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Concept of Assessment of Tsunami Early Warning System (TEWS) and Mitigation Volcanogenic Tsunami in Sunda Strait, Indonesia

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Abstract. On 22 December 2018, a flank failure during Mount Anak Krakatau (AK) volcanic eruption caused a silent tsunami disaster. Human casualties and material loss have been reported caused by this silent tsunami. This silent tsunami hindered any trigger from the existing earthquake-based tsunami early warning system (TEWS), it is due to the fact this tsunami is generated by the flank failure not an earthquake. To mitigate such disasters in the future, several research and strategies have been conducted by researchers and the government. One of the strategies is to utilize a sea level measurement instrument based on acoustics sensor called inexpensive devices for sea level monitoring (IDSL). In this research, prior to utilizing IDSL in the actual environments, assessment of IDSL algorithm sensitivity is conducted using a simulated tsunami height on several pseudo-observation points near AK. The simulation is based on 2018 AK tsunami using COMCOT model and validated with observed sea level from BIG tide stations. The results show the IDSL algorithm is capable to trigger the tsunami alert with the time lag since tsunami generation at the north of Panjang Island, north of Sertung Island, and south of Krakatau Island are 2.5 minutes, 3.5 minutes, and 2.25 minutes, respectively.

Keywords: *anak krakatau; tsunami simulation; COMCOT; early warning system.*

1 Introduction

Tsunami disaster in Indonesia is one of the main concerns from the government. In 2018, two tsunami disasters occurred on the 28 September 2018 Palu Tsunami, and the 22 December 2018 Anak Krakatau Tsunami. The latter occurred during the Anak Krakatau volcanic eruption, hence known as Anak Krakatau Tsunami (AK). BNPB reported that 437 dead, 31.942 injured. AK tsunami approached in silence, as the local communities received no warning. That fact is mainly the reason for the high human casualties. At the time, the government did not expect this rare process of AK tsunami generation. The existing TEWS system based on earthquakes does not trigger any possibilities of tsunami. Also, the fact that it occurred during night, limit visual anticipation and interaction from the local communities [1].

However, volcanic-eruption-induced tsunami is not a new kind, as there are several records including the 1883 Mount Krakatau eruption (MK). MK tsunami is massive, and it caused 70.000 deaths from the area near Sunda Strait until 3.000 km from the vicinity [2]. Although, compared to MK tsunami that AK tsunami is considered relatively small. Still, the 2018 tsunami in Sunda Strait did number of human casualties and severe impacts on the coastal area. Many researchers believe that AK tsunami was caused by a flank failure due to volcanic eruption with a volume about 0.25 km^3, commonly known as known as sub-aerial landslide [9]. Compared to a fault generated tsunami, a sub-aerial landslide tsunami may not give a massive earthquake, hence the AK tsunami hindered the trigger from earthquake-based early warning system.

In Indonesia, the development of Tsunami Early Warning System or TEWS for the tsunami disaster has been started since the tsunami in Aceh in 2004. The project known as the German-Indonesian Tsunami Early Warning System (GITEWS). In the present, the government rename this system as Indonesia Tsunami Early Warning System (InaTEWS). The first development of this system uses earthquake magnitude to determine the possible tsunami amplitude from experimental tsunami database researched by BMKG. Although, the government has upgraded this system to include offshore buoys monitoring, the fact that the maintenance of these buoys is challenging as 22 buoys were reported to have been damaged and missing from 2012 to 2018, it left the system vulnerable for a silent tsunami like AK [3].

In 2019, a collaboration between The Joint Research Center (JRC), the Indonesian Tsunami Society (IATsI), and the Indonesian government (including BMKG, KKP, BNPB) is initiated to design and implement new TEWS observation instrument. One of the inexpensive and affordable ideas from Husrin and Annunziato in 2019, is to utilize an acoustics water level measurement to monitor any anomaly that may be caused by tsunami. This idea is then called as Inexpensive Device for Sea Level Measurement (IDSL). IDSL is a high frequency tide gauge that is configured to collect water level data in 0.2 Hz frequency in near real-time, process it in the algorithm developed by Annunziato since 2015 [1][5]. In this research, a concept of assessment for the IDSL is proposed, to ensure that this device can serve as TEWS and help mitigate against AK volcanogenic tsunami. The assessment uses several pseudo-observation points from tsunami simulation which are considered close to the source.

