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# Review on Tsunami Wave Propagation and Their Interaction with Structures

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***ABSTRACT:*** *This paper reviews recent studies in tsunami wave generation and their interaction with structures. The main need for this investigation is to compare whether meshing methods or mesh-free particle method is suitable for a turbulence flow in a complex boundary condition. The main objective of this paper is to illustrate how the numerical simulation is created for a catastrophic event like a tsunami which is impossible in real-time. This review additionally incorporates a short description about governing equations which are used for a turbulence flow problem also its benefits and drawback on each other, the modeling and experimental techniques conducted to find the tsunami forces and its propagation are explained in some details. Further topics related to different techniques of numerical simulation for a turbulence flow problem with examples are discussed. This work concludes that using smoothed particle hydrodynamic (SPH), one of the mesh-free particle methods is acceptable for prediction of the flow and no defined grid structure makes it more accurate for a turbulence nature.*

***KEYWORDS:*** *Tsunami, wave propagation, turbulence flow, mesh-free particle method, smoothed particle hydrodynamics.*

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## I. INTRODUCTION

Tsunami waves are a progression of giant waves activated due to underwater disturbance by the seismic tremors or volcanic emissions or once in a while by atomic blast or space rocks happening close or underneath the sea. The tidal wave is for the most part brought about by seismic tremor. The heat from the earth's core tends to creates movement of molten rocks in the mantle layer. This causes the tectonic plate movement, which are divergence, convergence and transform. They tend to move at the pace of one to two inches for every year. These plates move continually and gradually. Sometimes the friction between them causes interlocking and pressure builds up. They finally release and transfer the energy to earth surface, which we can feel as shaking of ground. If this happens near oceanic plates this may creates tsunami. Not all movements create these giant waves; many give next to zero impact which depends on the source point of the earthquake from surface. A study says earthquake surpassing 7.5 Mw causes a destructive tsunami. The large amount of energy created is carried through water particles. During the release of energy, the process of potential energy is changed over to kinetic energy as the water displaces. Because of these occasions in sea, the wave moves outwards and away from it. Before a tidal wave hit, the water level drops in the coastline. Explanation for this notice is tidal wave carries on like a tides, as they go outwards before they hit. As we are probably aware that first waves is not more grounded and greater. They need to confront the shallow water close to the land, it lessens the main wave's stature and its vitality and next back to back wave doesn't have these issues.

Tsunami wave averagely has a speed of 805 kilometers/ hour and its base height is about 3 m from the ocean level. The inland flooding will be up to 304 m. There are four stages of tsunami, which are initiation, split, amplification and run-up. During initiation, an enormous arrangement of sea waves is brought about by any huge and abrupt unsettling influence of the ocean surface, most generally seismic tremors yet now and again additionally underwater landslides. In the split stage, the underlying arrangement of waves is part into two, one set that movements out into the profound sea and another that movements toward a close by the coast. In the amplification stage, the tallness of the tsunami increase and the separation between two adjoining peaks (high focuses) as it goes toward the coast, so the principal wave of the tsunami gets steep. In the last stage, a peak of the wave hits the shore. This stage is known as the run-up. It is used to depict the estimation of the height of the water on the shore. Once ashore, some portion of the wave is reflected go into the sea, and another part is caught in waves that movement to and from close to the shore.

A tsunami is a catastrophic event and it might happen any time around the globe in the coastal regions and the effect it makes is unfathomable. At the point when it comes to the sense of structures, it can't be estimated progressively using the help of modeling and numerical simulation techniques, the wave forces on the structures can be predicted. In this way, the state and condition of the structures can be described, which will be useful for further occupancy and renovation process [1].

Indian Ocean tsunami happened 15 years back on December 26, 2004 and it assaulted 14 nations. The most grounded seismic tremor of 9.1 Mw happened at West Coast of Sumatra, Indonesia. Very nearly 230,000 individuals died, 1.7 million individuals lost their homes and 2 million announced uprooted by the disaster. Wave of 9.14 m high is recorded with the vitality of 1.1x1017 joules which is equivalent to multiple times of Hiroshima nuclear bomb [2].

