boussinesq-type models), they cannot capture the realistic wave breaking and overturning processes which are important in the vicinity of the generation region as well as run-up region. Shao (2008) used a model which is based on the Navier-Stokes (NS) equations to simulate wave-breaking and interaction between breaking waves and coastal structures. In addition, the NS equations were incorporated with a modern numerical technique such as smooth particle hydrodynamics (SPH) method to investigate the time-dependent wave breaking processes (Shao, 2008). It is a meshfree particle approach which is capable of tracking the free surfaces of large deformation in an easy and accurate way. The computed free surface displacements, turbulence intensities and undertow profiles are in good agreement with the experimental data and other numerical results. It is thus shown that the SPH method provides a useful tool to investigate the surf zone dynamics.

At the present time, no effective numerical model that could simulate simultaneously all stages of generation, propagation, run-up and impact of tsunami phenomena. The aim of present work is to give necessary application of a numerical method that cover all stages of slide tsunami waves with using NS equations. The present work deals with the complex problem of numerical modeling submarine landslide generated tsunami waves such as: extremely large deformation, free surface issue, deformable boundary, complicated geometry, time-consuming, costly process. The Smoothed Particle Hydrodynamics method, considered to be one of the most promising mesh-free methods, is due to the possibility of simulating generation, propagation, run-up and impact of impulse tsunami waves. Consequently, future catastrophes can be assessed and mitigated from these studies of slide dynamics, tsunami propagation and coastal impact.

To reduce the damages from these tsunami waves, one must be able to predict the structural behavior and its response, including collapse probability, accurately when they are exposed to these tsunami waves. To do this, an understanding of the hydraulic loading and the influence on wave forces is needed. The wave forces, i.e. tsunami wave impact forces, can be computed based on mathematical formulations or by using numerical simulations directly. Thus, the aim of this study focuses on contributing to the understanding of tsunami wave impact forces on coastal structures.

2. Submarine Slide Generated Tsunami

2.1. Physical Experiments

Tsunami generation process by submarine landslide sources has been modeled in many ways. These can be grouped into four categories: viscous fluid model, rigid-body, or block, model, initial static water surface profile, and moving kinematic water surface profile (Fig. 1).

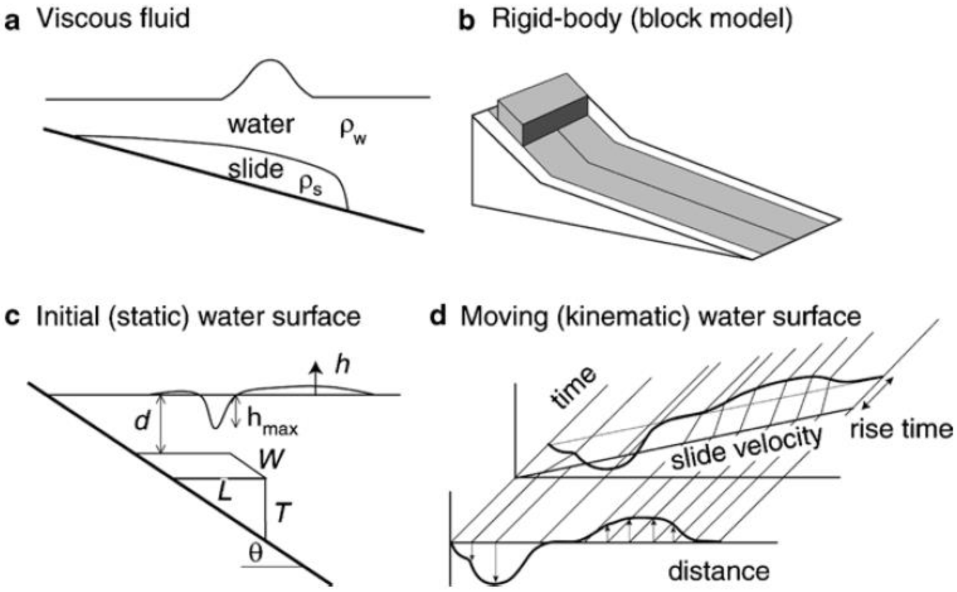

Figure 1. Four different approaches for tsunami generation from submarine landslides (Y. Yamada, 2012)

Most physical experiments involved using the rigid-body (block) approach to generate tsunami waves. With this approach, tsunami generation and propagation could be modeled very simple and got a good agreement with numerical simulation. Thus, in research, the experiment is carried out by using the rigid-body approach. Other physical experiments investigated the wave-structure interaction with four types: Breaking Wave type; High Run-up type; Slowly-Varying type; Overtopping type. They concluded that the most damage that occurs due to a wave-structure interaction is caused by overtopping. Besides that, little is known about how these effects ultimately influence the hydrodynamic forces resulting from the interaction of hydraulic bores with structures. The majority of the physical experiments were conducted in wave flumes; however, they still cannot be considered truly “large scale” due to the use of only centimeters to tens of centimeters of water depth. This brings into the picture the need for more numerical model research in order to decrease the high costs associated with real large scale physical experiments. Moreover, using properly verified and calibrated numerical models, one can investigate wave-structure impact scenarios otherwise difficult to achieve in laboratory conditions.