2 Methodology

2.1 Water Level Analysis

Water level variation consists of many waves, such as wind generated waves, ship wake, tidal, storm surge, and the tsunami. To analyze the long wave such as Tsunami, first we must first analyze the signal to describe each signal spectrum based on their frequency period. This could be done using Fourier Transform.

Fourier Transform is a method for expressing a function as a sum of periodic components, and for recovering the signal from those components. Fast Fourier Transform (FFT), which was known to Gauss (1805) and was brought to light in its current form by Cooley and Tukey (1965). Press et al. (2007) provide an accessible introduction to Fourier analysis and its applications.

The general 1D Fourier Transforms or known as FFT The FFT y[k] of length N of the length-N sequence x[n] is defined as:

$$y[k] = \sum_{n=0}^{N-1} \left(e^{-2\pi j \frac{kn}{N}} x[n] \right) \quad (1)$$

and the inverse transform is defined as follows:

$$x[n] = \frac{1}{N} \sum_{k=0}^{N-1} \left(e^{2\pi j \frac{kn}{N}} y[k] \right) \quad (2)$$

By transforming the signal into their respective frequencies, each signal could be shown as in wave classification. Therefore, by applying FFT analysis to water level observations, the type, magnitude and period of each wave class could be described. After the signal is separated, then the high pass filtering is applied to remove the tidal signal. In this case, the signal below 2 cycle per-day is removed. The available station from Indonesia Geospatial Information Agency (BIG) is given in Figure 1. The result sample is given in Figure 2.

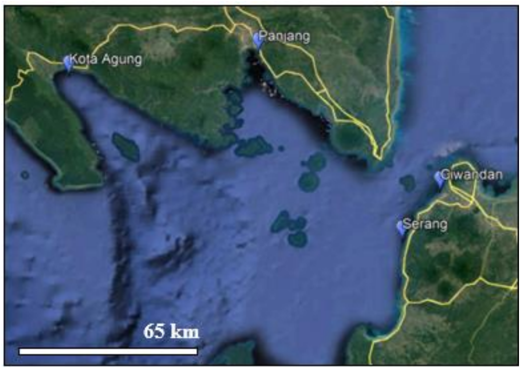

Figure 1 Illustration of Available Tide Station of BIG Before the Tsunami Event In 2018.

2.2 Tsunami Simulation

Tsunami simulations were performed using the Cornell Multi-Grid Tsunami Coupled Model (COMCOT). The COMCOT is a hydrostatic model that uses leap-frog finite difference method to solve shallow water equations with a staggered scheme. Both the nonlinear and linear shallow water equations can be selected in the model. The linear shallow water equations in spherical coordinate system used in COMCOT are as follows:

$$\frac{\partial \eta}{\partial t} + \frac{1}{R cos cos\, \varphi}\left\{\frac{\partial P}{\partial \psi} + \frac{\partial}{\partial \varphi}(cos\ cos\ \varphi\ Q)\right\} = -\frac{\partial h}{\partial t} \tag{3}$$

$$\frac{\partial P}{\partial t} + \frac{gh}{R cos cos\, \varphi}\frac{\partial \eta}{\partial \psi} - f\ Q = 0 \tag{4}$$

$$\frac{\partial Q}{\partial t} + \frac{gh}{R}\frac{\partial \eta}{\partial \varphi} + f\ P = 0 \tag{5}$$

Meanwhile, for nonlinear shallow water equations, COMCOT applies the following equations.

$$\frac{\partial \eta}{\partial t} + \frac{1}{R cos cos\, \emptyset}\left\{\frac{\partial P}{\partial \psi} + \frac{\partial}{\partial \emptyset}(cos\ cos\ \emptyset\ Q)\right\} = -\frac{\partial h}{\partial t} \tag{6}$$

$$\frac{\partial P}{\partial t} + \frac{1}{R cos cos\, \emptyset}\frac{\partial}{\partial \psi}\left\{\frac{P^2}{H}\right\} + \frac{1}{R}\frac{\partial}{\partial \emptyset}\left\{\frac{PQ}{H}\right\} + \frac{gh}{R cos cos\, \emptyset}\frac{\partial \eta}{\partial \psi} - f\ Q + F_x = 0 \tag{7}$$

$$\frac{\partial Q}{\partial t} + \frac{1}{R cos cos\, \emptyset}\frac{\partial}{\partial \psi}\left\{\frac{PQ}{H}\right\} + \frac{1}{R}\frac{\partial}{\partial \emptyset}\left\{\frac{Q^2}{H}\right\} + \frac{gH}{R}\frac{\partial \eta}{\partial \emptyset} + f\ P + F_y = 0 \tag{8}$$

