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Tsunami Generation Due to a Landslide or a Submarine Eruption

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Additional information is available at the end of the chapter

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Abstract

Tsunamis can be triggered by not only submarine earthquakes, but also by landslides, and submarine volcanic eruptions. First, several characteristics of tsunami generation due to a landslide, or a sector collapse, are studied, with the tsunamis simulated numerically, to represent their generation through an interaction between falling bodies, and seawater, in two vertical dimensions. The falling body is assumed to be a fluid, or a rigid body, which moves down a slope with a constant gradient. Second, the mechanism of tsunami generation caused by a submarine volcanic eruption, is discussed, focusing on a phreatomagmatic explosion, where after exposure to high temperature magma, seawater evaporates instantly, with an explosive increase in its volume. An index for submarine volcanic explosive force, concerning tsunami generation, has been developed, by assuming the relationship between a phreatomagmatic explosion, and the resultant initial tsunami waveform. A numerical simulation was also generated, with a specific value for this index, for the propagation of tsunamis due to a submarine volcanic eruption in Kagoshima Bay, where a submarine explosion, leading to tsunami generation, has been observed.

Keywords: tsunami, landslide, sector collapse, submarine volcanic eruption, phreatomagmatic explosion

1. Introduction

A mega earthquake off the Pacific coasts of the Tohoku region, Japan, caused tsunamis, with an inundation height over 20 m, in 2011 (e.g., [1]). These tsunamis were generated by a rise, or a subsidence, in the seabed. For example, if a part of the seabed rises, owing to an underground fault movement, then the seawater over the deformation lifts, resulting in an increase in the

seawater’s potential energy, then, in order to resolve this energy imbalance, waves, i.e., tsunamis are generated and travel in all available directions.

Tsunamis are, however, triggered not only by such a submarine earthquake, but also other phenomena as illustrated in **Figure 1**: landslide (e.g. [2]), sector collapse, glacier fall, submarine eruption, meteorite impact, and others. In the latter cases, where a tsunami source is not directly connected to an earthquake, the wave height of generated tsunamis could be underestimated or be beyond estimation, by the general prediction for tsunamis based on only seismic data, as in cases with a tsunamigenic earthquake [3]. In this chapter, we concentrate our discussion on tsunami generation caused by landslide, or submarine eruption.

Figure 1. An illustration for examples of tsunami sources.

Figure 2. A huge boulder, which was proposed to have been carried by tsunamis, on Ishigaki Island, Japan. This photo was taken in 2013, and provided by Dr. T. Iribe. He is the person in this photo and is 1.71 m tall.

First, we will study several characteristics of tsunamis induced by landslides, or sector collapses. It is proposed that the 1771 Meiwa Earthquake Tsunami occurred owing to a submarine landslide, for although the earthquake was not strong according to the Japanese archive, huge boulders on Ishigaki Island, Japan, were determined to have been carried by the tsunamis [4]. Shown in **Figure 2** is a boulder supposed to have been carried by an older tsunami, which hit the same island. In 1792, the tsunamis due to a landslide, or a sector collapse, at Mt. Mayu, Japan, traveled over the Ariake Sea, resulting in a runup on the opposite shore, which killed more than 15,000 people [5]. **Figure 3(a)**, and **3(b)**, show the eroded slope of Mt. Mayu, and the view of its opposite side, respectively; the distance between them is about 20 km. Such tsunamis are not necessarily generated only by sands or rocks: an excursion ship could be hit by tsunamis, due to a partial collapse of glacier near a coast on Svalbard Islands, Norway [6].

Figure 3. The eroded slope of Mt. Mayu in Nagasaki Prefecture (a), and the view of its opposite side in Kumamoto Prefecture (b). The distance between them is about 20 km. The author took these photos in 2012.

These tsunamis are generated through an interaction between water motion, and falling bodies, such that the tsunami generation process is rather complicated. An experimental study on tsunami generation due to a rigid object sliding down a slope, was reported by e.g. Wiegel [7], while tsunami generation due to particles moving down a slope, was studied by e.g. Walder et al. [8], and Shigihara et al. [9], using sands for falling bodies, Shigematsu and Kohno [10] glass beads, and Mohammed and Fritz [11] naturally rounded river gravel. In the laboratory experiments by Riu et al. [12], the falling bodies were glass balls with different diameters, glass beads, natural stones, acrylic rock-shape blocks, ice balls, etc.