2.2. Numerical modeling

A large amount of numerical experiments that involve slide tsunami waves are based on Navier-Stokes equations and they are applied in combination with varying turbulence models and surface tracking equations. Besides that, some models (e.g. NSW, BM, RANS) could be appropriate each stage of slides tsunamis, hence, the advantage from those are not too much. Rather than switching from one model to another, it should use a unique comprehensive method that automatically covers most of the range of effects of interest, from propagation out of the generation region, through propagation at ocean-basin scale, to run-up at affected shorelines by using Navier-Stokes equations.

There have been several studies using SPH that focus on simulating tsunami generation and a dam-breach case to produce a bore that impacts a slender vertical column or a vertical wall. Shao (2006) showed that using LES alongside SPH was sufficient to model the shoaling and wave breaking process. Other SPH experiments involved the use of a wave-maker to generate waves that impact vertical walls (Didier and Neves (2010), Rogers et al. (2010), Shao (2010)). In most of these cases, the waves were accurately generated and the surface profiles were deemed acceptable.

The main work will be carried out based on numerical simulation by incorporating the above issues into a unique model based on meshless method. The choice of the Smooth Particle Hydrodynamics (SPH) is due to the possibility of simulating generation, propagation, run up and impact of impulse tsunami waves, without any particular constraint on the free surface and avoiding the limitation of finite difference method. That requires understanding in numerical simulation based on some programming codes such as Fortran/C++. The availability of High Performance Computing (HPC) system, which has just set up at Universiti Teknologi Petronas (UTP), is advantageous for this study.

3. Smoothed Particle Hydrodynamics

The way to numerically solve differential equations of fluid dynamics is of increasing interest in the last decades. In particular, the standard approach to face with this problem is to define field variables on a fixed grid or a fixed volume. In problems involving great changes of the free surface or particular interactions between fluid and structures, the use of a meshfree method is preferable. In these models the fluid is represented as a series of points each one carrying out a particular mass, so we can refer to that as “particles”.

Derivatives are calculated by interpolation between neighboring particles.

Smooth Particle Hydrodynamics (SPH) is a Lagrangian numerical model introduced in Astrophysics by Gingold and Monaghan (1977) and Lucy (1977), because of its capability to reproduce complex and asymmetric problems in a relatively easy way. Beginning from the first 90’s SPH was utilized to model free surface flows (Monaghan, 1992) and then applied to a wide range of fluid dynamical problems. The main advantages of SPH compared to finite difference code can be resumed as follows: firstly, it is possible to simulate very complex phenomena in a relative easy way, and then there are no problems at the interface modeling different materials. In contrast with the finite difference schemes and finally it is possible to represent open boundaries in an extremely easy way, this is important in particular in astrophysical application. There are also some disadvantage in the use of SPH, such as the need of high computational time or particular attention needed to treat with complex boundary all aspects are to be carefully taken in consideration especially in engineering applications, and this is, for certain way, our challenge intention.

SPH was already used to model landslide generated waves (Panizzo and Darlymple, 2006). The choice of SPH upon the others numerical methods came from the fact that SPH is capable to reproduce by itself generation, propagation, run-up and impaction of the impulse wave without any particular restriction and any condition on the shoreline or the free surface.

To approximate the values of functions, derivatives at a particle using the information at all the neighboring particles. SPH approximation consists of kernel approximation and particle approximation

- Kernel approximation: field functions approximated by integral representation method (smoothing effect like weak form)

$$f(x) = \int_{\Omega} f(x_j) W(x - x_j, h) dx_j$$

- Particle approximation: replacing integrations with summations at the neighboring particles in a local domain so-called support domain (sparse matrices).

$$f(x) \approx \sum_{j=1}^{N} m_j \frac{f_j}{\rho_j} W(x - x_j, h)$$

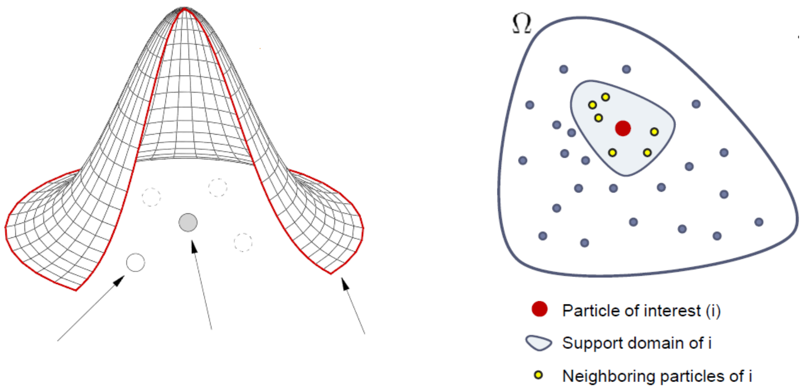

Figure 2. Particle approximation diagram (Shao, 2009)