## II. GOVERNING EQUATIONS

### a) SHALLOW WATER EQUATION

Water waves are classified into numerous sorts from a hydraulic perspective in that tsunami fits to long waves. The theory of long wave is an approximate theory appropriate to waves of small relative depth, for which the vertical acceleration of water particles is insignificant compared with the gravitational acceleration and the curvature of trajectories of water particles is adequately little. Consequently, the vertical movement of water particles has no impact on the pressure distribution. It is a good resemblance that the pressure is hydrostatic. Furthermore, the horizontal velocity of water particles is vertically uniform [3]. There are two approaches in shallow water equation, linear and nonlinear. Both are considered as accurate for tsunami wave propagation modeling. Shallow water wave theory used to express the equations of mass Conservation (1) and momentum (2) in the three dimensional problem. In shallow water equation wave length are longer than wave depth, which is only for long waves. In this equation the viscous effect is assumed to be neglected in the flow. The shallow-water equations are hyperbolic Partial derivative equation, so applying the method of characteristics can reduce them to a group of ordinary differential equations [4].

Conservation of mass

$$\frac{\partial \eta}{\partial t}+\frac{\partial}{\partial x}[(\eta+h)u]+\frac{\partial}{\partial y}(\eta+h)v=0 \quad (1)$$

Momentum Equation

$$\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial}{\partial y}+fu+g\frac{\partial \eta}{\partial y}=0 \quad (2)$$

By method of characteristics, the non linear shallow water equation is;

$$\frac{\partial}{\partial t}(u-2c)+\frac{dx}{dt}\frac{\partial}{\partial x}(u-2c)=\frac{d}{dt}(u-2c)=g\frac{\partial h}{\partial x} \quad (3)$$

For linear shallow water equation, neglecting the second order terms and solving them;

$$\frac{\partial^2}{\partial t^2}(\eta\sqrt{g})=\nabla[\mathrm{gh}\,.\,\nabla(\eta\sqrt{g})] \quad (4)$$

Where, η is vertical displacement of free surface; $h$ is bottom topography; u & v are three dimensional velocities; f is coriolis parameter; $(u-2c)$ & $(u+2c)$ are Riemann invariants. The mathematical statement shows that the local speed of propagation of Tsunami over the open sea toward any direction with no scattering. Closer to the shore, the wave shrinks on horizontally and rises vertically, so the linear approximation never again legitimate. As the nonlinear shallow-water equation (3) being hyperbolic, they take into account wave breaking. The breaking mechanism is more complex than the shallow-water equations approach [5]. Toshitaka baba et al [6] investigated tsunami inundation modeling of the 2011 tohoku earthquake using 3D building in a nested grid scheme. Nearly 20 million grids are needed for the tsunami inundation modeling. They speed up the simulation by parallelizing the code. The wave generated by solving linear shallow water equation in the coarsest grid to spare computational time and stability. Non linear shallow water equation adopted for some interior grids. Yingchun Liu et al [7] compared linear and nonlinear shallow wave water equations applied to tsunami waves over the China Sea. From the analysis, they concluded that applying a linear shallow water equation provides good accuracy for his critical area and also permits an earlier prior notice. The linear calculation can be done on PCs in a continuous process. They also concluded that the bottom frictional properties of the seafloor play a vital in the calculation of tsunami waves. A similar explanation concerning the relevance of linear theory won't be valid for the eastern China Sea. As a result of its large shallower ocean bottom, they prefer the nonlinear shallow-water. The study on the magnitude of the tsunami wave forces that separated the land to a newly deserted small island caused by the 2004 Indian Ocean was carried by Musa Al ala et al [8]. They used COMCOT for linear modeling with a finite difference method to compute the shear stress required to isolate the land and Delft3D for dynamic modeling with shallow water equations to visualize the sediment transport process that happened. They utilized both the shallow water equation (linear and nonlinear) for different region flow propagation for managing time consumption.

**b) REYNOLDS AVERAGED NAVIER STOKES EQUATION (RANS)**

The Navier-Stokes equations describe the flow of continuous fluid. They are expressed from the conservation of momentum which is applied for fluid particles. By employing Time averaging and fluctuating quantities in Navier stokes equation and continuity equation for incompressible fluid; we obtained Reynolds Averaged Navier Stokes equation [9]. The general Navier- stokes equation in vector form is given in equation (5) [10].

$$\rho \frac{D\vec{V}}{Dt} = -\nabla P + \rho\vec{g} + \mu\nabla^2 \vec{V} \tag{5}$$

