Impact assessment of volcanic tsunamis in coastal regions for disaster risk reduction

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Abstract. Volcanic tsunamis are complex natural hazards triggered by a series of cascading effects, beginning with volcanic activity and culminating in massive ocean waves that can have catastrophic impacts on coastal communities. This paper presents an impact assessment of volcanic tsunamis in coastal regions aimed at enhancing disaster risk reduction efforts. The study begins with an exploration of volcanic tsunamis globally, focusing on the cascading effects and the impacts on coastal. Historical cases of volcanic tsunamis are analysed to understand their underlying mechanisms. The assessment draws on a detailed analysis of variables such as cascading effects, tsunami heights, wave travel distances, and fatalities. Monte Carlo simulations was used to quantify the risks of future tsunamis, emphasizing the variability in wave heights across different coastal regions. These insights help to inform the development of more effective early warning systems and disaster risk reduction strategies, particularly in vulnerable coastal areas. By understanding the unique risks posed by volcanic tsunamis, this research contributes to building stronger, more resilient communities prepared to face these rare but catastrophic events.

1 Introduction

Volcanic tsunamis represent a rare but devastating natural hazard, triggered by volcanic activity that can initiate a series of cascading events, culminating in massive ocean waves. These tsunamis have caused significant destruction in coastal regions worldwide, with impacts ranging from infrastructure damage to considerable loss of life. The cascading nature of volcanic collapses beginning with volcanic eruptions, followed by flank collapse, and ending in ocean displacement creates complex scenarios for disaster management and prediction [1]. As coastal populations continue to grow, there is an urgent need to enhance our understanding of the risks associated with volcanic tsunamis to develop more effective disaster reduction strategies [2].

Historically, volcanic tsunamis have led to some of the deadliest natural disasters, including the infamous Krakatoa eruption in 1883, which generated waves over 30 meters high and caused over 36,000 fatalities [3]. Similar events, though smaller in scale, have occurred across the Pacific and Mediterranean regions, highlighting the need for more detailed risk assessments of these rare but high-impact hazards [4]. These tsunamis often follow volcanic collapses or pyroclastic flows entering the ocean, creating waves that

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propagate over long distances, affecting coastal communities far from the eruption site [5]. However, the unpredictability and the multifaceted nature of these tsunamis make their risks difficult to assess using traditional seismic-based early warning systems [6].

This study aims to fill this gap by conducting an impact assessment of volcanic tsunamis, focusing on the cascading nature of volcanic activity and the variability of their impacts, including wave height, travel distances, and fatalities. Moreover, by utilizing Monte Carlo simulations, the study aims to quantify the potential risks posed by future volcanic tsunamis, focusing on one of important variables such as wave height. The insights gained from this research contribute to the part of early warning systems development and disaster risk reduction efforts, particularly for volcanic tsunamis. Through historical analysis and simulation-based modelling, this study provides a clearer understanding of the unique risks posed by volcanic tsunamis and informs the necessary steps to build more coastal resilient [7].

2 Methodology

This study employs a risk assessment workflow by combining historical case analysis and Monte Carlo simulations to evaluate the potential impact of future volcanic tsunamis. The methodology is designed to capture the variables influencing tsunami risk and use one of volcanic tsunamis case study as an example impact assessment application.

2.1 Historical and tide gauges data collection

The primary dataset for this research was compiled from multiple sources, including historical records and academic studies such as the Smithsonian Institution's Global Volcanism Program (GVP), including publications from Oregon State University. Historical data were used from selected volcanic tsunami events that had well-documented and recorded, such as tsunami height, travel time, and fatalities. These events were specifically selected for their comprehensive documentation to facilitate data analysis. These records span from the earliest known volcanic tsunami event in 1640 to the recent 2018 Anak Krakatau tsunami. In addition, this study used wave height data recorded by tide gauges at Kota Agung (KA) and Marina Jambu (MJ) (Figure 1) during the 2018 Anak Krakatau event as case study for wave height simulation. This data sourced from the Indonesian Geospatial Agency (BIG) and especially valuable, as they offer a critical opportunity to study and better understand volcanic tsunamis. Moreover, this data will also serve as validating simulations.