By deploying particles at specific positions at the initial stage before the analysis, the free surfaces, material interfaces, and moving boundaries can all be traced naturally in the process of simulation regardless the complicity of the movement of the particles. SPH does not use a grid/mesh. This allows a straight forward handling of very large deformations, since the connectivity between particles are generated as part of the computation and can change with time.

4. Open Source Code

Through the collaboration of three different universities; University of Vigo in Spain, John Hopkins in the United States, and Manchester University in the United Kingdom, open source codes have been developed which allow the use of the SPH theory to solve various types of free-surface flow problems. A brief description of serial and parallel versions is given in the following subsections. The general execution methodology for SPHysics is given in the flow chart shown in Fig. 3.

❖ SPHysics

The most basic version of the open source code, called SPHysics, is written in FORTRAN programming language for both a two-dimensional (2D) and a three-dimensional (3D) type problem. This code requires only a central processing unit (CPU) in order to execute.

The SPHysics model allows the introduction of obstacles, such as trapezoidal seawalls, through the definition of their coordinates with respect to the origin. The user can also add a slope in the bottom of the domain to create beach-type geometry. Waves can be modeled by various methods such as using paddle- or piston-type wave-makers with a prescribed motion input file or simply a sine wave equation. Other features include the modeling of floating objects and dam-breach cases using gates. The experimental case can be run in both 2D and 3D although the 3D model will require more running time due to the significantly higher number of particles required to model the same domain. A visualization of the case with a wave formed by a paddle on a beach using SPHysics can be seen in both 2D and 3D in Fig. 4. For additional details about the code's structure and implementation, the reader is referred to the SPHysics user manual (Gomez-Geistera et al. 2010a).

