e-ISSN 2580 - 0752
BULLETIN OF
GEOLOGY
Fakultas Ilmu dan Teknologi Kebumian (FITB)
Institut Teknologi Bandung (ITB)

POTENTIAL TSUNAMI DUE TO SUBMARINE LANDSLIDE IN THE SOUTH OF BALI ISLAND: A PRELIMINARY STUDY

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Sari – Berdasarkan peta batimetri di Selat Lombok, profil kedalaman di di bagian selatan Selat Lombok berubah secara drastis dari 400 m ke 2000 m membentuk tebing bawah laut (*submarine canyon*). Dengan pengamatan lebih detil, ditemukan sebagian kecil dari tebing yang memiliki bekas gerusan berbentuk mahkota dengan tumpukan sedimen di bagian bawahnya. Fitur ini diinterpretasikan sebagai endapan longsor bawah laut dan dapat ditemukan 24 km ke arah barat daya dari Pulau Nusa Penida serta sekitar 30 km ke arah tenggara dari tengah Teluk Benoa. Gerusan terletak di sekitar kedalaman 950 m. Berdasarkan luas area gerusan, volume massa longsoran diperkirakan dan jumlahnya serupa dengan volume longsor Anak Krakatau yang menyebabkan tsunami di tahun 2018. Jika longsoran di Selat Lombok ini juga mampu membangkitkan tsunami, wilayah selatan Pulau Bali dan Pulau Nusa Penida memiliki kemungkinan terdampak tsunami paling tinggi. Pada penelitian ini, digunakan COMCOT – sebuah model numerik tsunami yang menggunakan persamaan perairan dangkal linier dan non-linier untuk melihat karakteristik gelombang tsunami dengan pembangkit longosor yang berpotensi menerjang wilayah selatan Pulau Bali dan Pulau Nusa Penida.

Kata kunci: Longsor bawah laut, model tsunami, Selat Lombok.
(Dianjurkan maksimal 5 kata, misalnya terkait metode, area penelitian, obyek penelitian, dsb.).

Abstract *– Based on the bathymetry map of Lombok Strait, the seabed morphology in the south of Lombok Strait was primarily a submarine canyon where the depth profile change drastically from 400 m to 2000 m. In a closer look, there was one part of the canyon that has crowning scar with mounded sediment just below it. This feature was interpreted as a landslide deposit and it was discovered in the south part of Lombok Strait, around 24 km from the south-west of Nusa Penida, and 30 km from the center of Benoa Bay. The scar was found around depth 950 m. According to the area of the scar, the estimated volume of lost surface area was illustrated around the volume of Anak Krakatau landslide that generated tsunami in 2018. By assuming this landslide was also tsunamigenic, it will impact the coastal area that surrounding the sea which are the south of Bali Island and the south of Nusa Penida Island. In this preliminary study, a tsunami numerical model – COMCOT which adopts linear and non-linear Shallow Water Equation will be utilized to investigate the characteristics of the landslide-induced tsunami on the surrounding coastal area of south of Bali Island and the south of Nusa Penida Island.*

Key words*: Submarine landslide, tsunami model, Lombok Strait.*

1. INTRODUCTION

Bali is one of area in Indonesia that is susceptible to earthquake tsunami. According to Horspool *et al*. (2014), there is more than 10% probability for Bali to be struck by tsunami that is more than 0.5 m high annually. However, currently, most tsunami hazard map of Bali that can be found on the internet is only covering Tanjung Benoa area to the north (Hall *et al*., 2019; Khomarudin *et al*., 2010). There is one from GITEWS (2010) that covering the whole part of Bali Island but only in the scale of 1:100,000 making the very southern part almost unseen even though this area is the one that directly face the subduction zone. This is quite understandable since the morphology of the south of Bali Island is domantly a cliff where the land is located more than 70 m above the mean sea level and no historical tsunami have ever reached this area (Afif and Cipta, 2015). Having the same morphology, there is also no tsunami hazard map for Nusa Penida. Looking closer at the Google Earth (**Figure 1**), there are so many beaches both private and public in south of Bali that located just below the cliff - the most famous one is Pandawa Beach. While in Nusa Penida, there is snorkeling and diving spot called Manta Point and Sunfish Beach. Having these area, the tsunami risk in south of Bali and Nusa Penida should be re-evaluate.