where:

$$f = \Omega sin\varphi \tag{9}$$

$$F_x = \frac{gn^2}{H^{\frac{7}{3}}}P(P^2 + Q^2)^{1/2} \tag{10}$$

$$F_y = \frac{gn^2}{H^{\frac{7}{3}}}Q(P^2 + Q^2)^{1/2} \tag{11}$$

$$H = \eta + h \tag{12}$$

Here, P is the volume fluxes in x-direction (east-west direction), which is equal to hu, and Q is the volume fluxes in y-direction (south-north direction), which is equal to hv, where h is the depth at the grid to the mean sea level, and (u,v) are the velocities at x- and y-direction, respectively. Furthermore, η is the water surface elevation, (φ, ψ) are the latitude and longitude for spherical coordinate system, R is the earth radius, g is gravitational acceleration, and h is the water depth at the grid. The component of $-\partial h/\partial t$ denotes the effect of transient seafloor motion; the Coriolis force coefficient due to the earth's rotation is expressed as f. Meanwhile, Ω is for the rotation rate of the earth; H is the total water depth. F_x and F_y represents the bottom friction in the ψ and φ direction, respectively; and *n* is Manning's roughness coefficient. A complete explanation of the COMCOT module can be referred to Wang (2009) [8].

In this research nonlinear shallow water equation is used as the main forcing will be subaerial landslides. The simulation will use nonlinear shallow water equation to retain the effect of water depth. The volume of the landslide will be determined using volumetric study from the measured elevation of AK. The historical morphology changes of the Anak Krakatau before and after the fault failure shown in Figure 3.

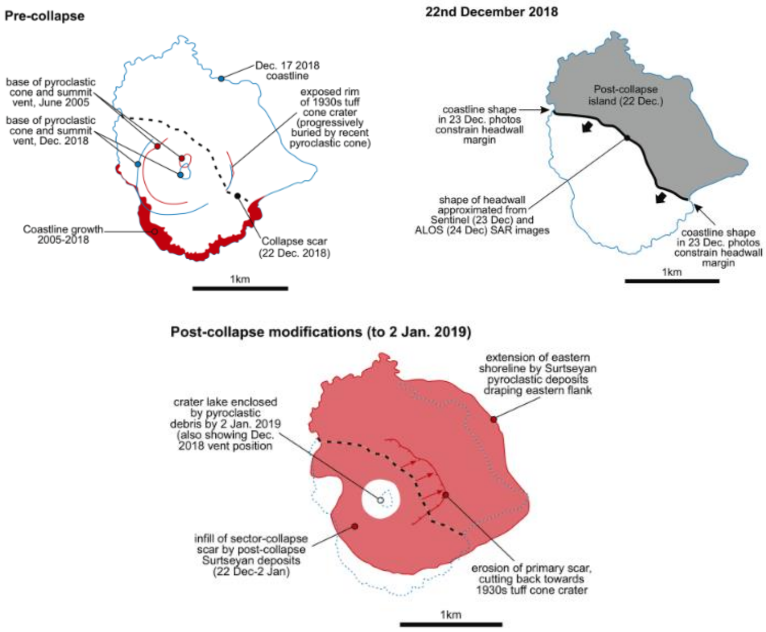

Figure 2 Morphological Changes at Anak Krakatau Spanning The 22 December 2018 Lateral Collapse. Features Are Interpreted from Various Satellite Images [7].

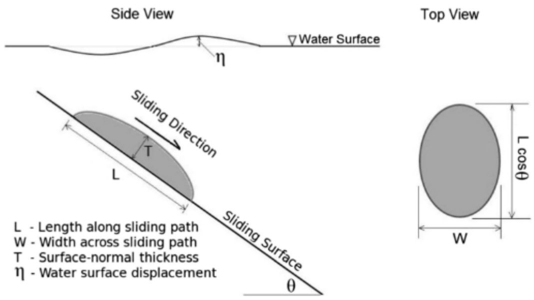

Figure 3 Sketch of Landslide Block Used in COMCOT [6].

The use of a sliding block model in this is justified by the translational nature of the landslide sources. The sliding function of Enet and Grilli is used built in COMCOT to describe the submarine landslide motions with a deceleration phase introduced at the locations where the slope merges with the flat floor [8]. Assuming the landslide mass as a semi-ellipsoid defined by its length L, width W, and thickness T as shown in Figure 4. The edge area where the semi- ellipsoid approaches the sliding surface is smoothed through an exponential function to avoid singularities due to the discontinuity of spatial derivatives at the edge of the sliding mass. In Figure 5 we give the start and end points of the sliding motion of these block models. The details of the landslide scenario are given in Table 1.