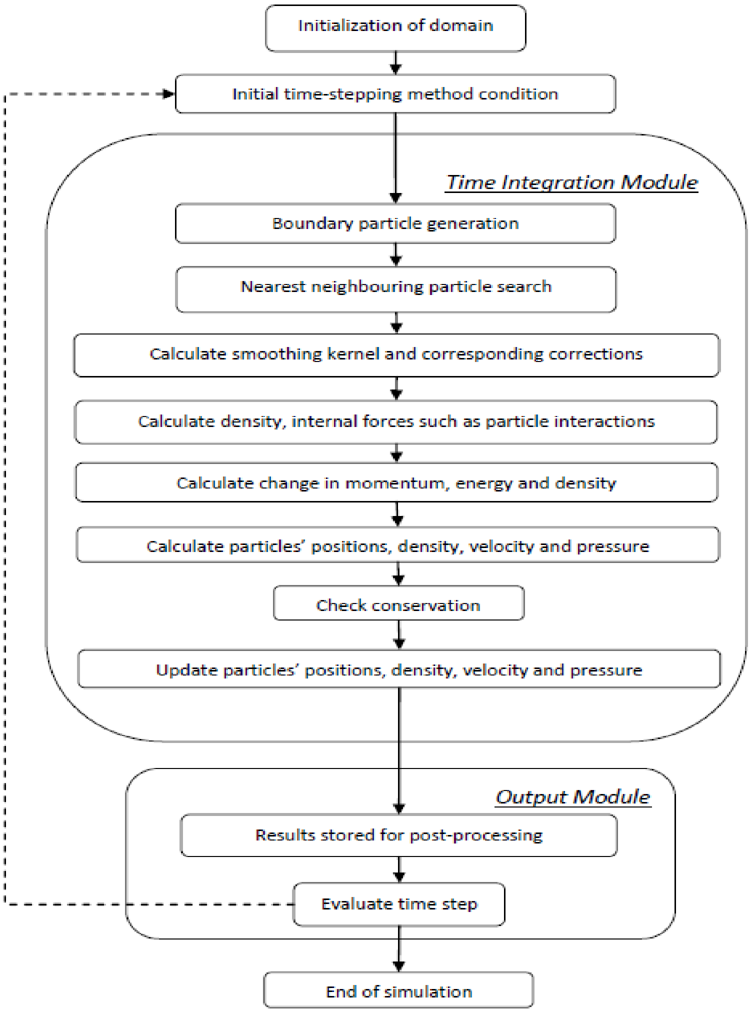

Figure 3. General execution methodology of SPHysics

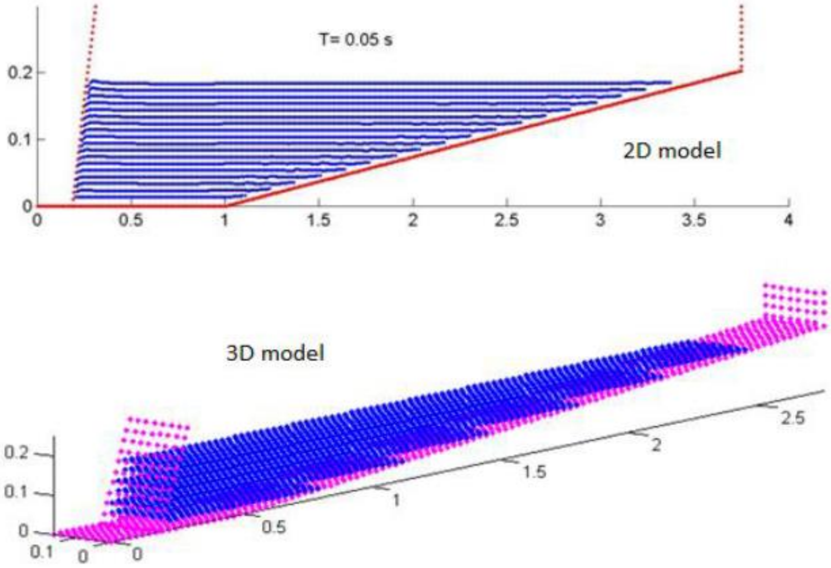

Figure 4. Case example from SPHysics for a wave paddle on a beach (Gomez-Geistera, 2010)

❖ Parallel SPHysics

Parallel SPHysics is an implementation of Smoothed Particle Hydrodynamics. The use of parallelism allows significant reduction of computational time, even more with large number of particles.

- Domain decomposition

To cope with large number of particles and to compute the previous cases with higher performance, parallel SPHysics has been parallelized. The present program has been designed to handle flows in open basins, so we chose to distribute the computational effort by dividing the domain into vertical subdomains. There are as many vertical sub-domains as the desired number of processors. All communications are realized thanks to the use of dedicated MPI libraries, in order to optimize the number and the size of the messages between processors. The size of these interaction zones is then optimized for applications, where the domain height is weak compared to its length. Moreover, the initial domain division between processors is easily made thanks to the use of the first position coordinate of the particles. For extended computational domains, this allows a significant gain in memory since all particles data is never stored on a single machine. The number of information updates is minimized too, since one processor have a maximum of two neighboring processors.

- Load balancing

At the end of a time step, particles may have crossed processors interfaces. These particles and their related information are then transferred towards the processor treating the considered domain, to preserve the vertical shape of each sub-domains. However, these transfers may lead to important load imbalances, which eventually damage the CPU time consumption. To handle with this, the processor interface is updated at the end of each time step in order to keep a constant number of particles in the interaction zones.

- Grid sweep

To parallelize the code, the workload needs to be distributed amongst the available processors. Figure 4 displays a typical situation where the domain has been split amongst three different processors.

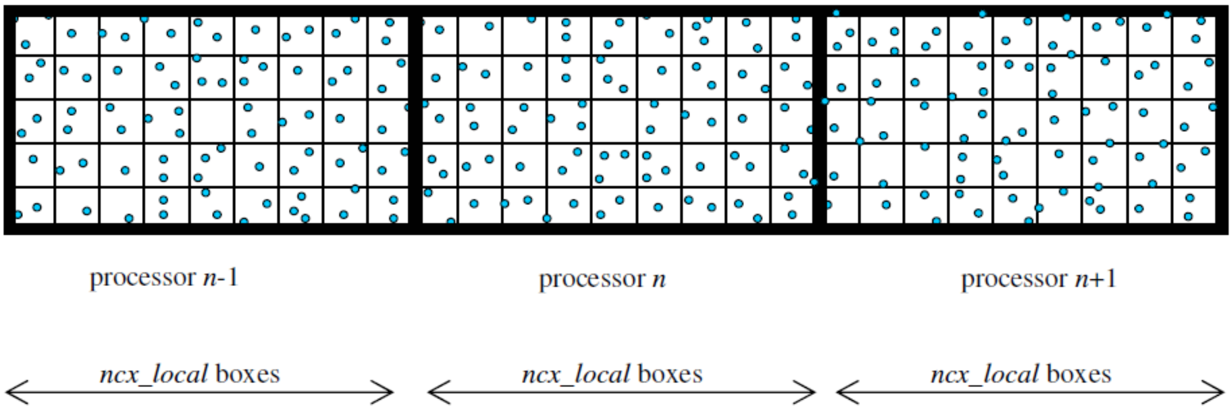

Figure 5. Domain decomposition in parallel SPHysics (Gomez-Gesteira, 2011)

However, when the domain is split up amongst several processors and box ii is located on the boundary of the processor, the code needs to know the contents of box-position ii+1, i.e. E & NE which lie on a different processor. The easiest method to accomplish the necessary transfer of information is to use a column of ghost cells of width 2h as shown in Fig 5.