For a three- dimensional turbulent flow, velocity is given by sum of time averaged velocity $\bar{u}$ and the fluctuating component u´with respect to time in equation (6),

$$u(x,y,z,t) = \bar{u}\,(x,y,z) + u'(x,y,z,t) \tag{6}$$

The assembled Reynolds Averaged Navier Stokes equation after time averaging is given as,

$$\rho\left[\frac{\partial}{\partial x}(\bar{u}^2) + \frac{\partial}{\partial y}(\bar{u}\bar{v}) + \frac{\partial}{\partial z}(\bar{u}\bar{v})\right] = -\frac{\partial \bar{p}}{\partial x} + \mu\left[\frac{\partial^2\bar{u}}{\partial x^2} + \frac{\partial^2\bar{u}}{\partial y^2} + \frac{\partial^2\bar{u}}{\partial z^2}\right] - \left[\frac{\partial}{\partial x}(\rho\overline{u'^2}) + \frac{\partial}{\partial y}(\rho\overline{u'v'}) + \frac{\partial}{\partial w}(\rho\overline{u''})\right] \tag{7}$$

$\left[\frac{\partial}{\partial x}(\rho\overline{u'^2}) + \frac{\partial}{\partial y}(\rho\overline{u'v'}) + \frac{\partial}{\partial w}(\rho\overline{u''})\right]$ Terms in equation (7) are called Reynolds Stresses that creates the turbulent disturbance [11]. Aggelos el al [12] referred previous literature and worked on advanced numerical modeling of tsunami wave propagation, transformation and run-up to determine the accuracy, applicability and limitation in a CFD model by solving 3D- Navier stokes equation. As it is an incompressible multiphase fluid flow, wave breaking may occur. So large eddy simulation (LES) is utilized and decomposition of turbulence is utilized into large-scale and small-scale structure. In this paper, Bjarke Eltard Larsen and David R. Fuhrman [13] performed 14 full-scale tsunami simulations with RANS models, utilizing a stabilized k-ω model from their past work on CFD Performance of interFoam on the simulation of progressive waves. The stress limiting coefficients were taken as λ1 = 0.2 and λ2 = 0.05 and scalar field γ used to track the two fluids which are pure air and pure water are assumed as γ = 0 and 1 respectively. The new k-ω model keeps away the aggressive growth of the turbulent kinetic energy in a potential flow region underneath surface waves, which is normal for two-equation closures. In earlier attempt, Hatice Ozmen-Cagatay and Selahattin Kocaman [14] compared experimental and numerical results relating to dam break flow solving Reynolds averaged navier-stokes equation with k-ε model involving shallow-water equation. Later they performed on dam-break flow in the presence of obstacle [15]. In both work, they concluded as free surface profiles during the dam break stages indicate that although both models predicts the flow with a reasonable accuracy, the RANS model is better than SWE model.

**c) SMOOTHED PARTICLES HYDRODYNAMIC (SPH)**

Smoothed particles hydrodynamics is one of the mesh-free particle methods computing the trajectories of fluid particles, which associate according to the Navier–Stokes equations. In other words, the fluid domain is defined by nodal points that are dispersed in space with no grid structure and predefined connectivity between nodes. All nodal points consist of scalar information, density, pressure, velocity components, etc. to identify the value of a specific quantity at an arbitrary point x.

$$f(x) = \sum_j f_j W(x - x_j)V_j \tag{8}$$

From equation (8) $f_j$ is the value of f associated with particle j, located at $x_j$, $W(x-x_j)$ represents a weighting of the contribution of particle j to the value of f(x) at position x, and $V_j$ is the volume of particle j, defined as the mass, $m_j$, divided by the density of the particle, $q_j$. The weighting function, $W(x-x_j)$, is called the kernel and varies with distance from x. Its form is an approximation to a delta function [16]. The SPH equations are acquired from the continuum equations of liquid elements by interpolating group of nodes that may be disconnected. The interpolation depends on the theory of integral interpolants. The interpolants are analytic functions, so it can be differentiated neglecting the use of grids. In fluid using dynamical equations, the value of gradient and divergence terms can be identified from information at nearby points. As a result, the fluid dynamics equation decreases to ordinary differential equations at each particle position [17]. Zhangping Wei and Robert A. Dalrymple [18] investigated mitigating tsunami forces on bridges using weakly compressible SPH method on graphics processing units (GPU-SPH). A numerical boundary condition has a vital role in getting appropriate numerical outcomes in the SPH model. As the particle moves toward a wall boundary, its kernel has no complete acceptance domain anymore. For overcoming this issue they adopted a method similar to ghost particle method in which the particles are placed at the wall boundary that in turn helps to achieve a complete kernel support along the boundary [19]. They assumed smoothing length $h_s$ as 1.3 times of the particle size $\Delta p$ and only three layers of dynamic boundary particles are used. The particles in the boundary have the same properties like fluid particles inside the domain, but it behaves as a rigid particles. The rigid boundaries are mostly piers, girders and decks of the bridge structure. For estimation of total hydrodynamic forces on them is equal to summation of forces on all wall boundary particles.