Earthquake-tsunami is not the only one hazard that endanger the south of Bali and Nusa Penida. Through bathymetry slope map of Lombok Strait that is generated from BATNAS BIG data, a submarine landslide mark was identified. This finding was then compared to unpublish high resolution bathymetry map of Lombok Strait (Trismadi, 2018) to get more detail information such as the exact location and dimension. The volume of the landslide was then estimated and it is about the same with the one in Anak Krakatau which generated tsunami in 2018 (Grilli *et al*., 2019). Hence, there might be a chance that this landslide in Lombok Strait could generate a tsunami too. Using the landslide location and dimension, a tsunami numerical model was built using COMCOT to investigate the characteristics of the tsunami wave that is generated by the landslide.

Though this is still a preliminary study, we hope this could be used as a consideration to re-evaluate and renew the risk assessment and mitigation plan in the south of Bali and Nusa Penida Island.

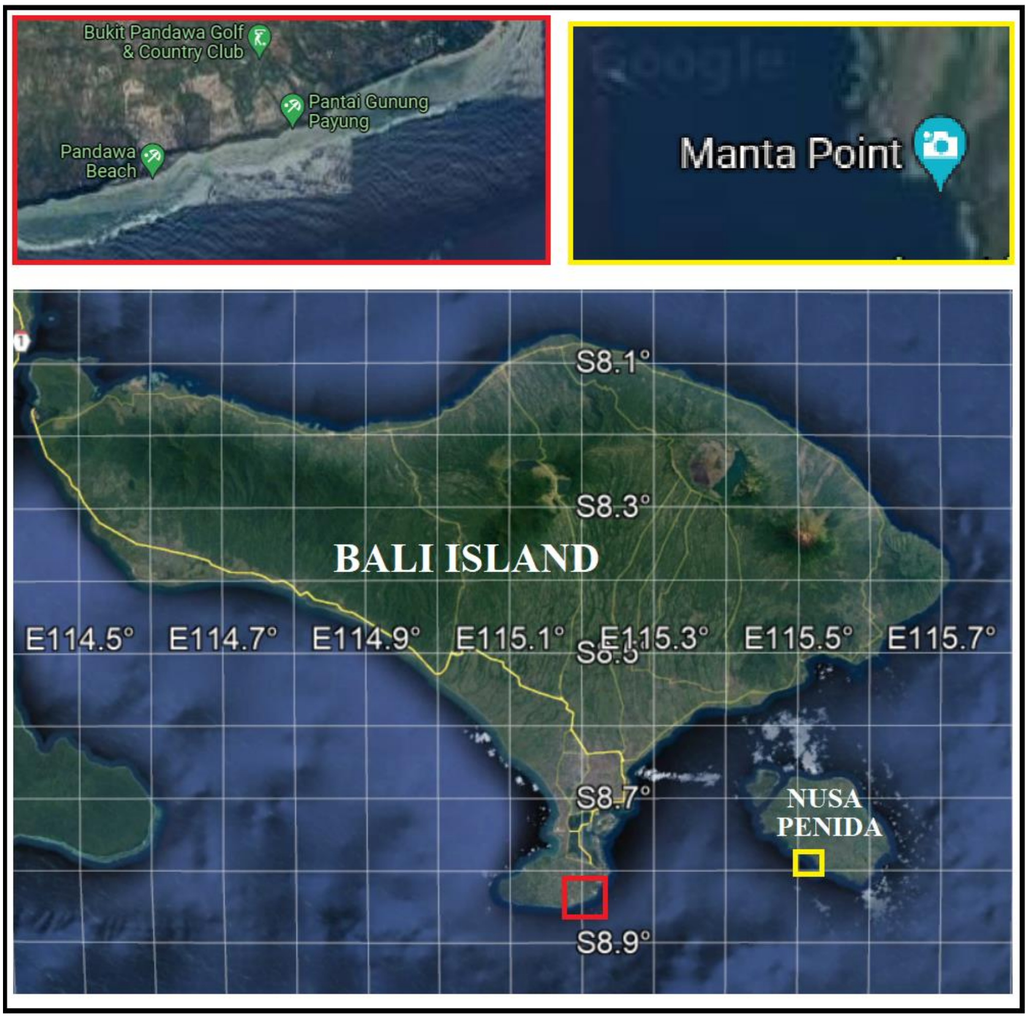


Figure 1. Location of Pandawa Beach and Manta Point which are one of famous tourist attraction points in south of Bali and Nusa Penida (Google, 2021).

2. DATA AND METHODOLOGY

This study used bathymetry and topography data from Indonesian Information and Geospatial Agency (BIG) that can be accessed through https://tanahair.indonesia.go.id/. The bathymetry data has 6 arc-second resolution (185 m) that is generated form assimilation of altimetry data and both of multi-beam or single-beam echo sounder survey data. On the other hand, the topography data has the resolution of 0.27 arc-second (8.325 m). Both of this bathymetry and topography data were combined and interpolated to generate new bathymetry data with resolution of 0.06 arcminute (111 m) that will be used as input of the numerical model.