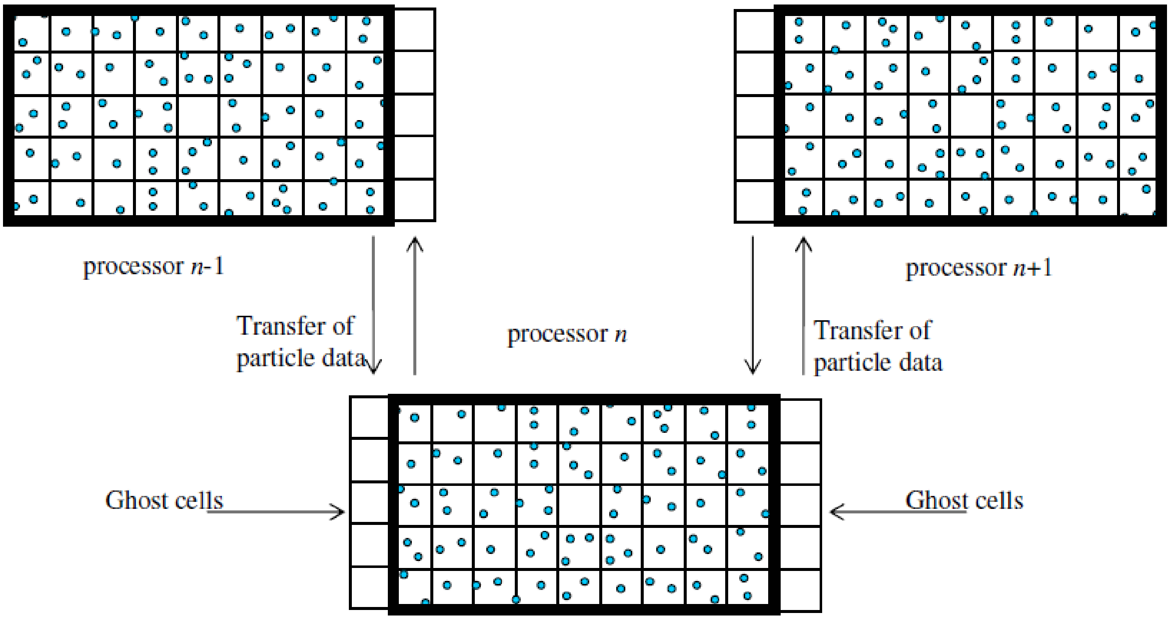

Figure 6. Importing particle information into ghost cells from neighboring processor (Gomez-Gesteira, 2011)

- Boundary particles

Boundary particles represent a slightly difficult problem since while they can be considered to be disordered; their explicit connectivity needs to be known when calculating boundary surface normal. To calculate boundary surface normal requires the knowledge of the local boundary shape. Therefore, the approach taken herein was to keep an array on the root processor that stores the positions of immediately adjacent boundary particles. This list is then broadcast to all other processors. When there is a moving boundary, this list is updated accordingly and again broadcast. This is especially important when a moving object stretches over the interface between two processors and the local connectivity needs to be known in order to calculate the new boundary normal.

5. Description of Physical and Numerical Experiments

❖ Experimental set-up

To simplify the tsunami wave generation triggered by submarine slide, the experiments were conducted in narrow wave flume at Offshore Laboratory, Universiti Teknologi PETRONAS.

Experimental test about tsunami wave will be carried out in concrete flume of 20 m length, 1.5 m width and 1 m depth. The side walls are composed of 1.28 cm thick tempered glass windows which are each 63.5 cm high and 1.52 m long. The bottom is constructed of high strength concrete.

Fig. 7 shows the schematics of the experiments. The experimental set up included two inclined platforms. One of the inclined platform was made for sliding down solid blocks and another one for observation of impact of slide-generated tsunami waves. The sliding surface was smooth and was also lubricated in order to provide a frictionless slope. Tsunami waves were generated by sliding down solid blocks along the inclined bed. The blocks had different shape, volume and thick ness and they have been made of steel plates with rock inside. The total weight of block was determined based on the weight of steel plates, weight of rock inside and the filling water weight. It was considered the block was full of water.

