A Unique Comprehensive Model: Application to Submarine Slide Generated Tsunami

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Abstract - **Submarine slides can trigger local tsunamis with high run-up affecting offshore structures, subsea facilities and human lives along the shoreline. Unfortunately, slide-generated tsunami is a difficult problem due to the source of sliding of mass failure by itself or by the other earthquakes; and yet no effective numerical models could simulate simultaneously all stages of generation, propagation and run-up of tsunamis phenomena. This paper presents, through the literature review, necessary application of a unique comprehensive model that covers all aspects of slide induced tsunami from source mechanism to coastal inundation and better understanding in mitigating risks from geo-hazards. This paper makes also recommendation on future research directions.**

I. INTRODUCTION

Tsunami wave is known as one of the causes that affect infrastructures, both offshore and onshore structures with their facilities, and human lives along the shoreline. The most popular events resulting in catastrophic loss of life and property are 1998 Papua New Guinea (PNG) tsunami [1] and December 2004 Indian Ocean tsunami [2]. The source of the PNG tsunami, which killed more than 2000 people and destroyed completely three villages, remains controversial and has been postulated as due either to co-seismic seafloor dislocation or sediment slump. Tsunami phenomenon has thus put us on the challenge in understanding from generation mechanism to run-up stage, and mitigating risk from it.

The seafloor movement (e.g. underwater earthquakes); subaerial mass failures (e.g. landslide, pyroclastic flow and avalanche); volcano explosions and submarine mass failures (SMF) generally cause tsunami waves. Tsunami is one of the most hazardous that occur in the coastal area and about 8% tsunamis around the world induced by SMF (following the 2007 ITDB catalogue) including rotation slumps, translational mud flows and turbidity currents. The submarine mass failure is also a vexed issue due to the source of sliding of mass failure by itself or by other earthquake. Such a slide tsunami, therefore, requires understanding of four main fields, namely seismology, geotechnical, geology and hydrodynamic.

Nowadays, with the development of computer processing system, numerical tools play the very important role in simulating of slide tsunami while experimental setups in coastal hydrodynamics and offshore engineering are expensive and only limited to laboratory applications. Numerical simulation thus becomes a great tool in predicting the tsunami waves triggered by submarine slides.

For numerical simulation of tsunami problem, a number of governing equations that express physical principles have been established from the conversation laws for mass, momentum and energy. Some applications were based on conventional Nonlinear Shallow Water (NSW) model [3], [4] due to its simplicity while other applications were based on Boussinesq-type model (BM) [5–7]. Generally, Boussinesq-type model is more efficient and accuracy than one developed based on NSW model, particularly for waves generated in intermediate and deep water [6]. Furthermore, Lynett and Liu [8] have made a comparison between BM and NSW models in order to quantify the effect of frequency dispersion on the slide-generated tsunami. They indicated that the NSW model was a poor estimator of wave heights. Besides, the NSW model was not suitable for modeling entire process of submarine slide tsunami [9], whereas the BM model was able to simulate all stages [6], [7] or separated stage of generation [8], propagation [10], [11], and run-up [10]. Despite of using widely NSW and BM models, they cannot capture the realistic wave breaking and overturning processes that are important near the generation region as well as run-up region. Yuk et al. [12] have used a model which is based on the Reynolds averaged Navier-Stokes (RANS) equations with the $k-\varepsilon$ turbulence model to simulate wave-breaking and interaction between breaking waves and coastal structures. The capacity and accuracy of the RANS model in predicting wave generation by SMF and propagation have been validated. A good agreement was observed. In addition, the RANS approach was incorporated with a modern numerical technique such as Smooth Particle Hydrodynamics (SPH) method to investigate the time-dependent wave breaking processes [13]. A mesh-free particle approach 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 shown that the SPH method provides a useful tool to investigate the surf zone dynamics.

The above models have had a measure of success, but the fact remains that those are still not a comprehensive model that could covers all aspects of slide-induced tsunami from initial generation through subsequent evolution, and final run-up stage. The objective of this paper is to present the idea in applying an improved model into the entire phenomenon of tsunami wave generated by submarine mass failure. Here we discuss the modeling issues, point out the important characteristics and drawn conclusions.