Figure 4 Starting Point to Ending Point of The Landslide Scenario.

The landslide scenario is given by a volumetric calculation, and it is on a very wide range based on the previous research in the same interest from the smallest with the volume of 0.104 km^3 in Williams [9] to 0.326 km^3 in Heidarzadeh [4]. As it varies between research, several scenarios are tested and the relatively best fit with the observed water level measurements given in Table 1. Pseudo-observation points are selected to represent the area facing opposite to the AK that fit for IDSL placement given in Table 2.

Table 1 Landslide Scenario of Krakatau Tsunami 2018.

Items	Value
Volume (km^3)	0.284
Length (m)	2450
Width (m)	1550
Thickness (m)	75
Angle (°)	8.2
Duration (s)	410
Start X Coordinate (°)	105.423
Start Y Coordinate (°)	-6.102
End X Coordinate (°)	105.392
End Y Coordinate (°)	-6.129

Table 2 Pseudo-observation Points Each Station.

Location	Description	Coordinates (Latitude, Longitude)
PS1	North Sertung	6.06 S, 105.38 E
PS2	South Krakatau	6.17 S, 105.47 E
PS3	North Panjang	6.06 S, 105.47 E

2.3 TEWS Algorithm Assessment

The TEWS detection algorithm developed by Annunziato in the JRC [1]. The algorithm objectives are to identify the tsunami signal from all non-tsunami sea level signals. To achieve this, one needs to separate mainly the tidal signal and the tsunami signal. It needs fast and robust calculations as it needs to be done in every data tick (hence in IDSL it's calculated in the frequency of 0.2 Hz). It relies on the absolute differences between a long-term forecast (LTF) with longer time window (1.5 to 3 hour) which has tidal like behavior and the short-term forecast (STF) with shorter time window (10 to 20 min) which represent the occurring anomaly signal. The algorithm written in mathematical expressions as below:

$$A_s(t) = |STF\ (t) - LTF\ (t)| \tag{12}$$

Where A_s is the alert signal. For every consecutive A_s calculated it increase the alert level by 1. When the alert level exceeds 7 it sends a warning notification to the server, and when the alert level exceeds 10 it confirms the tsunami occurrence.

The sea level timeseries processed in this algorithm is derived from the tsunami simulation, combined by tidal signals procured from BIG online tidal prediction service. The combination of these signals is needed to represent the tide during the actual measurement. The algorithm is assessed by testing its sensitivity in the area considered protected from direct tsunami propagation given in Table 2.

This research used the TEWS algorithm provided by JRC in https://github.com/annunal/pyTAD [1].

3 Preliminary Result and Discussion

3.1 Water Level from the Tide Gauge

Several tide gauges from BIG on Selat Sunda strait detected the tsunami during the 22 December 2018. The selected stations in Figure 1 are extracted and analyzed. The analysis of the arrival time and estimate tsunami height described in Table 2.

Table 3 Summary of Tsunami Amplitude and Time of Arrival on Each Station.

Location	Province	Amplitude (m)	Time of Arrival	Estimate Travel Time
Ciwandan	Banten	0.81	22/12/2018 14:38	47 minutes
Serang	Banten	1.50	22/12/2018 14:36	45 minutes
Lampung	Lampung	0.26	22/12/2018 14:40	49 minutes
Panjang	Lampung	0.80	22/12/2018 15:00	59 minutes

3.2 Tsunami Reconstruction

Water level data, and time arrival data are used to verify numerical simulation results. The result of tsunami simulation is compared to the water level data of Serang Tide Station depicted in Figure 5 and Figure 6.

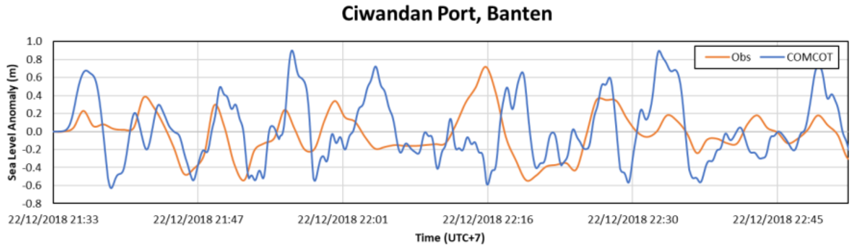

Figure 5 Tsunami Simulation Comparison to Recorded Sea Level Anomaly in Ciwandan Port, Banten Province.