Tsunami generation due to a landslide, has been also investigated numerically, using various methods (e.g., [13–21]). Wu and Liu [22] had simulated tsunami generation from a rigid wedge sliding down a slope, using a modified volume of fluid (VOF) method, as well as a moving boundary algorithm, and compared their three-dimensional numerical results, with the corresponding experimental data obtained by Raichlen and Synolakis [23]. In this chapter, we

will study several fundamental characteristics of tsunami generation caused by a landslide, or a sector collapse, on the basis of two-dimensional vertical results, obtained through a numerical simulation using a moving particle semi-implicit (MPS) model [24], where the falling body is assumed to be a fluid, or a rigid body, which moves down a slope with a constant gradient.

Second, we examine tsunamis caused by a submarine eruption. When a submarine explosive eruption occurs, volcanic products are blown out, as in case for an explosion from a subaerial active volcano. Conversely, if some volume of magma is released out of a chamber, owing to a submarine volcanic eruption, ground subsidence occurs, leading to a creation of a caldera. Although both volcanic products, and a caldera, should cause tsunamis as mentioned by Egorov [25], and Maeno et al. [26], respectively, we take up a different tsunami source, peculiar to a submarine eruption, for discussion in this chapter, i.e., a phreatomagmatic explosion [27]. In the process with a submarine phreatomagmatic explosion, seawater contacts high temperature magma in the seabed neighborhood, after which the seawater evaporates with an explosive increase in its volume, resulting in a water surface displacement that generates tsunamis. A new index for submarine volcanic explosion, concerning tsunami generation, is developed by assuming the relationship between a phreatomagmatic explosion, and the resultant initial tsunami waveform. We specifically assume the value of this index, to generate a numerical simulation for tsunamis caused by a submarine volcanic eruption in Kagoshima Bay, Japan, where a submarine explosion with tsunami generation has been observed [28].

2. Tsunamis due to a landslide or a sector collapse

2.1. Numerical model

Numerical computations have been performed that represent tsunami generation due to a body, which moves down a slope. In the present calculation, the numerical model, developed by Iribe and Nakaza [24], based on the MPS method designed by Koshizuka and Oka [29], is applied to consider the furious water motion. The water surface level is determined using the spatial gradient of particle-number density, to inhibit pressure disturbance at the water surface. No turbulence model is utilized for fluid motion, and both the elasticity, and the plasticity, of the falling bodies are neglected for simplicity.

2.2. Model validation for tsunami generation due to a falling fluid

2.2.1. Experimental setup

In order to validate the applicability of the numerical model, several numerical results for water surface displacements, are compared with the corresponding experimental data. **Figure 4** depicts a setup for laboratory experiments, with an acrylic basin, where h_{off} denotes the still water depth off of the slope, i.e., the offshore still water depth, and the water density is 1000 kg/m^3 . The vertical steel gate, installed on a slope with a constant gradient of β , can be pulled up quickly, and smoothly, by operating two levers as shown in **Figure 5**, resulting in the

release of objects, stacked on the onshore side of the gate. When the gate is closed, its bottom edge touches the shoreline in the still water condition. The height of the falling-body front face along the vertical gate, is denoted by h_s . In the experiments for model validation, the falling body is water, with the same density as that of the offshore water, i.e., 1000 kg/m^3 .

Figure 4. The hydraulic basin with a slope on which a gate is installed. The basin width is 2.0 m.

Figure 5. The gate, with two levers, set on the slope in the hydraulic basin as shown in **Figure 4**.

2.2.2. Calculation conditions

In the model computation, 17,000 particles are used to represent the above-described initial condition, where the particle grid is 0.005 m for the MPS model. In the present calculation, the numerical results for water surface displacements in the case where the particle grid is 0.005 m, are in good agreement with the case where the particle grid is 0.01 m. The water density on both the offshore side, and the onshore side, of the gate is 1000 kg/m^3 . The water on the onshore side of the gate, starts at the initial falling time, i.e., $t = 0.0 \text{ s}$.