## III. PREDICTION METHOD FOR TSUNAMI WAVES

### a) METHOD OF SPLITTING TSUNAMI (MOST)

The MOST is a basic tsunami modeling tool mainly used for forecasting and inundation modeling. It has three phases: The deformation stage, the Propagation stage, and Inundation stage. MOST uses finite difference approach and shallow water equation in numerical simulation technique. It requires two fundamental input data for modeling which are Seismic data about major dislocation in the sea depths and digital elevation modeling (DEM) data of the bathymetry and topography of the ocean floor and coastal environment. Other basic information and its process are briefly illustrated in Method of Splitting Tsunami Software Manual [20]. Mikhail Lavrentiev et al [21] suggested Tsunami wave modeling by MOST with shared memory systems (OpenMP) and CELL architecture for fast tsunami propagation coding, optimization and obtained results. They adopted 2500 x 1800 mesh size for estimating the time complexity of the MOST modeling. Around 1440 time-steps needed for modeling complete tsunami wave propagation in 24hrs. MOST code was carried out on Fortran 90, it need 3.31 seconds for one time-step. Then it was implemented in C/C++ language and it takes 3 seconds in a four dual-core CPU server. For portable version they implemented in Java which takes 18.5 seconds for running a one time-step. Elizabeth Martin et al [22] recreated tsunami and sedimentology happened on 1969

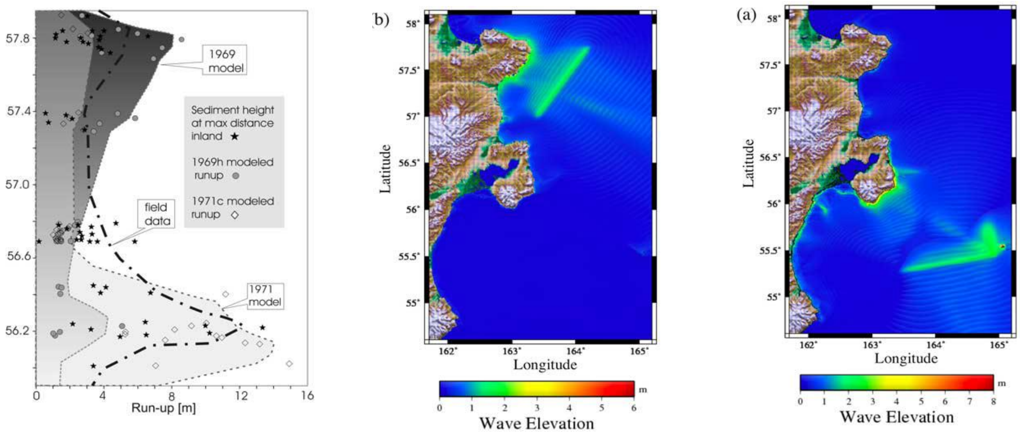


**Fig 1: Comparision of field data of tsunami run-up from numerical simulation by MOST [22]**

Ozernoi and 1971 Kamchatskii using MOST method. They collected field data of tsunami happened on 1969 and 1971, recreated it by giving input data in MOST. They concluded absence of low quality data of topographic and bathymetric tends to inaccurate model outcomes with sedimentological information. In fact that, modeling with MOST is restricted for fluids dynamics and it has limitation in sediment transport simulation. The result from fig 1 shows run-up data higher than sediment data. The run-up data were similar to field run-up data. Due to some flaws in the field observation the result may varied some. Similar type of work is performed by Jose´ C. Borrero et al [23] in Tsunami inundatio n modeling for western Sumatra. They collected data about previous earthquake happened around Sumatra and recreated the scenarios using MOST method and predicted tsunami inundation for future events that may happen. They created four future scenarios with a magnitude of 8.9 to 9.3 in MOST method. The simulation of 9.1 magnitude scenario is similar to the 2004 Aceh tsunami that happened later. V.V. Titov and F.I. Gonzalez [24] from Pacific Marine Environmental Laboratory implemented and tested the MOST model by simulating tsunami wave along the west coast of Okushiri Island.