Besides being used for model input, the bathymetry data from BIG will be used for generating bathymetry map and slope map so that seabed geomorphological analysis can be done. Then, the submarine landslide could be identified and parameterized. The parameter that resulted from this analysis will then be used as input for tsunami model.

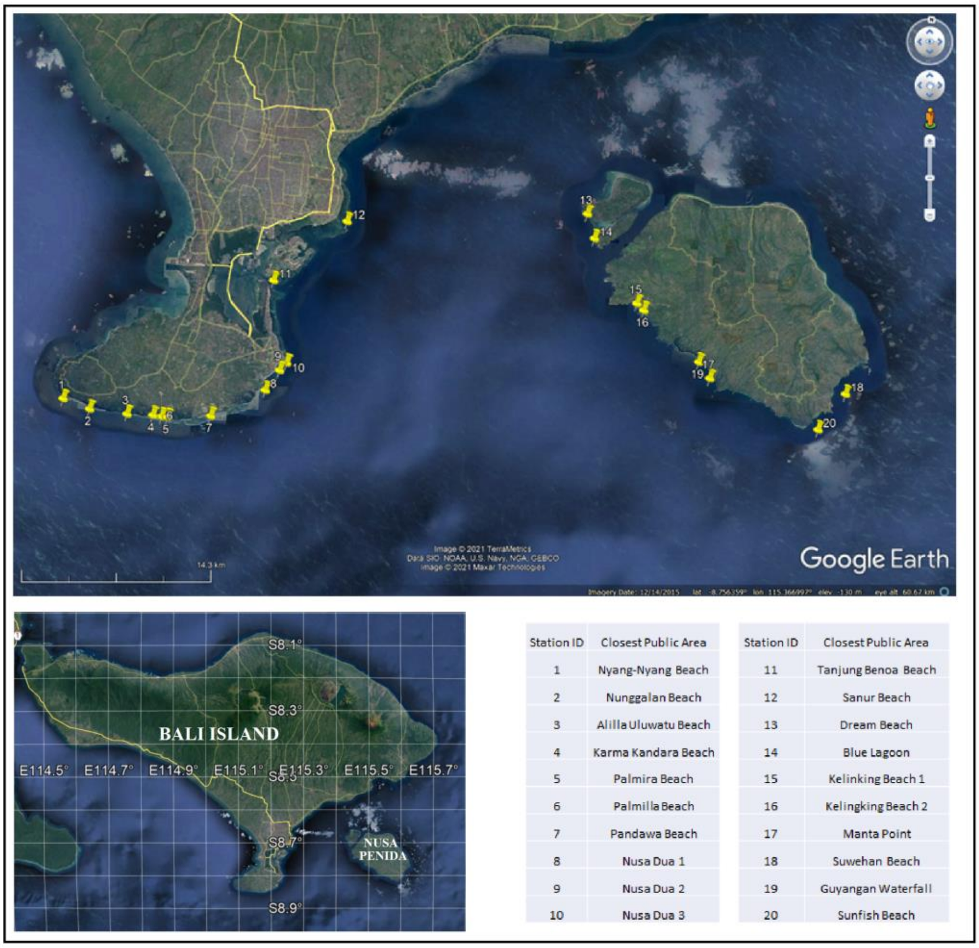
Additional information that useful for tsunami model but could not be found on the data mentioned above will be used from literature study.

After all needed data had been collected, the scenario for tsunami model was designed. In this study, we only created one scenario (**Table 1**). This scenario will be run for two hours to ensure that the model is stable. Using grid size that match the resolution of the new bathymetry data (0.06 arcminute), the time step was 0.2. This was chosen to fulfill the CFL criteria. The equation used for the model is non-linear with roughness coefficient 0.013 which is suitable for bays and shores (Garzon and Ferreira, 2016). This scenario will be run using COMCOT (Cornell Multi-grid Coupled Tsunami Model) which adopts explicit staggered leap-frog finite difference schemes to solve Shallow Water Equations (Wang, 2009). This model has been widely used for modelling landslide-induced tsunami (e.g., Iglesias *et al*., 2012; An *et al*., 2014; Gusman *et al*., 2019; Liu *et al*., 2020). This model can be used both in Spherical and Cartesian coordinates.

From COMCOT, tsunami wave propagation both in spatial and time will be analyzed. 20 virtual gauges were made as observation points along the south coast of Bali Island and south-west of Nusa Penida Island (**Figure 2**). These observation points were placed near public places. Since the resolution of the data is not good enough to draw all these narrow beaches down the cliffs, all points could only be put offshore. However, they are located as close as possible to the shore so we can imagine the characteristics of the tsunami wave just before hitting the land.