2.2.3. Comparison between the numerical results and the corresponding experimental data for water surface displacements

Shown in **Figure 6** are the numerical results for the water surface displacements, at the location for wave gauge (WG) 2 shown in **Figure 4**, in comparison with the corresponding experimental data. The slope gradient β is 30° , and 45° , in the cases shown in **Figure 6(a)**, and **6(b)**, respectively. The offshore still water depth h_{off} and the initial falling-body height h_s , are 0.1 m, and 0.15 m, in both the cases. The distance between the location for WG 2, and that for the gate, is 1.16 m. The experimental value for each case, is a mean value among values obtained through five runs of the experiment, with the same initial conditions. **Figure 6** indicates that, both the wave height, and the wave phase, of the first wave obtained using the MPS model, are in harmony with the experimental results.

Figure 6. The water surface displacement at the location for WG 2 shown in **Figure 4**. The falling body is water, with the same density as that for the offshore water, i.e., 1000 kg/m^3 . The offshore still water depth h_{off} is 0.1 m and the initial falling-body height h_s is 0.15 m.

2.3. Tsunami generation due to a falling fluid

Two-dimensional vertical motion in a water basin shown in **Figure 7**, is simulated numerically, where the slope gradient β is 30° , and the distance between the slope foot, and the offshore

vertical wall, is 3.5 m. The offshore still water depth h_{off} is 0.1 m, or 0.2 m. Also in the following computation, the offshore water density is 1000 kg/m^3 , and the particle grid is 0.005 m.

Figure 7. The target domain for computation, where the offshore still water depth h_{off} is 0.1 m, or 0.2 m; the slope gradient β is 30° .

Sketched in **Figure 8** are the initial positions of a falling body in Cases 1–4, where the initial level of the falling-body bottom from the seabed, is 0.1, 0.2, 0.3, and 0.4 m, respectively, whether the offshore still water depth h_{off} is 0.1 or 0.2 m. The initial shape of the falling body is a right triangle, where the height of its vertical front face is 0.1 m. The body on the slope starts at the initial falling time, i.e., $t = 0.0 \text{ s}$. The falling body is assumed to be a fluid, or a rigid body. The fluid, and the rigid body, with the same density as that of the offshore water, i.e., 1000 kg/m^3 , we call, a “light fluid” and a “light rigid body”, respectively, while the fluid and the rigid body, with a density of 2600 kg/m^3 , we call, a “heavy fluid” and a “heavy rigid body”, respectively.

Figure 8. A sketch of the initial positions of a falling body in Cases 1–4.

Figure 9 shows the numerical results for the water surface displacements at Point P, in Cases 1–4, when the falling body is a light fluid, and the offshore still water depth h_{off} is 0.1 m. The distance between the location for Point P, and that for the offshore vertical wall, is 1.5 m, as shown in **Figure 7**. If the vertical distance between a particle, and its nearest particle below it, is larger than the particle grid, i.e., 0.005 m, then the upper particle is defined as a droplet, which is located over a particle at the water surface, around the horizontal location for the upper particle.

Figure 9. The water surface displacements at Point P ($x = 1.5$ m) for the different initial positions of a falling light fluid, with a specific gravity of 1.0. The offshore still water depth is 0.1 m.

Conversely, in **Figure 10** are the numerical results for the water surface displacements at Point P, in Cases 1–4, where the falling body is a heavy fluid, and the offshore still water depth h_{off} is 0.1 m. The tsunami height is defined as the maximum value in water surface displacement at each location. In each of our cases, the tsunami height from the heavy fluid is twice as large as that from the light fluid. Thus, if both the initial position, and the volume, of a falling body are the same, the tsunami height increases as the density, i.e., the initial potential energy, of the falling body is increased.

Figure 10. The water surface displacements at Point P ($x = 1.5$ m) for the different initial positions of a falling heavy fluid with a specific gravity of 2.6. The offshore still water depth is 0.1 m.

However, it is in Case 4, where the falling-body initial potential energy is largest, that the tsunami height at Point P, is the minimum value, whether the falling body is a light fluid, or a heavy fluid, as shown in **Figure 9**, or **10**, respectively. Conversely, the tsunami height at Point P, is the maximum value in Case 2, when the falling body is a light fluid, as shown in **Figure 9**, while in Case 1, when the falling body is a heavy fluid, as shown in **Figure 10**. How is this possible?