II. LITERATURE REVIEW

Tsunami waves due to submarine slides are complex phenomena that may be divided into four parts: *triggering mechanism, tsunami generation, propagation and run-up at the beach*. The literature part presents an overview of this phenomenon:

A. Submarine Slide Triggering Mechanism

A fundamental aspect of submarine slides research is needed to understand trigger mechanisms. In most of the circumstances, submarine slides were triggered by ground acceleration due to earthquakes, by anthropogenic (i.e. coastal construction without due consideration for the local geological and geotechnical conditions), and by gas accumulation provided by dissociation of gas hydrates. Either trigger, natural or anthropogenic, tends to cause excess pore pressure and reduction in stress condition. Despite this, the ability to accurately measure, monitor and predict pore pressures in offshore sediments is limited. Therefore, it is important to improve the understanding of excess pore pressure genesis, accurate measurement and its implications.

During the run-out of a submarine block, the change of properties is complicated. In fact, the failed material progressively breaks down and weight properties and strength transform accordingly. Initially, the slide is an intact block and then transitions into debris flow, with the soil deforming and weakening. As the debris flow advances, further degradation of the material takes place and water becomes entrained in the soil, leading to operative strengths as low as 0.1kPa illustrated as in Fig. 1. Some experimental tests shown that the superposed effects of significant water entrainment controls the sliding length during the sliding process and softening of the material, as shear strain accumulates [14].

To assess the risk of submarine slope failure effectively, it is ideal to require a large areal coverage including sediment properties, changing surface and subsurface morphologies. Detailed digital elevation (bathymetric) maps and correlation with seismic reflection profiles can assist in this requirement. It is however rare to know pre-failure conditions and likely impossible to know mechanics of the flow during failure, but numerical simulation can provide insightful information to these important issues. Therefore, it requires incorporating the change of excess pore pressure response into the slope's analysis and takes into account the change of viscous effects and watering entrainment processes into models of slide materials and it should be an important focus of future work.

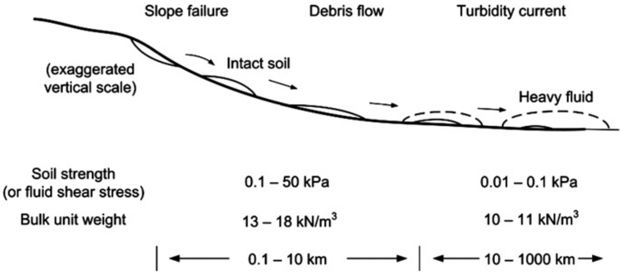

Figure 1 Stages of submarine slide breakdown and typical properties

It is clear that the assumption of a non-deformable slide (i.e. rigid body) could change the generated water waves significantly compared to real deformable slides. Hence, a number of researchers have introduced different approaches to describe the slide motion by a flow of liquids differing in their density, viscosity, etc. [3], [4], [15] or by flow of a two-layer liquid with layers having different densities and viscosity coefficients [16]. Recently, Capone et al. [17] introduced a bi-viscosity rheological Bingham model of slide deformation and its interaction with water to produce the tsunami waves. However, further research on the implemented numerical model involves in using of rheological models or something else to simulate the slide deformation before and after the impact with water.

B. Tsunami Generation by Submarine Slides

Tappin [18] has pointed out that all forms of submarine slides have potential to create tsunamis, yet there is a paucity of data relating tsunami generation. The first simplest way to describe a slide is solid body motion sliding down a constant slope [19]. However, most slides disintegrate into a debris avalanche and eventually turbidity currents. Turbidity currents are irrelevant in the generation of tsunami because by the time the sediment has become mixed with water and begun to stratify in the water, the tsunami has been generated and is moving away from it source area. In addition, the application of models to express generating wave is also important. The first application for tsunami wave's simulation was based on Nonlinear Shallow Water (NSW) wave equations due to its simplicity. Nevertheless, the NSW equations do not correctly capture the interaction between slides and wave generation [5]. Lynett et al. [8] have derived and used a fully nonlinear BM rather than an NSW model to simulate SMF tsunami generation.

C. Tsunami Propagation

Nature of tsunami waves can be characterized as nonlinearity effect and frequency dispersion that causes shorter waves to propagate at a slower speed and thus causes an initial packet of waves to disperse as it propagates. Regarding this, the Boussinesq-type models are more efficient and accuracy than models developed based on NSW equations which can lead to errors in the wave shape and arrival time [8]. The BM model relaxes the restriction on nonlinearity of NSW model and originally includes the effect of frequency dispersion. Fig. 2 shows the difference in waveform for a tsunami when the dispersive terms are included and when they are not [20]. Clearly, the inclusion of the dispersive effects is important for the determination of the time history of the wave motion at a point.

The numerical model GEOWAVE that based on the Boussinesq theory has also been used for simulating a real case study of PNG tsunami event [10]. The BM model has shown a significant improvement over previous simulation made with an earlier tsunami source and shallow wave propagation models by reproducing correctly times of tsunami arrival relative to strong after shock that occurred roughly 20min after the main shock.