Table 1. Model Scenario.

Run Time (s)	Time Step (s)	Grid Size (minute)	Equation	Manning Roughness Coefficient
7200	0.2	0.06	Non-linear	0.013



Station ID	Closest Public Area	Station ID	Closest Public Area
1	Nyang-Nyang Beach	11	Tanjung Benoa Beach
2	Nunggalan Beach	12	Sanur Beach
3	Alilla Uluwatu Beach	13	Dream Beach
4	Karma Kandara Beach	14	Blue Lagoon
5	Palmira Beach	15	Kelinking Beach 1
6	Palmilla Beach	16	Kelingking Beach 2
7	Pandawa Beach	17	Manta Point
8	Nusa Dua 1	18	Suwehan Beach
9	Nusa Dua 2	19	Guyangan Waterfall
10	Nusa Dua 3	20	Sunfish Beach

Figure 2. Locations of observation points (Google, 2021).

3. RESULTS

Seabed Geomorphology

From generated bathymetry map (**Figure 3**), Lombok Strait has depth that range from 0 m to 4000 m. in the northern part. The depth changes gradually from 0 m to around 1000 m creating an almost flat seabed. In the middle part, the depth is very shallow. With depth ranging from 0 m to 300 m, the seabed forming a continental shelf. This shelf broadly surrounds the middle to southern part of Bali Island and the whole Nusa Penida Island. Moving to the south, the depth starts to change rapidly in a short distance. In just about 50 km, the depth has changed from 300 m to 4,000 m. this rapid change of depth marks the location of submarine canyon.

From the Bathymetry slope map (**Figure 4**), the slope in this area is around 10 to 20°. It is already well known that the steeper the slope, the more instable it gets. Moreover, it tends to create failure. Looking closer to the submarine canyon area, a tiny u-shaped scar was found in just 24 km to the south of Nusa Penida (black box in **Figure 4a**). Comparing this bathymetry slope map to an unpublished high-resolution bathymetry map of Lombok Strait by Trismadi (2018), exactly where the u-shaped scar located, the u-shaped scar had more detail feature (**Figure 4b**) just like the landslide morphology sketched by Nicoll (2010) (**Figure 4c**). Even though the morphology could be seen clearly through this map, the time occurrence and the triggering mechanism of this landslide is still unknown.

We estimated the dimension of the landslide roughly by measuring the area of the main scarp. The upper part of the scar, which we interpreted as main scarp, is 1 km in width (N-S direction) and 1 km in length (E-W direction).

We assumed this to be the length and width of the landslide.

To estimate the thickness of the mass failure, two vertical cross sections were made (**Figure 5a**) and interpreted by assuming that before the landslide occur, the slope in line B-B' was identical to the one in line A-A'. With this assumption, we consider the zone between line A-A' and line B-B' in vertical cross-section (**Figure 5b**), is the estimated area of the landslide which is around 200 m thick.

Another important parameter for building a landslide-induced tsunami is the velocity of the landslide which will be calculated from landslide duration. Since the time of this landslide occurrence is still unknown, we could not define the exact starting time and ending time of the landslide. However, since the volume of this landslide is similar to the one which cause a tsunami in Anak Krakatau 2018 (Grilli *et al.*, 2019), we assume this landslide would have the same velocity with the Anak Krakatau landslide. For this case, we consider the landslide duration is 400 s. all landslide parameters can be seen in Table 2.