Figure 11. The simulation result for the particle motion in Case 3, where the falling body is a heavy fluid with a specific gravity of 2.6; the offshore still water depth is 0.1 m. The red points denote the falling-fluid particles, while the blue ones the offshore-water particles.

The particle motion numerical result for Case 3, is shown in **Figure 11**, where the falling body is the heavy fluid, and the offshore still water depth h_{off} is 0.1 m. The red points denote the heavy-fluid particles, while the blue ones the offshore-water particles. **Figure 11** indicates that when the initial position of a falling body is high, the falling-body group while moving down a slope, transforms and flattens, resulting in a flattened body rushing into the water, such that

the volumetric flow rate of the falling body decreases, and pushes the water weakly. This is the reason why the tsunami height at Point P, is lower in Case 4, where the falling-body initial potential energy is large, when the falling body is the heavy fluid, and also for the light fluid.

2.4. Tsunami generation due to a falling rigid body

Shown in **Figure 12** are the numerical results for the water surface displacements at Point P, in Cases 1–4, when the falling body is a light rigid body, and the offshore still water depth h_{off} is 0.1 m. The tsunami height at Point P, shows its maximum value in Case 4, where the falling-body initial potential energy is largest. This is not true when the falling body is a light fluid, or a heavy fluid, as described above.

Figure 12. The water surface displacements at Point P ($x = 1.5$ m) for the different initial positions of a falling light rigid body with a specific gravity of 1.0. The offshore still water depth is 0.1 m.

On the other hand, shown in **Figure 13** are the numerical results for the water surface displacements at Point P, in Cases 1–4, when the falling body is a heavy rigid body, and the offshore still water depth h_{off} is 0.1 m. The tsunami height at Point P, is lowest in Case 4, where the falling-body initial potential energy is largest. This is another challenge!

The particle motion numerical result for the Case 3, is shown in **Figure 14**, where the falling body is the heavy rigid body, and the offshore still water depth h_{off} is 0.1 m. The red points denote the rigid-body particles, while the blue ones the offshore-water particles. The front face of the falling rigid body pushes the water, generating a large wave height plunging-type wave, after which a turbulent tsunami propagates, with a bore, generated at its front face. Thus in both the generation, and the propagation, of this tsunami, the energy loss is larger, owing to the generation of splashes, the turbulence, and the bore. This is the reason why the tsunami height at Point P, is lower in Case 4, in which the falling-body initial potential energy is large, when the falling body is a heavy rigid body. It should also be noted that the water surface profile for this tsunami, is forwardly inclined, such that the peak in the water surface

displacement at Point P, appears earlier in **Figure 13**, in the case of the falling heavy rigid body, than in **Figure 12**, concerning the falling light rigid body.

Figure 13. The water surface displacements at Point P ($x = 1.5$ m) for the different initial positions of a falling heavy rigid body with a specific gravity of 2.6. The offshore still water depth is 0.1 m.

Figure 14. The simulation result for the particle motion in Case 3, where the falling body is a heavy rigid body with a specific gravity of 2.6; the offshore still water depth is 0.1 m. The red points denote the rigid-body particles, while the blue ones the offshore-water particles.

2.5. Effect of the offshore still water depth on tsunami generation due to a falling body

The numerical results for the tsunami-height distribution are shown in **Figure 15(a)**, and **15(b)**, where the offshore still water depth h_{off} is 0.1 m, and 0.2 m, respectively, when the falling body is a light fluid. As the offshore still water depth decreases, the tsunami height near the gate, i.e., the shoreline increases, as shown in **Figure 15(a)**, for the falling body does not move seabed seawater. With less volumetric flow rate wasted, the falling body contributes to tsunami-height growth, while it progresses near the seabed. Note, however, that as the offshore still water depth decreases, there is decreased rate in the tsunami height in tsunami propagation, which increases especially for $2.0 \text{ m} \leq x \leq 2.5 \text{ m}$, as shown in **Figure 15(a)**.

Figure 15. The distributions of the tsunami height η_{max} for the different initial positions of a falling light fluid with a specific gravity of 1.0.