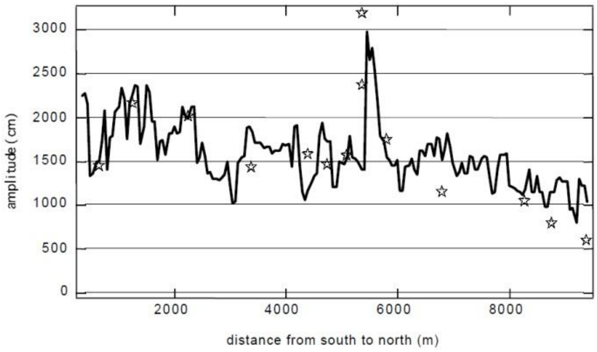


**Fig 2: Comparison of computed (solid line) and measured (stars) maximum run-up values along the west coast of Okushiri Island. [24]**

Fig 2 shows a correlation of simulated and measured maximum inundation results in west coast of Okushiri. They recommended that with sufficient bathymetric and topographic data, the MOST model simulation is a promising tool to create hazard mitigation and forecasting inundation maps.

**b) TUNAMI CODE**

Tohoku University's Numerical Analysis Model for Investigation (TUNAMI) is a tsunami numerical simulation with the staggered leap-frog theory. TUNAMI has different manual as TUNAMI N1, N2, N3, F1 and F2. In this TUNAMI N2 is majorly used code for tsunami numerical simulation with linear theory, shallow water equation and constant grids. TUNAMI-N2 code was implemented in INCOIS centre to simulate tsunami wave propagation. In this, the data files transferred to a grid system. For this a 3D mapping, modeling & analyzing software (Surfer®) that runs under MS windows is used [25] . Shito Motoaki et al [26] examined three different scenario happens during a seismic tsunami in experimentally and numerically using TUNAMI N2, CADMAS Surf/3D and Particle works V3.01.

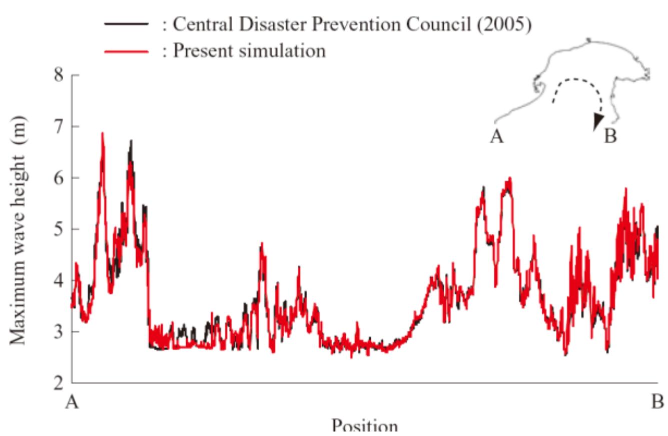


**Fig 3: Comparison of maximum wave height of tsunami events with its simulation data [26]**

This research concluded (from fig 3) that comparison of three interrelated seismic tsunami data gathered from Central Disaster Prevention Council with its numerical simulation results seems to be comparably same. TUNAMI N2 also predicted arrival time of the first wave and maximum wave height. Niroshinie M.A. et al [27] generated TUNAMI N2 code using shallow water equation as main model. For simulating tsunami wave, sub modules are created includes bathymetry, fault and stability. For pictorial representation of the output file MATLAB and Surfer tools are used. They simulated for 2006 Indian ocean tsunami and the model area was near Colombo, Srilanka.