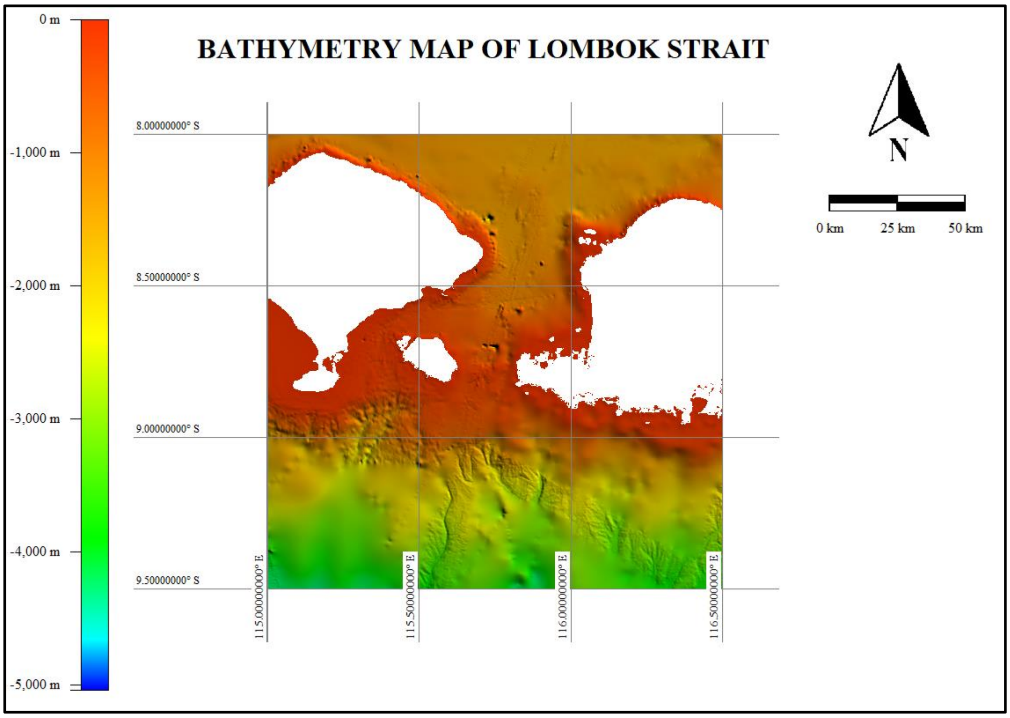


Figure 3. Bathymetry map of Lombok Strait.

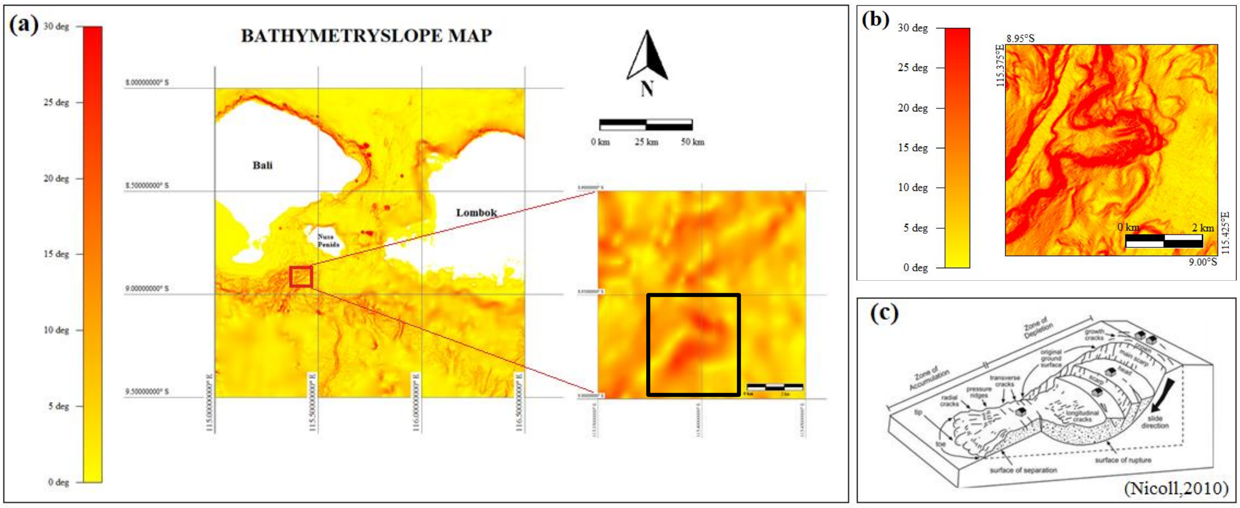


Figure 4. (a) Slope map of Lombok Strait with closer look to the u-shaped scar (black box); (b) Slope map from high resolution bathymetry map from Trismadi (2018); (c) Landslide morphology sketch (Nicoll, 2010).

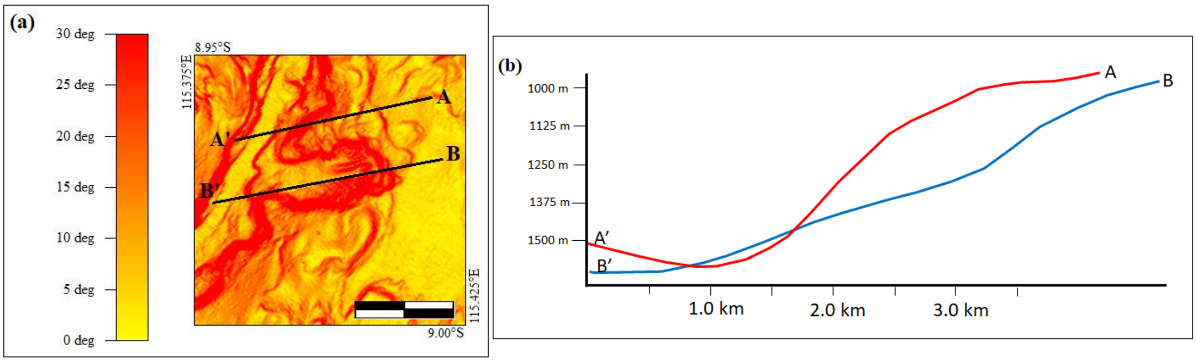


Figure 5. (a) Location of Line A-A' and Line B-B'; (b) Vertical cross section from Line A-A' and Line B-B'.