2.6. Tsunami generation due to a submarine landslide

Two-dimensional vertical motion in a water basin, as illustrated in **Figure 16**, is numerically simulated to examine tsunami generation due to a submarine landslide. The slope gradient β is 45° , the offshore still water depth h_{off} is 0.305 m, and the offshore water density is 1000 kg/m^3 . The particle grid is 0.005 m, the same as in the present computation. The initial level of a falling-body bottom from the offshore still water level, is -0.205 , -0.105 , 0.0 , 0.1 , and 0.2 m in Cases U1, U2, O1, O2, and O3, respectively, such that the falling body is under sea level even at the initial falling time in both Case U1, and Case U2, creating a submarine landslide, whereas the falling body is above sea level at the initial falling time in Cases O1, O2, and O3, with a subaerial landslide. The falling body is a heavy fluid, with a density of 2600 kg/m^3 , and the initial shape of the falling body is an isosceles right triangle, where the initial height of its vertical front face is 0.105 m, in all cases.

Figure 16. A sketch of the initial positions of a falling body, in Cases U1, and U2, with a submarine landslide, and Cases O1, O2, and O3, with a subaerial landslide. The offshore still water depth h_{off} is 0.305 m, and the slope gradient β is 45° .

Shown in **Figure 17** are the numerical results for the water surface displacements at Point Q, where the distance between the location for Point Q, and that for the shoreline in still water, is 0.71 m, as shown in **Figure 16**. **Figure 17** indicates that the tsunami height is lower when a falling body is initially submerged, as in both Case U1, and Case U2, the reason for which is the third question.

Figure 17. A relative value for the water surface displacement η at Point Q, indicated in **Figure 16**, where the falling body is a heavy fluid, with a specific gravity of 2.6. The offshore still water depth is 0.305 m, and g denotes gravitational acceleration, i.e., 9.8 m/s^2 .

In the cases with a submarine landslide, a falling body is surrounded by seawater, from the time falling starts. In both Case U1, and Case U2, the density ratio between the falling heavy fluid, and the offshore water, is $2600 \text{ kg/m}^3 / 1000 \text{ kg/m}^3 = 2.6$, which is much smaller than the density ratio between the falling heavy fluid, and the air, i.e., about $2600 \text{ kg/m}^3 / 1.0 \text{ kg/m}^3 = 2600$. Thus the initial relative potential energy of a submerged falling body is lower, resulting

in a slower motion, with a smaller volumetric flow rate, in the falling body. This is the reason why the tsunami height is lower in the cases where the submarine landslide occurs than in the cases where the landslide occurs above the offshore water level.

3. Tsunamis due to a submarine eruption with a phreatomagmatic explosion

3.1. Submarine explosive index concerning tsunami generation

3.1.1. Cubic expansion of water through heat-induced evaporation

In this section, the process of tsunami generation due to a submarine volcanic eruption, is discussed considering a phreatomagmatic explosion, where the seawater touches high temperature magma in the seabed neighborhood, after which the water evaporates instantaneously with explosive increase in its volume, lifting the water over the water vapor bubble. We will develop a model for tsunami generation due to a submarine eruption with phreatomagmatic explosion, and introduce a submarine explosive index concerning the relationship between the submarine phreatomagmatic explosion, and the resultant initial tsunami height.

Remember the following characteristics of water: the mass, and the density, of 1.0 mol of liquid water, are around 18.0 g, and 1.0 g/cm³, respectively, such that 1.0 mol of liquid water, occupies a volume of 18.0 ml. Conversely, 1.0 mol of vapor, assumed to be an ideal gas, occupies a volume of 22,700 ml at the standard temperature and pressure (STP), where the temperature, and the pressure, are 0.0°C, and 1.0 bar, i.e., 1.0×10^5 Pa, respectively. Thus, when liquid water transforms to vapor at STP, the volume of the vapor becomes $22,700/18.0 \approx 1.261 \times 10^3$ times as much as that of the liquid water.

If the pressure is p (Pa), then the volume of a gas at temperature τ (°C), V , is evaluated by $V = V_0 (10^5/p) (1 + \tau/273)$ according to Boyle-Charles' law, where V_0 denotes the volume of the gas at 0.0°C.