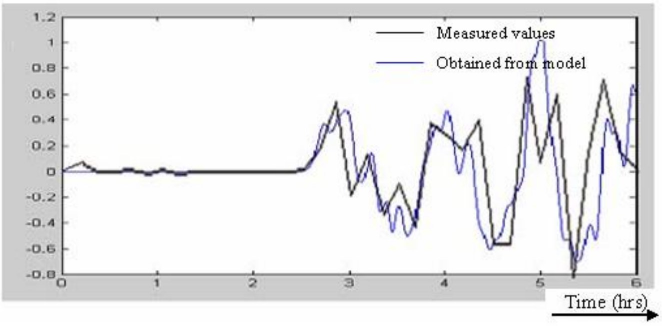


**Fig 4: Time history analysis of water level at Colombo, Srilanka [27]**

The measured values and the model data of water level at Colombo for 6 hours of tsunami model analysis are shown in fig 4. These values were compared with the measured values in Colombo area. The pattern of the graph and the results are comparable same. Similarly Chenthamil Selvan et al [28] investigated effect on Koodankulam region of Tamil Nadu Coast for the same 2004 Indian Ocean tsunami using TUNAMI N2 through assessment of tsunami run-up height and inundation. The tool was also used in koodankulam Nuclear power plant for continuous monitoring of potential risk due to tsunami events. The study also revealed for various tsunami sources the impact on the koodankulam coast was low as the area of Nuclear power plant is located in a high elevation to that of the coastal profile. The model was analyzed for worst case sceneries and it recommends that height above 3.54 m of tsunami affects the power plant. Numerous tsunami inundation and forecasting works in a similar pattern was also carried throughout the globe [29-31].

**c) FLOW 3D**

It is fluid flow simulation software which runs in the base of volume of fluid (VOF) method. Flow 3D is a powerful modeling tool that provide accurate prediction of free surface flow problems. It enhances the tracking ability of interface and boundary condition accuracy. For the flow, it adopts FAVOR technique. Flow 3D is convenient for grid based system, it is efficient and simple. So the solving ability is easy and simulation period is less [32]. Tiecheng Wang et al [33] calculated analysis of tsunami effect and structural response for two different cases shown in fig 5. FLOW-3D software is utilized for assembling a 3D FE model for tsunami wave interaction with an RCC framed structure to evaluate the hydrodynamic wave forces on the structure. For comparison, the same model was analyzed in ANSYS software for seismic impact calculation. Both models are compared to form an idea on prevention and control measures to resist the load.

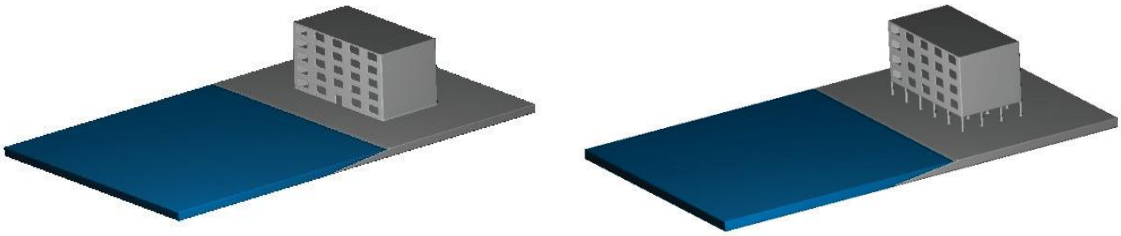

**Fig 5 Two different cases of RCC model [33]**

They concluded that for 5m tsunami wave on the two cases, open and transparent bottom layer model (no wall on ground floor) has good results in tsunami event as it has less tsunami impact and over turning force compared to other model. Tze Liang Lau et al [34] examined Tsunami force around I shaped girder bridges in both experimentally at laboratory and simulated numerically with Flow-3D. They prepared a prototype of a real time bridge and with the help of sensors they noted the value of tsunami normalized force and pressure on the bridge. Then utilizing simulation tool they created a bridge model to calculate the parameters such as normalized pressure and force (Fig 6 & 7). They also derived an empirical formula for calculation of the tsunami forces and pressure on the bridge.

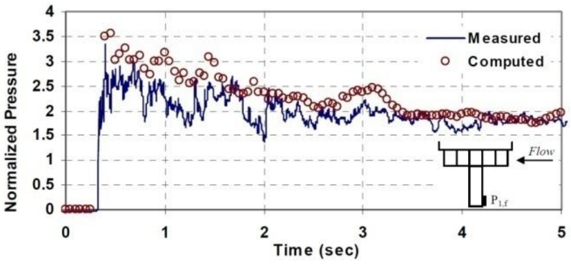


Fig 6 Normalized Pressures on Pier bed in bridge [34]