Table 2. Landslide parameter for tsunami model.

Start Point		End Point		Slope Angle	Dimension (m)			Duration
Lat (°)	Lon (°)	Lat (°)	Lon (°)	(°)	L	W	T	(s)
-8.971	115.408	-8.974	115.389	15	1000	1000	200	400

Tsunami Propagation

From the result of the tsunami model, the movement of the landslide causing a tsunami wave with maximum amplitude more than 40 m high (**Figure 6**) above the location of the landslide. This wave the propagated to the surrounding area with maximum amplitude focusing to E-W direction. However, as the bathymetry varied, the amplitude of the wave changed. It decreased as the bathymetry went deeper and it increased when the batymetry became shallower. When reaching the continental slope, the maximum amplitude drastically decreased. Hence, it was only around 2 – 3 m high when reaching the shoreline.

The tsunami wave reached the shoreline less than 10 minutes both in south Bali and Nusa Penida (**Figure 7**). The first wave that arrived in Bali was a crest while in Nusa Penida was a through. However, the first through is very small and could not reach the whole island. This can be seen better in time series record (**Figure 8b**). before 15 minutes, the wave had reached to the middle part of Bali Island and in 20 minutes, the wave had covered all domain area and the model had reached a steady-state condition.

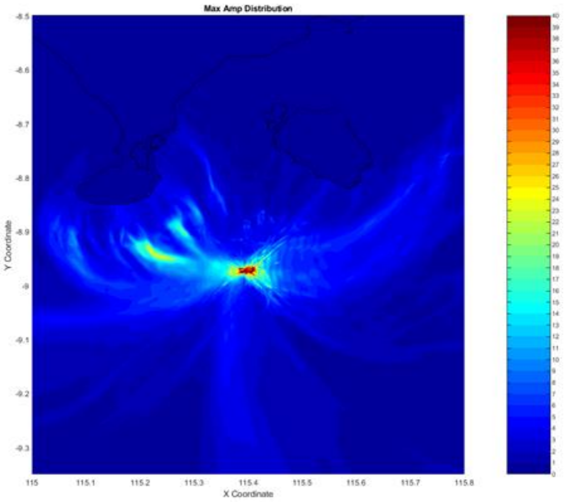


Figure 6 Distribution of maximum amplitude during the whole simulation time.

From the time series data (**Figure 8**) at observation station as listed in Figure 2, the first point that was hit by the wave in Bali Island is Station ID 8, 9, and 10 (close to Nusa Dua Beach) (**Figure 8a**). The waves arrive before 10 minutes after the landslide with maximum amplitude around 3 m. Then, in around 11 minutes, the wave arrived in Station ID 7 which was located on Pandawa Beach. The maximum amplitude was around 2.5 m. After that, in about 12 – 13 minutes, all stations in the west (Station ID 1 to 6) were hit with the highest amplitude – almost 3.5 m – in Station ID 5 and 6. Then, the wave arrived in Station ID 12 before arriving in Station ID 11 even though the distance to Station ID 12 seem further. In this area, the tsunami amplitude had decreased to below 2 m.

Even though the tsunami wave arrived in Nusa Penida first, the wave amplitude was not as high as the one that hit Bali (**Figure 8b**). The wave arrived in Station ID 17 (Manta Point) and 19 (Gunyangan Waterfall) in about 8 minutes after the landslide with very low trough – even less than 0.5 m. But then, a trough with -1 m amplitude came followed by 1 m high crest. The next stations that were hit by the wave were Station ID 15 and 16 which located near Kelingking Beach with maximum amplitude around 1.5 m. the highest wave amplitude was recorded in Station ID 20 which located near Sunfish Beach with maximum amplitude reaching more than 2.5 m that came in around 12 minutes. The last station that hit by the wave is Station ID 18, near Suwehan Beach, with maximum amplitude more than 1 m. The wave that hit the stations in the northern part of Nusa Penida (Station ID 13 and 14) was the lowest wave (only about 0.5 m).