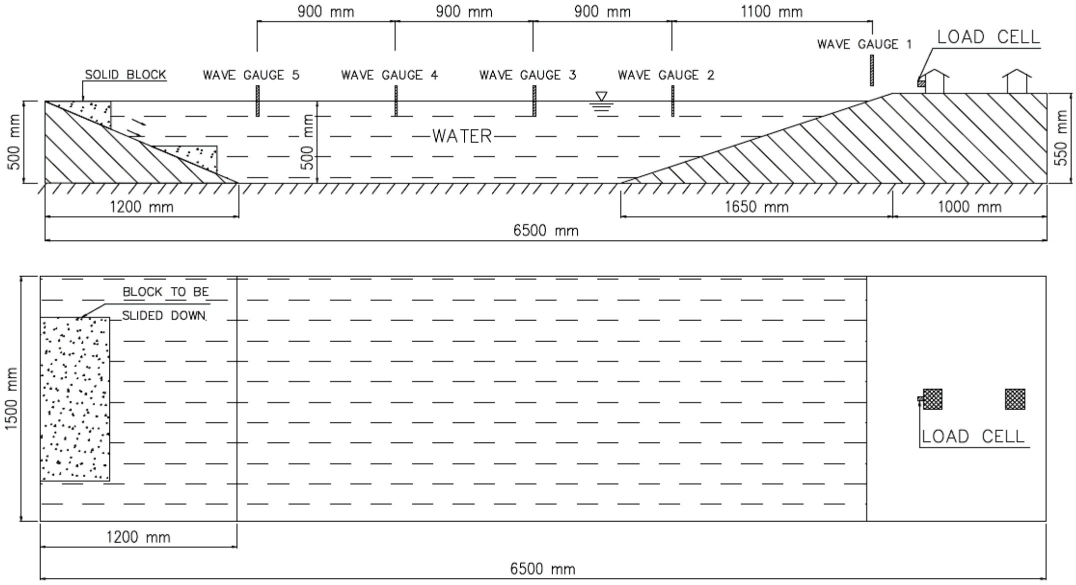

Figure 7. Schematic of experimental set-up for submarine slide generated tsunami waves

The water surface fluctuations were measured in 5 points located at the central axis of the flume, using wave gauges. A 1:25 scale model of the houses (100 cm x 100 cm x 100 cm) was built using steel plates. In addition, load cells were attached to the model houses, which were then placed on the shore in the flume.

- ❖ Numerical Simulation

The parameters selected for each simulation were selected based on a parameter sensitivity analysis as well as recommendations from previous research by Didier and Neves (2010) and Gomez-Geistera et al. (2010a,b).

Table 1
Numerical model parameters selected

Parameter	Value
Particle Spacing [dx and dz] (m)	0.001, 0.001
Smoothing Distance [h] (m)	0.003
Smoothing Distance Coefficient	0.027
Kernel Type	Cubic
Density Filter	None
Riemann Solver	Non-conservative
Riemann Solver`s Slope Limiter [Beta-limiter]	1.2
Reference Speed of Sound (m/s)	32.21
Coefficient of Speed of Sound (B)	15
Time Stepping Method	Simplistic
Viscosity Treatment	Laminar + Sub-Particle Scale
Viscosity term (α and β)	0.15 d 0