Consequently, when liquid water with a volume of V_w at STP, transforms to vapor with a volume of V at τ (°C), and p (Pa), the volume expansion ratio between liquid water, and vapor, is

$$\alpha = V / V_w = 1.261 \times 10^3 (1 + \tau / 273) / p. \quad (1)$$

3.1.2. Volume expansion ratio of water through a phreatomagmatic explosion

Immediately after magma touches water, the following equation explains their interface [30]:

$$(\tau_m - \tau_i) / (\tau_i - \tau_w) = (\rho_w c_{pw} k_w / \rho_m c_{pm} k_m)^{1/2}, \quad (2)$$

where τ_i is the temperature at the interface between magma and water; ρ , c_p , and k are density, isopiestic specific heat, and heat transfer coefficient, respectively; the subscripts m, and w, denote the variables of magma, and water, respectively. The general values of these parameters are as follows [26]:

[The general values of the parameters for magma]

Density $\rho_m = 2400 \text{ kg/m}^3$

Temperature $\tau_m = 973 \text{ K}$

Isopiestic specific heat $c_{pm} = 1.2 \times 10^3 \text{ J/kgK}$

Heat transfer coefficient $k_m = 1.2 \text{ W/mK}$

[The general values of the parameters for water]

Density $\rho_w = 1000 \text{ kg/m}^3$

Temperature $\tau_w = 273 \text{ K}$

Isopiestic specific heat $c_{pw} = 4.2 \times 10^3 \text{ J/kgK}$

Heat transfer coefficient $k_w = 0.61 \text{ W/mK}$

We substitute these general values into Eq. (2), and obtain the temperature at the interface, τ_i , as

$$\tau_i = 649.0 \text{ K} = 376.0^\circ\text{C}. \quad (3)$$

This value is larger than the spontaneous nuclear generation temperature of water, which is approximately 583 K at 1.0 atm. Note that the temperature increases by around 10.0 K as the pressure is increased by 2.0 MPa [26].

3.1.3. Relationship between the still water depth and the volume expansion ratio for seawater near the seabed

The water pressure at a submarine crater in still water, p , is defined as

$$p = \rho_w gh = 9800 h (\text{Pa}) \quad (\text{unit length in meter}), \quad (4)$$

where h denotes the still water depth at the crater location, and the gravitational acceleration g equals 9.8 m/s^2 . Substituting the value of τ_i shown in Eq. (3), and the value of p given by Eq. (4), into τ , and p , in Eq. (1), respectively, leads to

$$\alpha = V / V_w = 30,600 / h (\text{unit length in meter}), \quad (5)$$

where the water surface displacement is assumed to be much smaller than the still water depth. Eq. (5) determines the relationship between the volume expansion ratio of water over the crater, and the still water depth at the crater location; for instance, $\alpha \approx 10.2$ when h is 3000 m, while $\alpha \approx 6.1 \times 10^2$ when h is 50 m.

3.1.4. Relationship between the submarine volcanic explosion and the initial tsunami profile

Assume that a circular crater (indicated with “A” in **Figure 18**) with a radius of r , appears at the horizontal seabed, with the seawater (B) over the crater then being vaporized to expand vertically in an instant (C), such that the initial tsunami profile becomes a cylinder (D) with a height of η_0 . E in **Figure 18** indicates the still water surface, where the still water depth is h . Although in case with a seabed rise, the initial tsunami height decreases, as the seabed-rise speed decreases, and also as the still water depth increases, as described by Kakinuma and Akiyama [31], these effects on tsunami generation are neglected for simplicity. Thus both the shape, and the size, of the cylinder D, are the same as that of the cylinder C, such that the volume of these cylinders, V , equals $\pi r^2 \eta_0$, where η_0 is the initial tsunami height.

Figure 18. A schematic for tsunami generation due to a submarine phreatomagmatic explosion. “A” denotes a crater with a radius of r , at the seabed; “B” the original water with a volume of V_w , before vapor transformation; “C” the generated vapor with a volume of V ; “D” the initial tsunami profile with a radius of r , and a height of η_0 ; “E” the still water surface, where the still water depth is h .