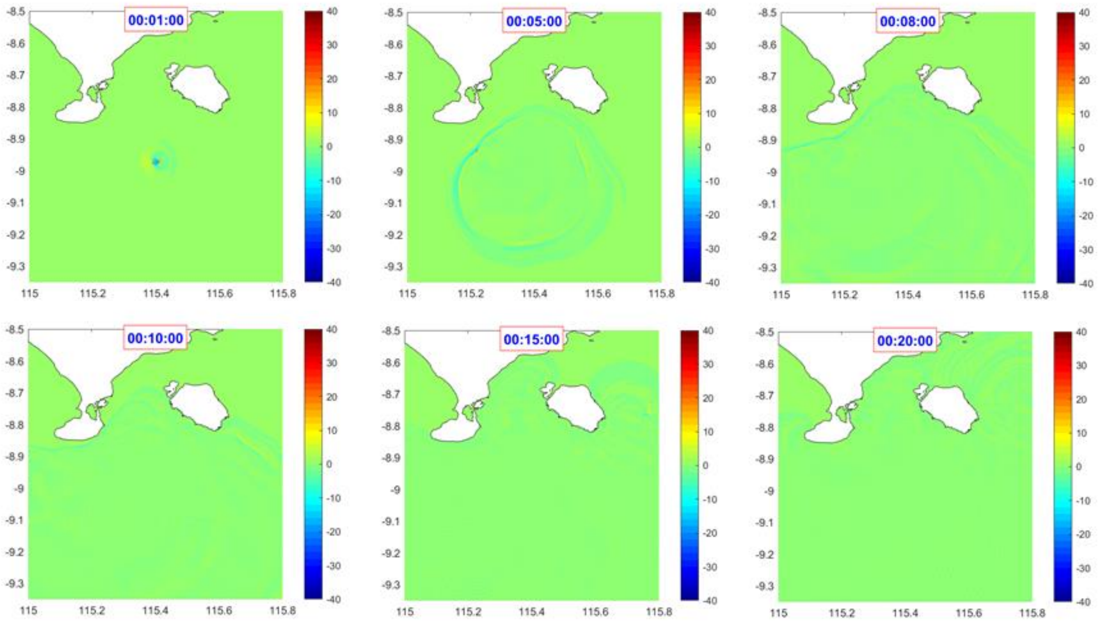


Figure 7 Tsunami wave propagation from time to time.

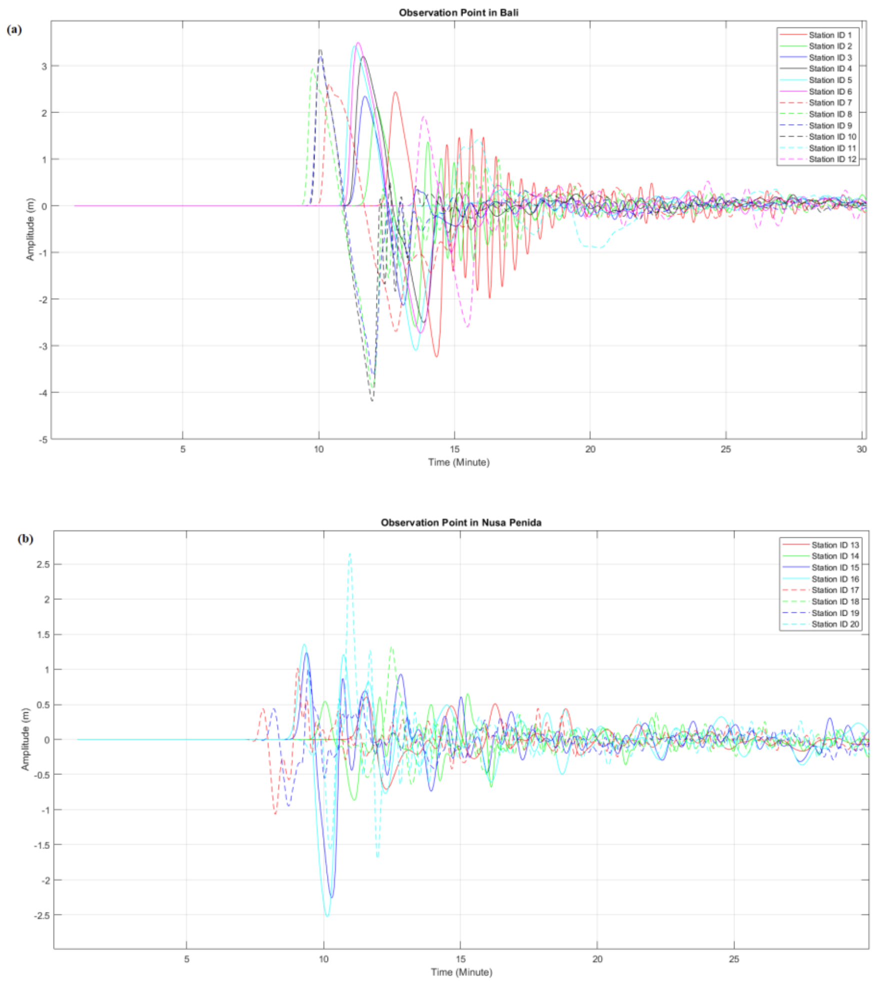


Figure 8 (a) Time series in Bali observation point; (b) Time series in Nusa Penida observation point.