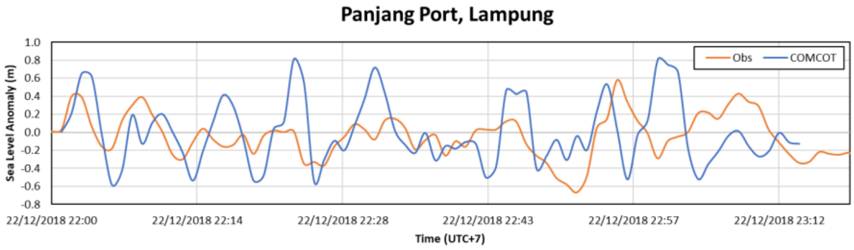

Figure 6 Tsunami Simulation Comparison to Recorded Sea Level Anomaly in Panjang Port, Lampung Province.

The maximum amplitude difference in Ciwandan Port is 0.20 m, and in 0.21 m with the simulation higher than the observed. The fact that the simulation has relatively higher amplitude than observed, it could be due to the bathymetry resolution obtained from BATNAS around 6 arcs second still considered as coarse for the nearshore wave transformation. The tsunami simulation could still be improved by using higher bathymetry resolution. The peak amplitude of tsunami in the Sunda Strait is depicted in Figure 7.

The result shows during the tsunami amplitude in the center area of Krakatau Islands is massive more than 30 m height. As it propagates, the tsunami is being reduced by losing its energy to the three islands nearby, namely Panjang Island, Sertung Island, and Krakatau Island. Tsunami exits the center area with an amplitude of 15 meters and propagates to Sunda Strait. Upon arrival in the Lampung coast, and Banten coast the tsunami is reduced to up to 1 m, and 2.5 m respectively.

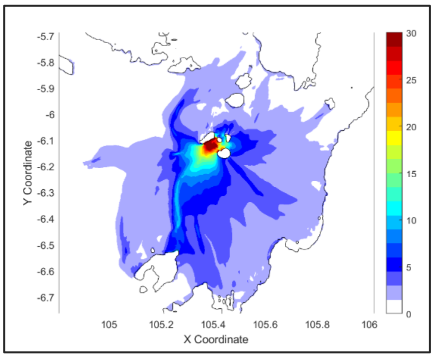

Figure 7 Peak amplitude of tsunami (in meter) from COMCOT simulation in Sunda Strait.

3.3 Tsunami Detection Algorithm Performance

The depiction of the pseudo-observation locations and their respective estimated tsunami arrival time (ETA) is given in Figure 8.

The tsunami simulation results in PS1, PS2, and PS3 is depicted in Figure 9. These data are also processed through the tsunami detection algorithm, giving the LTF, STF, and the Alert Level as depicted in Figure 11. The results confirm the capability of the tsunami detection model. It is also found that PS1 has the highest tsunami with 1.5 m, while PS3 is the lowest with 0.7 m height.

It is to be noted that in the actual environment, sea level will be much more complex due to local wave generated by the wind. This complexity will be a noise for the algorithm to perform. The actual data from the existing IDSL is depicted in Figure 10. Such noises differ for each location, further studies that include wave characteristics at the location either from the results of numerical simulations or observations are recommended for algorithm calibration.

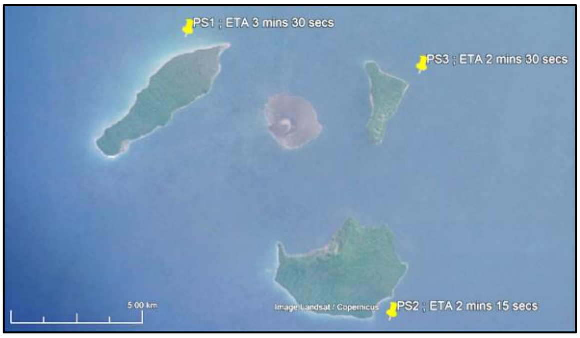

Figure 8 Depiction of Pseudo-Observation Locations and Estimated Tsunami Arrival from Tsunami Simulation.