However, both BM and NSW equations cannot model waves close to breaking area and, hence, are inaccurate for simulating very shallow and thick SMF as well. Reynolds averaged Navier-Stokes (RANS) equations with the $k-\varepsilon$ turbulence model could provide capacity and accuracy in predicting the breaking of wave in generation and propagation [12]. The wave profiles are in good agreement with experiment.

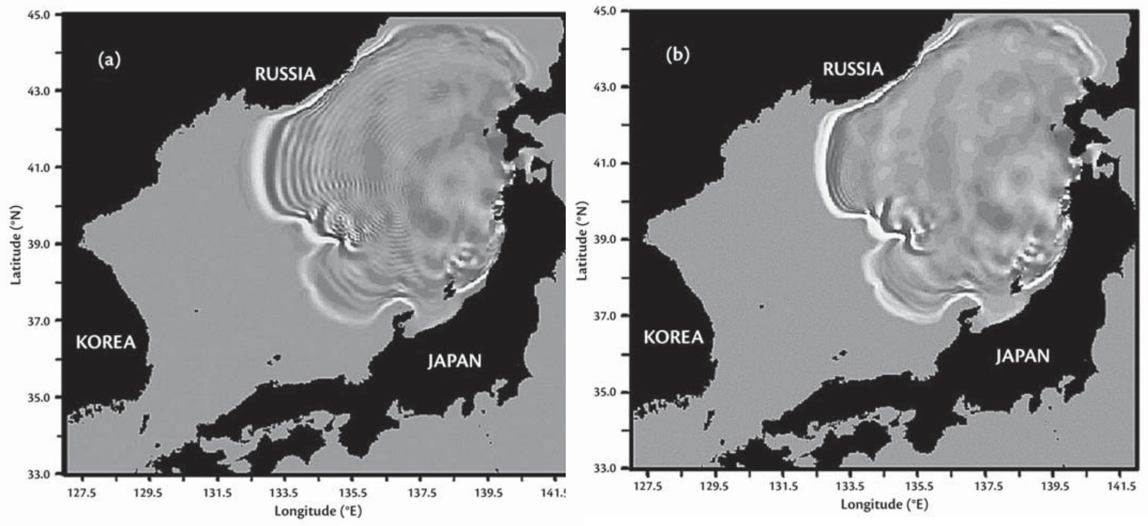

Figure 2 Simulation of Nihonkai-Chubu tsunami of May 26, 1983 in the Japan Sea. Numerical model results from Yoon [26]. Left frame shows simulated wave with dispersive effects included in the numerical model. Right frame shows results without dispersive effects.

D. Run-up and Inundation

The modeling of tsunami flows at most types of shorelines remains a difficult but important problem. For coastal communities within the wave run-up region, the tsunami flows around, through, and over buildings. This turbulent, fast-moving flow results in building damage, collapse, or floating away. People are drowned, due to the high water, the difficulty of withstanding the fluid forces, coping with the large turbulent eddies, or impact with debris. Pedersen [21] generalized from the progress of wave run-up modeling into two directions: one is the integration of run-up facilities in general wave propagation models with high order inherent dispersion and another is the involvement of the representation of accurate shore line in models.

Both NSW and BM models can provide good prediction with laboratory results of run-up height and inundation over coastal terrain. Fig. 3 shows the run-up of a tsunami, represented by a solitary wave, on a uniform slope [22]. The principal limitation to their accuracy in predicting shoreline inundation in tsunami applications stems from factors of frequency dispersion and the interaction with fixed obstacles and with the mass of transported debris resulting from destruction of structures. In addition, it is clear that, for the case of breaking tsunami wave, the Boussinesq-type model is superior to NSW due to the exclusion of accumulation of dispersion effects in the NSW model [21]. However, the use of Boussinesq-type models does not adequately predict the full structure of the flow, which is important given that upon landfall tsunamis are propagating over dry land and are often interacting with structures on the same scale as the depth [5]. In order to re-solve that issue, a numerical model such as RANS model [12], [23] was proposed to predict breaking wave in deep and shallow water, including wave pre-breaking, overturning and post-breaking processes. However, this more advanced method has been unable to capture fully flow of tsunami when it breaks onto a beach, and very computationally expensive.