4. DISCUSSION

The first wave that generated exactly above the landslide location is quite high. This was caused by the design of the scenario where the landslide was set to be 200 m thick. However, how the wave propagated next was controlled by the bathymetry. To the west, after the wave formed, it went through a deeper area so that the amplitude went lower. But, when reaching Bali Island, the bathymetry went shallower. This is where the wave had shoaling effect – the speed went slower, but the wave got higher to maintain the energy. However, as the wave goes higher and higher, at some point, when reaching the broad continental shelf, the bathymetry got too shallow for the wave to grow, so it broke instead (Prasetya *et al*., 2001). Even though the wave had been broken offshore, it still can reach south Bali shoreline with the highest amplitude more than 3 m. Unlike the propagation to the west, the wave that traveled to the east decreased significantly after being formed because to location of the landslide was very close to the shelf.

The form of the wave (crest/trough) that firstly arrive in the shore was also matched with the seabed deformation. Since the landslide move from east to west, the seabed in the east will become deeper and that will cause a downward movement of the water column. Hence, a trough was formed. On the other hand, after moving to the west, the added mass will cause the bathymetry became shallower so it will cause the water column moved upward and formed a crest.

The arrival time of the wave in this case was primarily depends on the distance to the tsunami source. Although in some cases there was some anomaly like the arrival time in Station ID 11 was longer than in Station ID 12. This is because Station ID 11 was located a little bit inside the bay, so the wave needed extra time to reach this location.

Generally, the hypothetical tsunami that generated by the landslide was not as bad as the one that happened in Sunda Strait back in 2018 (Grilli *et al*., 2018). However, this tsunami can be classified as Scale V to VI tsunami which is strong to slightly damaging (Papadopoulus an Imamura, 2001). In this scale, tsunami is considered will cause people to run to a higher place and will damage wooden structure near the coast. The small boats will be stranded to the land or hitting each other. Looking at this potential hazard, it is very important to re-evaluate the risk assessment and mitigation plan in this area. Primarily, in the public beach where the place could be packed by tourists. However, a new model with more scenario and higher resolution bathymetry data would be needed to have a better picture of the characteristics of the generated landslide-induced tsunami.

Moreover, the landslide that was identified in this study, also needed to be investigated further since the time of the occurrence, landslide frequency, and the triggering mechanism is still unknown. It is important to investigate these further since time occurrence and frequency of the landslide will be related to time occurrence of the tsunami while the triggering mechanism of the landslide will define how bad the tsunami can be. If the landslide is triggered by an earthquake, it could worsen the tsunami height that was originally created by the earthquake like what happened in Palu 2018 (Gusman *et al*., 2019). However, if the landslide is not earthquake-related, the characteristics of the generated tsunami might be just like what we have simulated here but, without an earthquake, this will be a ‘silent tsunami’ that could come in a sudden without people being aware

5. CONCLUSION

Based on bathymetry map of Lombok Strait, a submarine landslide was identified in the southern part of Lombok Strait. Using rough estimation, the dimension of the landslide was defined and it was similar to the one in Anak Krakatau that cause tsunami back in 2018.

Using COMCOT, tsunami wave propagation was simulated and the result showed a 2.5 – 3 m high tsunami could potentially hit the south coast of Bali while in Nusa Penida the wave height is 1 – 2.5 m. This tsunami might not be able to reach the land above the cliff but the beaches and snorkeling and diving spot just below the cliff could have devastating impact.

A further investigation for the landslide and more scenario with higher resolution bathymetry data for tsunami model would be needed to have a better picture about the potency tsunami that caused by the landslide, so that a new risk assessment and mitigation plan could be done for the southern part of Bali Island and Nusa Penida Island.

ACKNOWLEDGMENT

This research was a part of the project titled "Marine Science and Technology Cooperation between Korea and Indonesia (20180319)" and "Ocean Coastal Basic Survey and Capacity Enhancement in Cirebon, Indonesia (G52440)" funded by the Ministry of Oceans and fisheries, Korea.

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