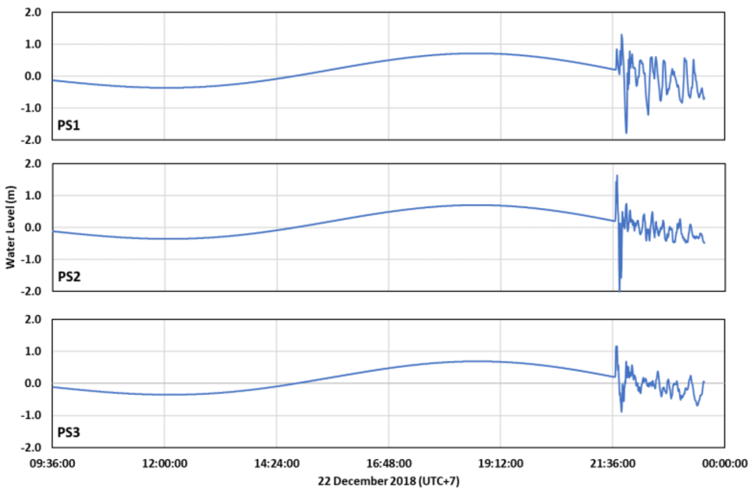

Figure 9 Sea Level Height from Numerical Simulation in PS1, PS2, and PS3.

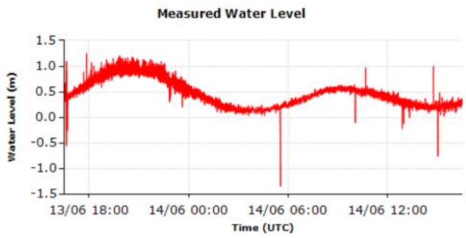

Figure 10 Sea Level Measurements from Existing IDSL (ID: IDSL-309) Published in JRC Website (https://webcritech.jrc.ec.europa.eu/TAD_server/ accessed at 14 June 2023).

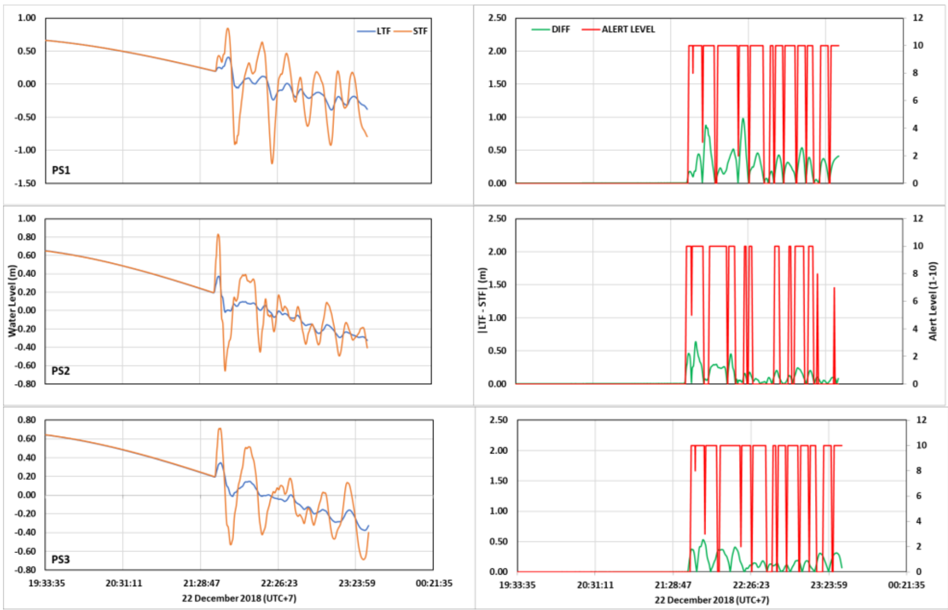

Figure 11 LTF, STF, and Alert Level Series in PS1, PS2, and PS3.

4 Conclusion

The tsunami simulation gives the best estimation for the AK tsunami with the landslide volume in 0.280 km^3, duration of the landslides in 410 s, and the angle of 8.2°. The peak amplitude of volcanic tsunami was 31.2 m upon impact and was reduced due to the path is blocked by the Sertung, Panjang, and Krakatau Island. In these islands side that back face the AK, the tsunami height gets lower than 2 m due to the energy dissipation in regards of shallow water wave transformation.

The performance of the TEWS algorithm shows a good result, considering that the tsunami height in the observation points is under 2 m. Therefore, as the system is sensitive enough, and the tsunami is not that rough, actual deployment of the system in these locations is recommended. However, it is suggested that to increase the reliability of the assessment in the future, a wind-wave parameter should be considered to mitigate the noise in the actual environment.

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