III. METHODOLOGY

As noted in state-of-the-art looking at slide tsunami hazards, the physical understanding of this hazard is poor, and there is an immediate need for research such that we can prepare for devastating events like Papua New Guinea or Indian Ocean. This is, of course, no simple task because of the complexity and multi-scale of process. Although the use of such models could be appropriate for entire process of slide tsunamis (e.g. BM, RANS models) or each stage (e.g. NSW, BM, and RANS models), the advantage from those are not too much. Rather than switching from one model to another, it should use a unique comprehensive model that automatically covers most of the range of effects of interest, from generation region, through propagation at ocean-basin scale, to run-up and inundation at affected shorelines. The main modeling challenge is to move across a sequence of spatial resolution needed to resolve wave crests as they move from the deep ocean into complex coastal environments. This hierarchical sequencing of model scale was implemented yet in a practical model. Now, it will be an important focus of future work.

Furthermore, for numerical simulation of a fluid mechanics such as tsunami phenomenon, a model algorithm can be divided into two main methods including grid-based method and meshfree method. Historically, computational fluid dynamics focuses on grid-based methods, where two different frames are usually considered for describing the physical governing equations, namely the Eulerian and the Lagrangian description. The finite element method (FEM) is the paradigm of Lagrangian method and the Eulerian description is commonly represented by the finite difference method (FDM) and finite volume method (FVM). The grid-based numerical methods have achieved remarkably, and they are currently the dominant methods in numerical simulations for solving practical problems in engineering and science. However, the major difficulties result from the use of grid/mesh, which can lead to various difficulties in dealing with problems such as free surface, deformable boundary, moving interface, and extremely large deformation and crack propagation. Moreover, for problems with complicated geometry, the generation of a quality mesh has become a difficult, time-consuming and costly process.

Alternative to grid-based method is meshfree approach. The development of meshfree method offers a reliable approach to tackle the simulation of difficult problems that was met with grid-based method due to its grid distortion. Of the meshfree techniques developed over past decade, Smooth Particle Hydrodynamics (SPH) invented by Lucy [24], Gingold and Monaghan [25], has been the most popular and successful when applied to coastal hydrodynamic and offshore engineering in general [26–31] and to free-surface hydrodynamics in particular [17], [32–34]. Therefore, this numerical tool will be feasible for simulation of tsunami phenomenon when incorporating with a unique model in re-solving the governing equations. This would be the main work of this project.

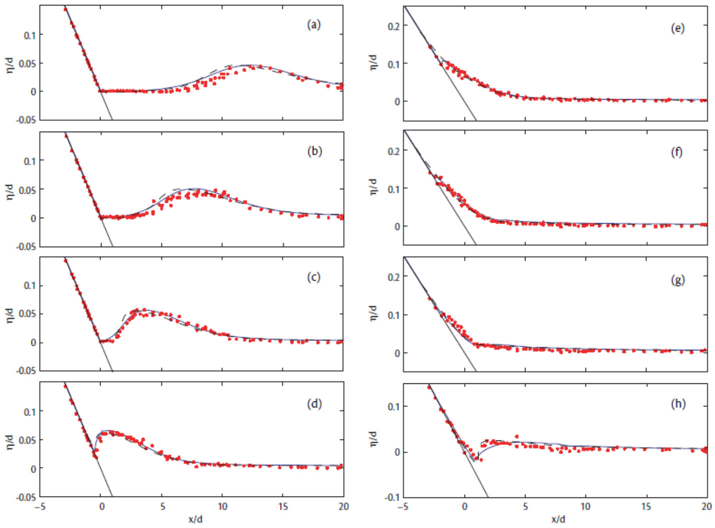

Figure 3 Sequence showing the approach and run-up of a breaking solitary wave. The dots represent laboratory data obtained by Synolakis **[22]**. The dash line is a nonlinear shallow water solution and the solid line represents numerical results of a Boussinesq model.

IV. BASIC SPH FORMULATION

The basic idea of SPH method is an integral interpolation theory, from that we can determine the value of any variables (e.g. mass, velocity, density, pressure…) at any location within the fluid. This interpolation theory is divided into two key steps. The first step is a kernel approximation of field functions. The second step is a particle approximation.

A. Kernel Approximation

In SPH formulation, the value of a flow quantity f at a position vector x is approximated by

$$f(x) = \int_{\Omega} f(x_j) W(x - x_j, h) dx_j \qquad (1)$$

where Ω is the volume of the integral that contains x; $W(x - x_j, h)$ is the weighting function referred to as the smoothing kernel and h is the smoothing length or support domain defining the influence area of the smoothing function W. Equation (1) implies that a function can be represented in an integral form and the integral representation in this equation can only be an approximation cause W is not the Dirac delta function.