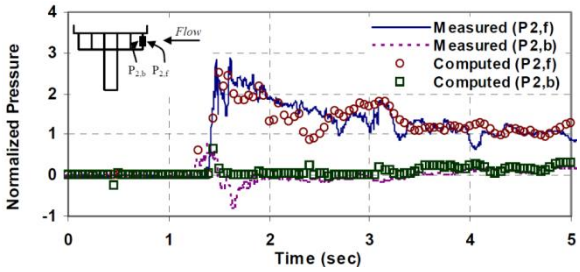


Fig 7 Normalized Pressures on front and back of Girder in bridge [34]

They suggest Laboratory experiments provide realistic wave flow for a model. Yet it is time consuming and uneconomical, using numerical tools for investigating the flow is quit promising and accurate. Similar process of work is carried out for predicting flow profile around a bridge [35] and numerical modeling of landslide-generated tsunamis around a conical island [36].

## d) DUALSPHYSICS

DualSPHysics code derived from SPHysics is an open-source Smoothed particle hydrodynamic model. DualSPHysics is performed in C++ and CUDA (Compute Unified Device Architecture) language to run on CPU (central processing units) or GPU (Graphics Processing Units). CPU code has some advantages over GPU, such as the proper operation of the memory and does multitasking, whereas GPU runs specific tasks rapidly. DualSPHysics runs the simulation in three main steps (fig 8) that are Neighbour list; Force computation and system update [37].

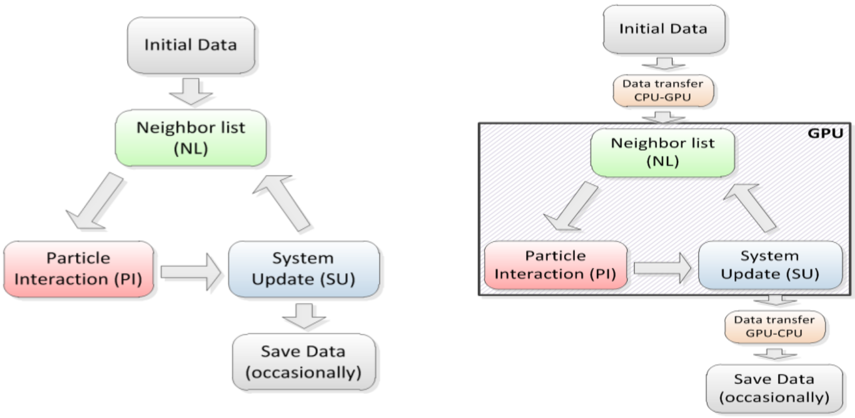


**Fig 8 Flow diagram of the CPU (left) and total GPU implementation (right) [38]**

Safiyari et al [39] simulated Tsunami wave interaction with a seawall caused by explosion. They adopted quintic kernel function by referring literatures. Kernel function used to convert the differential form into particle forms. At first, the SPH method is validated by available experimental data. Then, simulation of wave collision with coastal structure is done. At last, tsunami wave is simulated to calculate pressure on the wall. The number of water particles is increased in two consecutive sequences of the model, thus the error value is less than 5%.

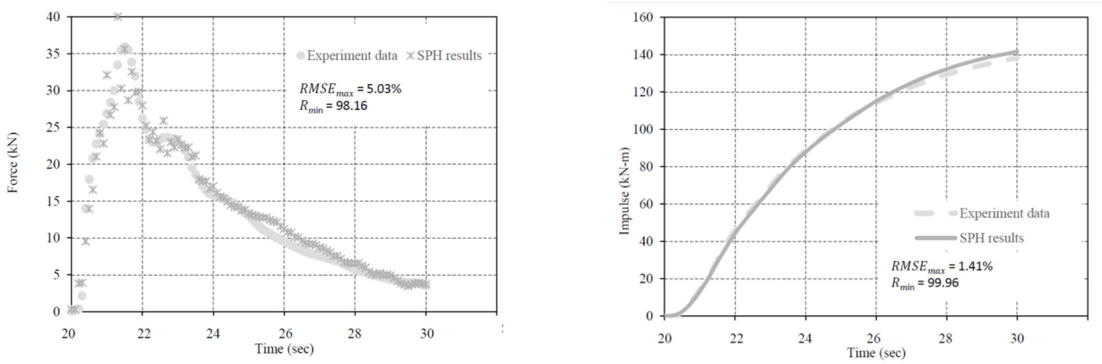


**Fig 9 comparison of force and Impulse of SPH result with experimental data [39]**

Sergey K. and Buruchenko [40] researched effect on low residential building with various facing orientation for a tsunami bore impact using SPH method. For this, they created a prototype of the model and done experiment on them to collect data for validation of DualSPHysics. The various orientation case of the model is given in fig 10.