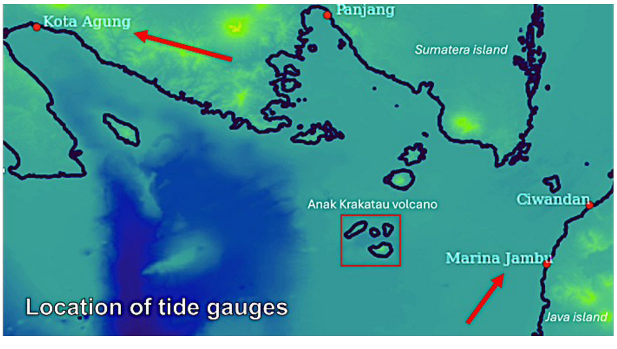

Fig. 1. The location of tide gauges (KA and MJ). Red rectangle is Anak Krakatau volcano

2.2 Simulation model and impact assessment

Monte Carlo simulation was employed to assess the potential risks associated with future volcanic tsunamis, with a particular focus on wave height variability. Monte Carlo simulations are a probabilistic technique used to model the uncertainty and variability in complex systems by generating a large number of random samples. This method is particularly suitable for tsunami risk assessment due to the inherent unpredictability of volcanic collapses, which lead to highly variable tsunami wave heights. The objective of the Monte Carlo simulation is to provide a range of possible outcomes for tsunami wave heights over time, reflecting the uncertainty in future events. By running multiple simulations, we can better understand the probability distribution of wave heights and identify the likelihood of extreme events that could pose a significant threat to coastal. The simulation utilizes wave height data from two tide gauges (KA and MJ) located near the Krakatau region. These datasets, which include historical 120 mins recorded time series data of tsunami wave heights, provide the basis for modelling future wave heights. The Monte Carlo simulation works as shown in Equation 1-2.

Input parameter. The time series data for wave heights from the tide gauges were extracted and analysed. The mean (μ) and standard deviation (σ) of wave heights for each tide gauge were calculated as follows:

$$\mu = \frac{\sum_{i=1}^{n} h_i}{n}\ ,\ \sigma = \sqrt{\frac{\sum_{i=1}^{n}(h_i - \mu)^2}{n}} \tag{1}$$

where h_i represents the wave height at time i, and n is the total number of data points.

Monte Carlo process. For each simulation, random wave height changes are generated using a normal distribution defined by the calculated mean (μ) and standard deviation (σ). The wave height at each time step is updated based on these random variations, and the cumulative sum of these changes is added to the initial wave height. This process is repeated for each of the $n_{simulations}$, which in this case is 100 simulations per tide gauge. The formula for generating new wave heights at each time step is:

$$h_{new} = h_{prev} + random\_change \tag{2}$$

Where random_change ~ $N(\mu, \sigma)$.

The wave height distribution is the output of the simulation that provides a distribution of possible wave heights for each tide gauge. The variability in wave heights across different simulations are summarized in statistical values and highlights the range of potential risks posed by future volcanic tsunamis.

3 Result and Discussion

This section discusses the cascading effects and impact analysis of volcanic tsunami events. Several significant events were selected to represent the cascading processes and their associated impacts. For the impact assessment, Monte Carlo simulations were employed, and the statistical summary is presented as a component of the impact analysis.

3.1 Cascading effects and impact analysis

Table 1 provides an analysis of the cascading effects and impacts from selected volcanic tsunami events, revealing correlations between the nature of volcanic collapses and the resulting tsunami characteristics.

Table 1. Analysis of cascading effects and impacts from selected volcanic tsunamis events

Event	Cascading effects	Tsunami wave height	Travel distance	Estimated death toll
Komagatake, Japan 1640	Lateral collapse	8 meters	50 km	700 people
Oshima, Japan 1741	Lateral collapse	14 meters	1200 km	2000 people
Unzen, Japan 1792	Dome collapse, debris avalanche	10-55 meters	50 km	15000 people
Krakatau, Ina 1883	Large explosive eruption, pyroclastic flow	40 meters	3000 km	33000 people
Ritter, Papua 1888	Lateral collapse, removing most island	14 meters	500 km	100-200 people
Llliwerung, Ina 1979	Debris avalanche	9 meters	100 km	500 people
Stromboli, Italy 2002	Subaerial and submarine landslide	8 meters	170 km	0
Anak Krakatau 2018	Flank instability, subaerial landslide	13 meters	50 km	437 people

Lateral collapses, such as those seen in Komagatake (1640) and Oshima (1741), typically generate moderate wave heights of 8-14 meters, with tsunamis capable of traveling long distances, up to 1200 km in some cases. This occurs due to the gradual but large-scale displacement of material into the ocean. Conversely, dome collapses and debris avalanches, like Unzen (1792), result in more variable wave heights, ranging from 10 to 55 meters, depending on the volume of material displaced. These events tend to have a more localized impact, with travel distances of around 50-100 km. Large explosive eruptions, as exemplified by Krakatoa (1883), produce the highest waves—up to 40 meters—and tsunamis that can travel the greatest distances, reaching up to 3000 km. These events are also associated with the highest fatalities, due to the combination of extreme wave heights and their ability to affect distant coastal populations. Similarly, the flank instability and subaerial landslide event at Anak Krakatoa (2018) generated a wave height of 13 meters and resulted in 437 deaths, highlighting the risk even moderate events pose to modern coastal populations. In terms of the death toll, events involving large explosive eruptions and dome collapses with debris avalanches show the highest fatalities, with Krakatoa (1883) and Unzen (1792) responsible for 33,000 and 15,000 deaths, respectively. Lateral collapses, while still deadly, result in fewer fatalities, generally in the range of 700 to 2000 people, depending on proximity to populated areas.