6. Results and conclusions

6.1. Results

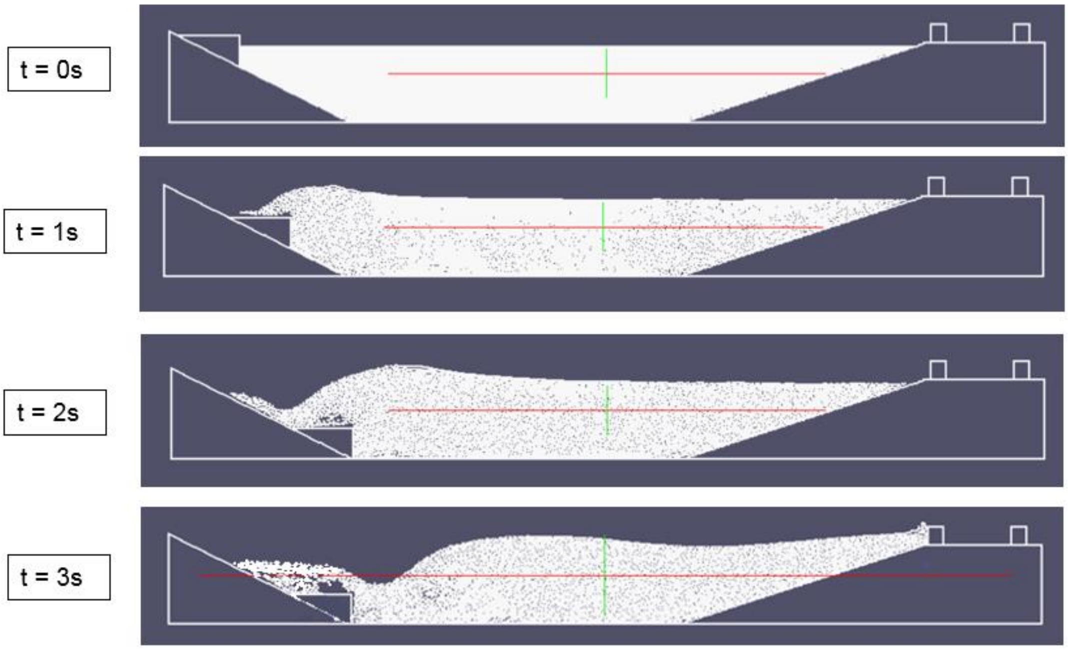

Figure 8. Tsunami wave in a flume simulated with parallel SPHysics code

Along the next frame (see Fig. 8), different instants of the propagation, run-up and impact can be observed: t = 0 s correspond to initial state of the simulation, t = 1s correspond to generate tsunami wave by sliding down solid block along on the inclined bed, t = 2s correspond to wave propagation and the tsunami run-up happens and hit house model at t = 3s.

We now consider a submarine slide of similar parameters as in 2D case above. The domain is larger in y-direction than for the 2D code. In 3D simulation, we can possible assess how far the tsunami wave can be inland after reaching to shoreline. (see Fig. 9)

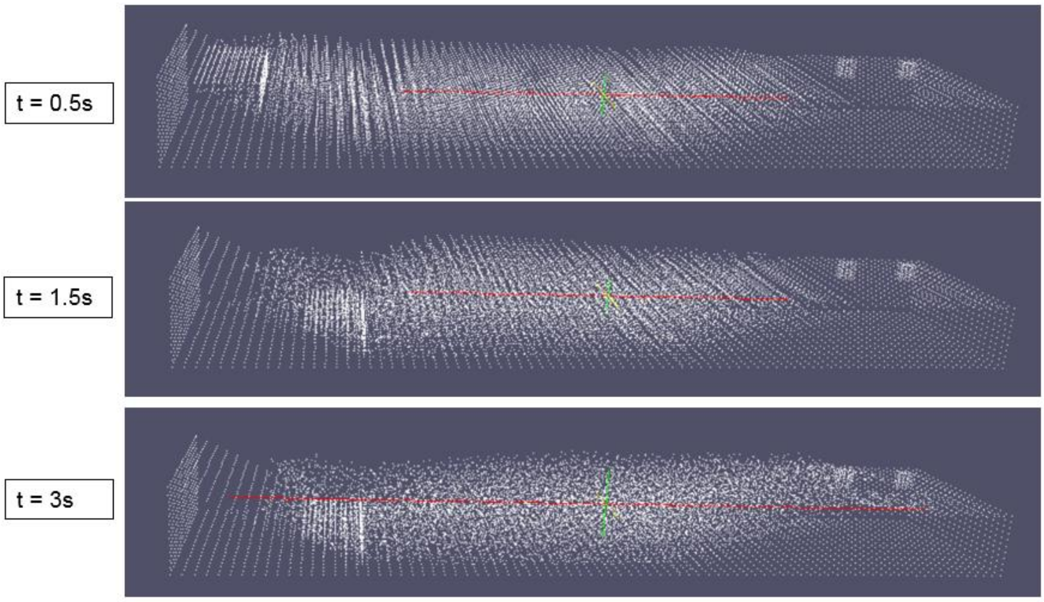

Figure 9. 3D simulation of tsunami wave generated by submarine slide

To confirm that slide tsunami waves were successfully modelled in the simulation, all four stages of the tsunami wave evolution: generation, propagation, run-up and impact (see Fig. 10; Fig. 11). The results of numerical model must be compared to the data recorded in the physical experiments. Results show that Parallel SPHysics code is an application of a unique comprehensive model that covers all aspects of slide induced tsunami from source generation to coastal impact.