B. Particle Approximation

In Lagrangian numerical model, and in particular SPH, the fluid is represented as a finite number of particles. Thus, the continuous form of kernel approximation expressed in equation (1) can be possible to rewrite in a discrete form, replacing the integral form by the summation of the neighboring particles as follows

$$f(x) \approx \sum_{j=1}^{N} m_j \frac{f_j}{\rho_j} W(|x - x_j|, h) \qquad (2)$$

where N is the total number of particles. This summation is referred to particle approximation, which states that the value of a function at a particle can be approximated by using the average of those values of the function at all the particles in the support domain weighted by the smoothing function. The use of particle summations to approximate the integral is, in fact, a key approximation that makes the SPH method simple without using a background mesh for numerical integration, and it is the key factor influencing the solution accuracy of the SPH method.

C. Kernel Function

The function W (as illustrated in Fig. 4) has a Gaussian-like shape, with the only constraint of having a compact support, so that the interaction between particles vanishes over a finite distance h. There are a variety of possible weighting functions such as bell-shaped function [24]; Gaussian function [25]; cubic B-spline function [35]; higher order (quartic and quintic) splines [36]; quadratic smoothing function [37]; or super-Gaussian function [35]. Obviously, the application of which functions depend on the problems those need to capture and it should be also satisfy a number of conditions:

$$\begin{cases} \int_{\Omega} W(x - x_j, h) dx_j = 1 \\ \lim_{h \to 0} W(x - x_j, h) = \delta(x - x_j) \\ W(x - x_j, h) = 0, \quad for |x - x_j| > \kappa h \end{cases} \qquad (3)$$

The first condition is called *normalization condition* or *unity condition* and the second one is *Delta function property* that is observed when the smoothing length approaches zero. The third one is *compact condition* where κ is a scaling factor.

$\left|x - x_j\right| \le \kappa h$ defines the support domain of the particle at point x. In the computational fluid dynamics (CFD), the most using is the quadratic smoothing function proposed by Johnson, et al. [37] and successfully applied in tsunami waves generation and propagation as in [34], [38].

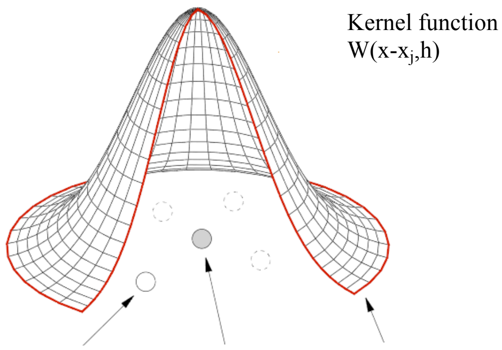

Figure 4 Example of suitable kernel function

D. *SPH Equations*

By using the afore-mentioned kernel and particle approximation techniques, it is possible to derive SPH formulations for Navier-Stokes equations controlling the fluid dynamic problems in a Lagrangian coordinates

$$\frac{d\rho}{dt} = -\rho\nabla.u$$
$$\frac{du}{dt} = -\frac{\nabla P}{\rho} + g + \frac{1}{\rho}\left(\nabla.\mu\nabla\right)u \tag{4}$$

where ρ is density, μ is laminar viscosity, u is velocity, P is pressure, g is gravity and t is time.

The above conservation of mass and momentum equations are expressed in particle form as following

$$\frac{d\rho}{dt} = \sum_j m_j\left(u_i - u_j\right).\nabla_i W_{ij}$$
$$\frac{du}{dt} = -\sum_j m_j\left(\frac{P_i}{\rho_i^2} + \frac{P_j}{\rho_i^2} + \prod_{ij}\right).\nabla_i W_{ij} + g \tag{5}$$

where m_j is the mass of the j^{th} particle, $\nabla_i W_{ij} = \nabla_i W\left(x - x_j\right)$, the first subscript i referring to the derivative of W with respect to the coordinates of particle i, and Π_{ij} is an artificial viscosity term.

V. CONCLUSIONS AND FUTURE WORK

The paper introduced the importance of the submarine mass movement in exploration and development in deep water; therefore, it requires an immediate need for research of this topic.

The paper proposed the feasible application of a unique model for numerical simulation of submarine slide generated tsunami waves. In addition, the SPH method was also introduced due to its salient features in dealing with the deformable boundary, moving interface, free surface and crack propagation problems. Advantages of SPH are its robustness, simple concept, ease of incorporating new physics and ability to handle the large deformation in a pure Lagrangian frame. However, to achieve a reliable solution, the computational accuracy, consistency, efficiency, stability and convergence need to be incorporated into good SPH algorithms.

Consequently, future catastrophes can be assessed and mitigated from these studies of slide dynamics, tsunami propagation and coastal impact.

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