The type of cascading effect significantly influences the severity of the resulting tsunami. Large explosive eruptions and dome collapses tend to produce the most devastating impacts, with higher wave heights, longer travel distances, and greater death tolls, while lateral collapses, although dangerous, generally result in less extensive impacts.

3.2 Simulation and impact assessment of tsunami wave height

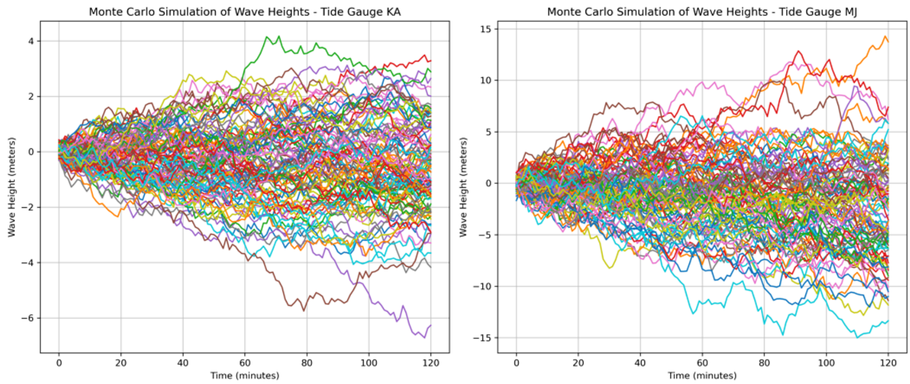

Fig.2. Monte Carlo simulation of wave heights at two tide gauges (KA and MJ)

This figure 2 represents the results of Monte Carlo simulations modeling the wave heights over 120 mins at two different tide gauges: KA and MJ. The simulations capture the variability and uncertainty inherent in volcanic tsunami wave behavior following a collapse event. At the KA tide gauge (left), the majority of wave heights fluctuate within a range of ±3 meters, with a few scenarios producing waves slightly above 4 meters. The tightly clustered wave patterns reflect relatively lower variability in this region, suggesting that the tsunami risk here is less extreme, though still significant. In contrast, the simulations for the MJ tide gauge (right) show a much broader spread of wave heights, with some scenarios resulting in waves as high as 15 meters, while others dip to -10 meters. This suggests that the MJ region is more susceptible to extreme wave events, reflecting the potential cascading effects that amplify tsunami impacts in this area.

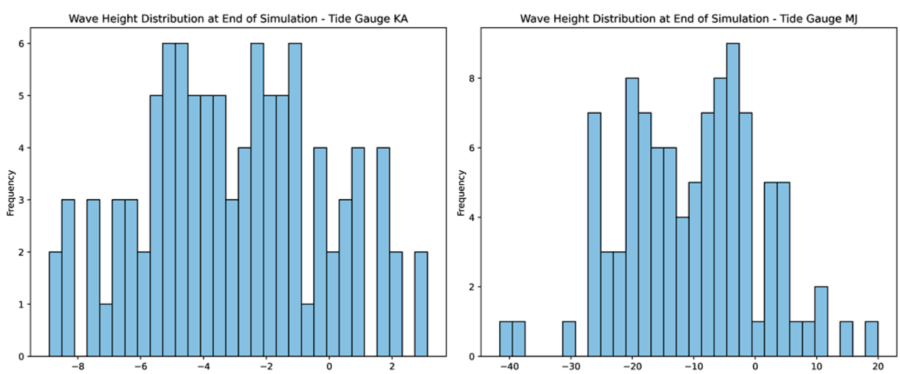

Fig. 3. Wave height distribution for tide gauges KA and MJ

The histograms in the figure 3 show the distribution of wave heights at the end of the 120-minute simulation for both tide gauges KA (left) and MJ (right). For the KA tide gauge, the wave heights are more concentrated around -4 to -2 meters, with the majority of simulated scenarios resulting in relatively moderate wave heights. This distribution reinforces the observation that the KA region experiences more predictable and less extreme wave behavior. On the other hand, the MJ tide gauge shows a much wider distribution of final wave heights, with peaks in the distribution occurring between -20 meters and -10 meters. The right tail of the distribution extends into positive wave heights exceeding 20 meters, indicating the potential for extreme tsunami events in this region. This wide distribution at MJ further highlights the elevated risk posed by cascading hazards and the need for targeted early warning systems in such vulnerable areas.