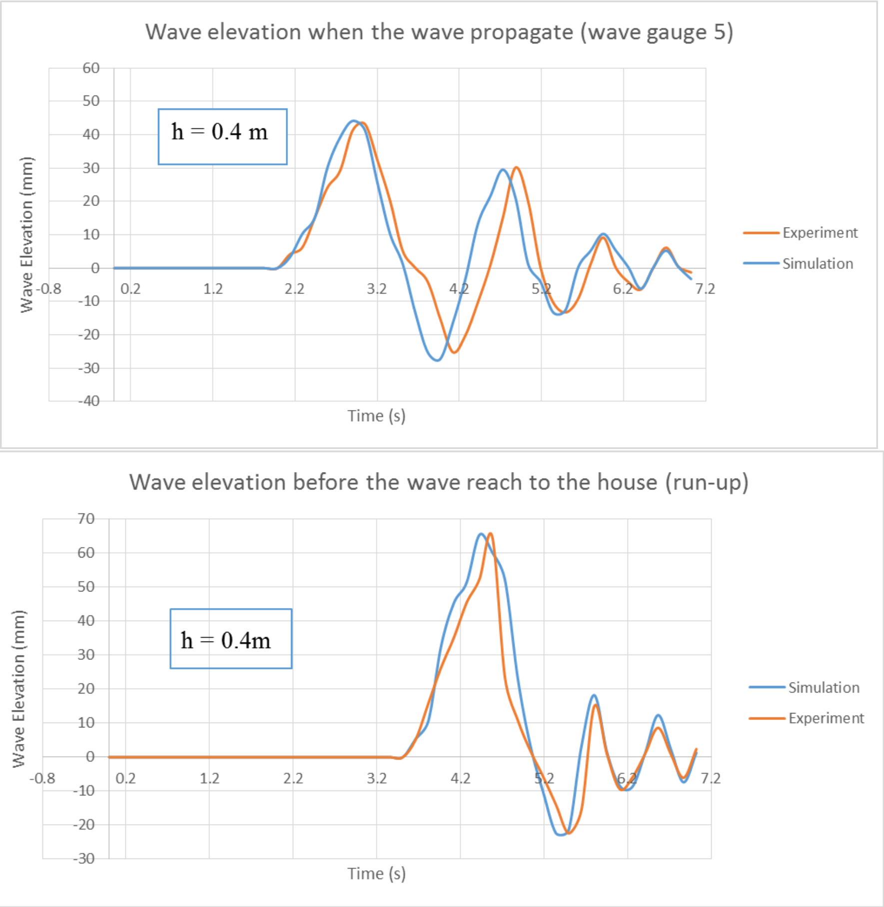

Figure 10. Comparison of tsunami propagation between numerical signal (blue-colored) and experimental signal (orange-colored)

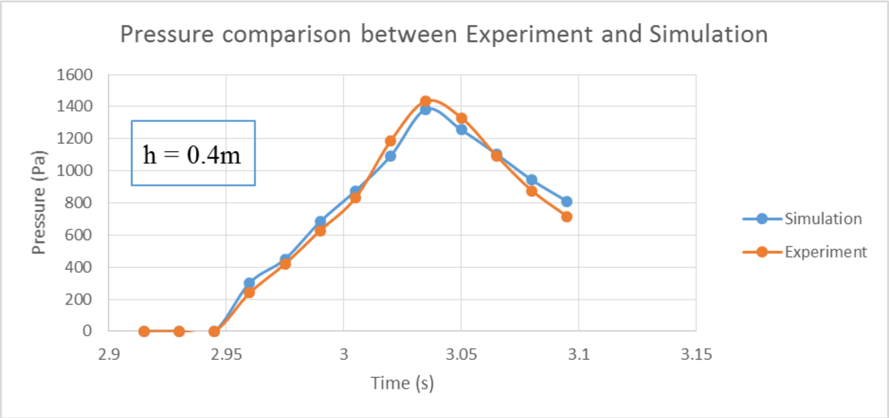

Figure 11. Comparison of impact pressure on coastal house between numerical signal (blue-coloured) and experimental signal (orange-coloured)

6.2. Conclusions

This paper has studied the numerical modelling of submarine slides generated tsunami waves with Smoothed Particle Hydrodynamics (SPH) numerical model. This work is dedicated to the study and testing of the accuracy of numerical model, through simple two and three-dimensional tests. The SPH model can reasonably well modeled tsunami wave generated by submarine slide. The quantitative comparison between the results of the numerical and physical models demonstrates the effectiveness of the SPH numerical model. In general, the SPH model used in this study was able to simulate all stages of tsunami waves generated by submarine slides. It has been possible after that to have a better view on the evaluation of the viscous term in Navier Stokes equation with SPH.

Very good agreement between the numerical and the experimental were found, especially with the introduction in our SPH code of a variable *h* scheme. An experimental, analytical, and numerical modeling research program, which is still in progress, has been undertaken with the purpose of providing a better understanding of the physical mechanisms of tsunami wave.

By using Open MP parallel libraries, this can be obtained assigning a parallel do loop cycle when updating the properties of particles in the fluid domain. In particular, with this technique, the work of each CPU is equally balanced with that of other CPUs, and the parallel architecture results well optimized. The reduction of computational time using parallel computing (supported by High Performance Computing Centre) with 32 CPUs resulted to be less than 40% the time required by a simple sequential computation■

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