By substituting $V = \pi r^2 \eta_0$ into Eq. (5), we obtain:

$$V_w = \pi r^2 \eta_0 h / 30,600 \approx 1.0 \times 10^{-4} r^2 \eta_0 h (\text{unit length in meter}), \quad (6)$$

where V_w is the original volume of the seawater (B), before vapor transformation. Eq. (6) indicates that the cylindrical initial tsunami profile with a radius of r , and a height of η_0 , is generated when a submarine eruption, transforms water with a volume of V_w at the seabed neighborhood, to vapor, where the still water depth is h . If we know all the values of V_w , r , and h , then we can evaluate the value of the initial tsunami height η_0 . Therefore, the original volume of seawater, which transforms to vapor through a phreatomagmatic explosion caused by it

touching high temperature magma, i.e., V_w , is a submarine explosive index concerning tsunami generation.

On the other hand, if we assume that the seawater over a crater is vaporized, becoming a half sphere with a radius of R , where the sphere center coincides with the crater center at the seabed, then the sphere volume V is $2\pi R^3/3$. If we assume also that the initial tsunami profile is a half sphere, with a radius of R , then we obtain

$$V_w \approx 6.8 \times 10^{-5} R^3 h \text{ (unit length in meter)}, \quad (7)$$

where V_w is the original volume of the seawater, before vapor transformation. Eq. (7) can be rewritten to

$$R \approx 24 (V_w / h)^{1/3} \text{ (unit length in meter)}. \quad (8)$$

According to an old document, the initial tsunami height η_0 was around 9 m, owing to a submarine volcanic eruption in Kagoshima Bay, Japan, on September 9, 1780 [27], where the still water depth at the eruption location is about 200 m. In this case, we substitute both $R = 9$ m, and $h = 200$ m, into Eq. (7), resulting in $V_w = 9.9 \text{ m}^3$. It should be noted, however, that future work is required to know accurately both the profile, and the size, of the initial tsunami, for instance, by performing laboratory experiments using both high temperature material, and water.

3.2. Numerical simulation for propagation of tsunamis due to a submarine phreatomagmatic explosion in a bay

3.2.1. Examples of values of the submarine explosive index concerning tsunami generation

The relationship between the crater radius r , and the eruption amount V_e is expressed by Sato and Taniguchi [32] as

$$r = 0.97 V_e^{0.36} \text{ (unit length in meter)}. \quad (9)$$

For example, the volcanic explosive index (VEI) introduced by Newhall and Self [33], is assumed to equal three, larger than two for a standard explosion, then the eruption amount V_e is between $1.0 \times 10^7 \text{ m}^3$ and $1.0 \times 10^8 \text{ m}^3$; hence the crater radius r becomes approximately between 321 m and 736 m, based on Eq. (9). Thus we assume that the crater radius r is 700 m, in the present computation. Conversely, owing to the submarine explosion in Kagoshima Bay on September 9, 1780, the sea level rose by around 9 m over the explosion, as described above, such that we assume that the initial tsunami height η_0 is 9.0 m. If the initial tsunami profile becomes a cylinder, as shown in **Figure 18**, then the value of submarine explosive index

concerning tsunami generation, V_{wr} is evaluated by Eq. (6) as 2.3×10^4 (unit length in meter) when the still water depth at the eruption location, h , is 50 m, while 4.5×10^4 (unit length in meter) when h is 100 m.

3.2.2. Numerical model and calculation conditions

Numerical simulation for tsunamis due to a submarine volcanic eruption in Kagoshima Bay, is generated using the shallow water version of the nonlinear wave model [34], where the computational program developed by Nakayama and Kakinuma [35] to simulate internal wave propagation, is partially rewritten to solve the set of finite difference equations for nonlinear surface waves. **Figure 19** shows the seabed level in the northern bay, where the still water level is described by $z = 0.0$ m. The shorelines are assumed to be vertical walls with perfect wave reflection, while the Sommerfeld radiation condition is applied at the open boundaries inside the sea area. The initial tsunami height η_0 is assumed to be 9.0 m, as described above.

Figure 19. The seabed level in the northern area of Kagoshima Bay, Japan.

3.2.3. Water surface displacements

Water surface displacements are obtained through numerical calculation for the trial cases where the craters are located at Point ① and Point ③, the locations of which are shown in **Figure 20**, as well as for the above-described actual case on September 9, 1780, where the crater is located at Point ②.