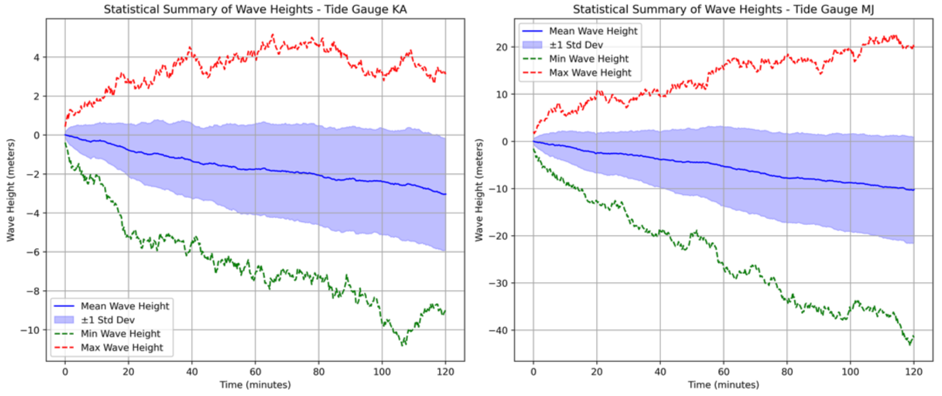

Fig. 4. Statistical summary of wave heights over time at tide gauges KA and MJ

Figure 4 provides a statistical summary of the simulated wave heights over time, showing the mean wave height (blue line), the standard deviation (shaded region), and the maximum and minimum wave heights (dashed lines) for both the KA (left) and MJ (right) tide gauges. At KA, the mean wave height remains relatively stable, fluctuating around 0 meters, with a small downward trend. The standard deviation, represented by the shaded blue region, indicates that most wave heights fall within ±2 meters of the mean, and the overall variability in the wave heights is low. The maximum wave height remains under 5 meters, while the minimum stays above -8 meters.

In contrast, the MJ tide gauge shows a much higher degree of variability. The mean wave height decreases steadily over time, reflecting the potential for large negative wave heights as the collapse event progresses. The standard deviation is also significantly larger than at KA, indicating that the wave heights in MJ are more spread out and unpredictable. The maximum wave height reaches over 20 meters, and the minimum wave height dips as low as -40 meters, highlighting the extreme variability and the potential for dangerous wave conditions in this region. This statistical summary underscores the importance of accounting for cascading effects in tsunami modelling, as they can lead to extreme and highly variable outcomes.

Table 2. Impact assessment of selected volcanic tsunamis

Statistical summary		
	Tide gauge KA	**Tide gauge MJ**
Mean Wave Height	-3.03 meters	-10.22 meters
Std Dev of Wave Heigh	2.85 meters	11.24 meters
Min Wave Height	-8.90 meters	-41.56 meters
Max Wave Height	3.13 meters	19.97 meters

Table 2 shows clear differences between wave height characteristics at the KA and MJ tide gauges. At KA, the mean wave height is -3.03 meters, with a relatively low standard deviation of 2.85 meters, indicating more consistent wave heights. The minimum wave height is -8.90 meters, and the maximum is 3.13 meters, reflecting moderate wave activity with lower risk of extreme events. On the other hand, MJ exhibits much greater variability, with a mean wave height of -10.22 meters and a larger standard deviation of 11.24 meters. The wave heights at MJ range from -41.56 meters to 19.97 meters, suggesting a higher likelihood of extreme events. These values highlight MJ's vulnerability to more severe volcanic tsunamis.

4 Conclusion

The severity of a volcanic tsunami is significantly influenced by the type of cascading effect that triggers it. Large explosive eruptions and dome collapses tend to produce the most devastating impacts, characterized by higher wave heights, longer travel distances, and greater death tolls. In contrast, lateral collapses, while still dangerous, generally result in less extensive impacts. The impact assessment result reveal that the MJ region is more susceptible to extreme wave events and posed high risk compared to KA. The wave heights at MJ range from -41.56 meters to 19.97 meters, with a mean of -10.22 meters and a larger standard deviation of 11.24 meters with the wave height distribution extends beyond 20 meters. On the other hand, KA shows more consistent wave heights, with values mostly concentrated between -4 to -2 meters, a mean of -3.03 meters, and a standard deviation of 2.85 meters. The wave heights range from -8.90 meters to 3.13 meters, indicating moderate wave activity and a lower risk of extreme events. These findings underscore the importance of implementing targeted, priority early warning systems in coastal vulnerable areas like MJ to mitigate the impacts of severe volcanic tsunamis.

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