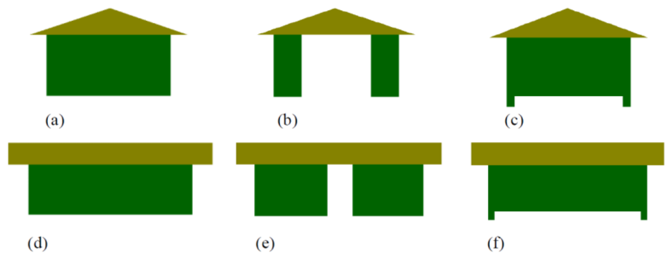


**Fig 10 various facing orientation cases of the model for tsunami wave**

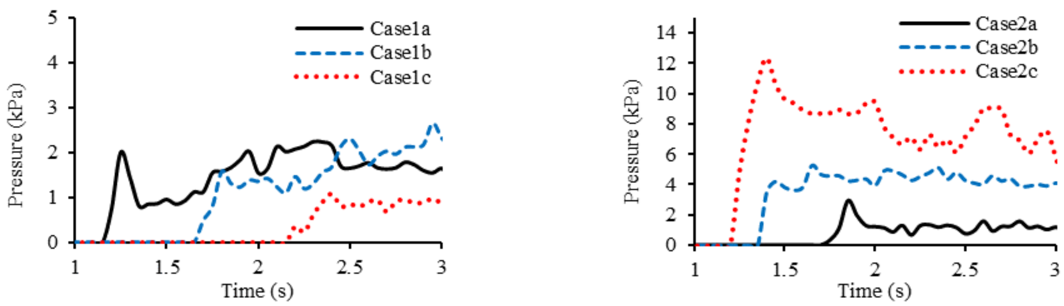


**Fig 11 impact pressures on the model for different cases [40]**

Fig 11 clearly shows that presence of openings on the face of the tsunami minimizes the tsunami impact pressure to 50% compared to other cases. Pringgana et al [41] simulated tsunami impact on rectangular timber structure in mesh-free based software DualSPHysics and from the output data (pressure-time histories); the dynamic response analysis is carried out in ABAQUS for 2.6 seconds on the model. Similar small scale modeling simulation is conducted in literature [42, 43].

## IV. CONCLUSION

This paper illustrates shortly about tsunami wave simulation and its interaction with the structure. The principle source and significance of the tsunami study are mentioned. The main need for the study is expressed by referring the impact happened on the 2006 Indian Ocean tsunami. Several of the past and ongoing research on tsunami wave simulation is discussed. The most common governing equations for propagation and simulation of the flow and method for predicting the tsunami wave parameters are reviewed. The following are summarized points from the review that contains a conclusion on tsunami wave modeling and its interaction with structures:

- The fundamental purpose behind the tsunami simulation is to perform a damage analysis for determining the condition of the structures and also to create a continuous monitoring system.

- The grid-based method software like MOST, FLOW 3D and TUNAMI CODE faces troubles to deal with the high-velocity impact due to large deformations and free surfaces.
- Adopting Finite difference method or finite volume method tools for complex boundary flow can cost high simulation time. For modeling they use two techniques that are ALE (Arbitrary Lagrangian Eulerian) method in which mesh displace with domain, this takes more time consuming in meshing process. The other one is immersed boundary method in which boundary inserted into mesh as this take less time compared to ALE
- Smoothed particle hydrodynamics (SPH) is one of the earliest mesh free methods that were initially developed for modeling astrophysical phenomena in 1977. Then later used for computational fluid dynamics. The mesh-free method does not need the boundary treatment that makes it faster.
- SPH uses Lagrangian simulation as it has conserved mass particles instead of control volume which makes the calculation easier.
- Particles will naturally organize themselves in a condition of less vitality. They behave as quasi-isotropic particle distribution which makes them rigid particles unless an external force is applied. Which makes SPH method adoptable for turbulence flow problems
- Over all, a case of minor displacement event where you required finding large scale variation. We can use FEM or FDM tools. For complex boundary sceneries like Tsunami simulation adopting SPH method is more accurate for its benefits of no meshing, no errors occur in interface diffusion and running time is shorter.

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