There are many submarine fumaroles in Kagoshima Bay, and an active volcano exists in Sakurajima, as shown in **Figure 21**. Sakurajima, where “sakura” means cherry, while “jima”, or “shima”, means island, in Japanese, was an isolated island prior to its violent eruption in

1914, when Sakurajima was connected to the Ohsumi Peninsula by the eruption with a large amount of ejecta. As shown in **Figure 20**, Point B is located in the West Sakurajima Channel, on the western side of which lies the most urban area in the prefecture, Kagoshima City.

Figure 20. The point locations in Kagoshima Bay, Japan. Sakurajima, which was an isolated island, has an active volcano. Point B is located in the West Sakurajima Channel.

Figure 21. The active volcano with an eruption on Sakurajima, Japan. The author took this photo in 2015.

Figure 22. The water surface displacements at Points A and B for different crater locations, i.e., Points ①, ②, and ③. The point locations are indicated in **Figure 20**.

Shown in **Figure 22(a)**, and **22(b)**, are the numerical results for the water surface displacements at Point A, and Point B, indicated in **Figure 20**, respectively. The tsunami height for not only the first wave, but also the several following waves, is larger than 1.0 m at Point A, where it takes a longer time for the oscillation to attenuate because of multiple reflections of tsunamis at the bay head.

Although Point ③ is more distant from Point B than Point ②, the maximum tsunami height at Point B, near the highest population area, is larger in the case where the crater is located at Point ③ than that in the case where the crater appears at Point ②; for in the former case, the wave energy is large for the wave component approaching Sakurajima in a direction oblique, or parallel, to the seashore of Sakurajima, resulting in a tsunami traveling along the shoreline of Sakurajima toward the west.

3.2.4. Distribution of the maximum water level

The numerical results for the distributions of the maximum water level $\eta_{\max}$ for $0.0 \leq t \leq 2.0 \times 10^3$ s, are shown in **Figure 23(a)–23(d)**, where the crater locations are depicted with white circles off the north of Sakurajima, off Hayato, off Ryugamizu, and off Kurokami-cho, respectively. The still water depth at the crater, h , is assumed to be 1.0×10^2 m in all the cases, such that the value of the submarine explosive index concerning tsunami generation, V_w , is about 4.5×10^4

Figure 23. The distributions of the maximum water level for $0.0 \leq t \leq 2.0 \times 10^3$ s, for different crater locations. The crater locations depicted with white circles, are as follows: (a) off the north of Sakurajima, (b) off Hayato, (c) off Ryugamizu, and (d) off Kurokami-cho.

(unit length in meter). The tsunamis propagation starts at $t = 0.0$ s. In every case, the maximum water level $\eta_{\max}$ decreases at $(x, y) \approx (20.0 \text{ km}, 14.0 \text{ km})$, for the still water depth is deeper, i.e., about 200 m at the location.

Figure 23 indicates that there are three areas where $\eta_{\max}$ increases, irrespective of the crater location, i.e., near the northern shore of Sakurajima, the bay head off Hayato, and near the western shore of the Ohsumi Peninsula, for the still water depth suddenly decreases toward the land near these three areas.

As shown in **Figure 23(a)**, the tsunamis generated off the north of Sakurajima, travel toward the north, after reflecting at the northern shore of Sakurajima; while as shown in **Figure 23(b)**, the tsunamis generated off Hayato, propagate toward the south, after the reflection at the bay-head shore. In the cases shown in **Figure 23(c)**, and **23(d)**, however, the tsunamis generated off Ryugamizu, and Kurokami-cho, propagate toward the east, and west, respectively, where the maximum wave height of these components is larger.

4. Conclusions

First, several characteristics of tsunami generation due to a landslide, or a sector collapse, were studied, with the tsunamis simulated using the MPS model, that represents their generation through an interaction between the falling bodies, and the seawater, in two vertical dimensions. The falling body was assumed to be a fluid, or a rigid body, which moved down a slope with a constant gradient.

Second, the mechanism of tsunami generation due to a submarine volcanic eruption, was discussed, focusing on a phreatomagmatic explosion. A submarine explosive index concerning tsunami generation, was developed, by assuming the relationship between a phreatomagmatic explosion, and the resultant initial tsunami waveform. A numerical simulation was also generated, for the propagation of tsunamis due to a submarine volcanic eruption, with the specific value for this index, agreeing with the observed data from the submarine explosion leading to a tsunami generated in Kagoshima Bay.

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