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Simulation of Oil Spill Pollution due to Tsunami in Cilacap, Central Java, Indonesia

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***Abstract*— Cilacap, located on the south coast of Java Island, is an "oil and gas city". Cilacap has many oil refineries, storage, and loading & unloading facilities. However, these facilities' existence is threatened by the potential for earthquakes and tsunami in Cilacap because Cilacap is very close to the Eurasia and Indo-Australian plates' subduction zone. The earthquake and tsunami waves can damage these facilities and cause secondary disasters, namely oil spill pollution. The first step to anticipate is to predict the direction and distribution of the oil spill due to tsunami through simulation and numerical modeling. This simulation and modeling used the TUNAMI model, hydrodynamic model, and spill analysis model based on the worst-case scenario (Mw 9.0 earthquake). This study simulates and models the oil spill in the west and east monsoons. Based on this simulation and modeling result, we know that the direction and distribution of the oil spill in the west and east monsoons are relatively the same and move more dominantly in the current direction. The spread of the oil spill caused by the tsunami was faster than the oil spill in general. Some of the oil spills spread inland more than 1 km north of the Teluk Penyu coast. The authors expect this study's results can be used as material for preparing of contingency plans for handling oil spills to minimize negative impacts.**

***Keywords*— Cilacap; numerical modeling; oil spill; tsunami.**

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I. INTRODUCTION

Cilacap is a city located on the southern coast of Java - Indonesia, which faces the Indian Ocean. As one of the oils and gas industry cities, Cilacap has the largest oil refinery in Indonesia. Apart from oil refineries, Cilacap also has other supporting facilities for oil and gas activities, such as storage facilities and loading and unloading facilities. However, this facility's existence is threatened by the potential for earthquake and tsunami waves in Cilacap because Cilacap is very close to the subduction area of the Eurasian and Indo-Australian plates, making it prone to earthquakes and tsunami waves [1].

Since 1900 in the south of Java Island, there have been six tsunamis [2]. Two major tsunamis in Southern Java, namely the Banyuwangi tsunami in 1994 and the Pangandaran tsunami in 2006, killed hundreds of people [2]. Besides, the sea waters of Cilacap are also prone to oil spill pollution. The oil spill incident has happened seven times in Cilacap Regency, i.e., in 2000, 2004, 2007, 2008, 2010, 2015, and 2016 [3]. Meanwhile, according to other researchers during the period 1989-2019, there have been at least 17 oil pollution cases in Cilacap sea waters [4], [5].

The threat of earthquake and tsunami waves in Cilacap can damage oil storage and oil loading and unloading facilities, causing secondary disasters, namely oil spill pollution. The impact of the oil spill on the environment is hazardous to marine and terrestrial ecosystems in coastal areas. The oil spill also disrupts coastal communities' economic activities, with indications of reduced catches and contamination of cultivated land such as fish and seaweed ponds [6]. By considering this, it is necessary to anticipate steps as early as possible to minimize this impact. The oil spill response plan is one of the essential requirements owned by the various business units with operations in port and waters [7]. One crucial initial step is with oil spill modeling. Oil spill modeling is vital in determining the effective and efficient strategy for the oil spill response [8]

Through this modeling (tsunami and oil spill modeling), we can predict the direction and distribution of the oil spill in the event of a tsunami. Many studies and models of tsunamis in Cilacap and the southern coast of Java have been carried out, but studies of the tsunami that caused the oil spill has never been carried out. Fauzi et al. [9] studied the tsunamigenic earthquake's potential in the Java subduction zone with magnitude scenarios 8.9, 9.0, 9.2. Hartoko et al. [10]studied spatial tsunami wave modeling for the south Java coastal area. Widiyantoro et al. [11]stated that based on the worst-case scenario, the tsunami height in West Java could reach 20 m, and in East Java, it could reach 12 m. Hanifa et al. [12]stated that the 2006 tsunami in southern Java caused an average inundation of 3-8 m on Java's southern coast. Kongko et al. used a 2D non-linear shallow water equation model for modeling the potential tsunami south of Java, especially Cilacap City. The model validation for the 2006 Java tsunami showed fair-good results in terms of the tsunami run-up distribution, tsunami marigram analysis, and the inundation in the study area [13]. Other research on tsunamis in southern Java, especially Cilacap, has been conducted by Rahmawan et al. [14], Kongko et al. [15], DLR/GTZ [16]. Meanwhile, research related to the southern Java tsunami, especially the 2006 Pangandaran tsunami, was conducted by Mustika [17], Mori et al. [18], and Sujatmika et al. [19].

Researchers have also carried out many studies and modeling of the oil spill in Cilacap. Widhayanti et al. (2015) stated that based on simulation results, after 24 hours, the crude oil spill had spread as far as 1.8 km into the waters between Cilacap Regency and Nusakambangan Island [20]. Wibowo stated that the oil spill from SPM was evenly distributed throughout the Cilacap water area with a spill thickness between 0.001-1 mm [4]. Rezki et al. state oil spill in the west monsoon, the oil spill moves to the east and east monsoon toward the Indian Ocean. The oil spill moves to the west and northwest toward the Segara Anakan Estuary [3]. Trenggono et al. state that oil spills in Cilacap water moved forward to the south, west, and southeast at low tide and moved north and west at high tide [21]. Another study states that the Teluk Penyu area, the eastern of the island of Nusakambangan and Donan River estuary, is an area with a high probability of a polluted area [5].

The oil spill in Cilacap sea waters is a severe problem, apart from the high frequency of incidents and huge economic and environmental losses. According to Mauludiyah [5], if it is assumed that the oil spill is 150,000 tonnes, the cost of ecological damage is IDR. 45.10^{16}, the socio-economic loss of IDR. 156.10^{9}. Besides, based on the environmental sensitivity index study on the coast of Cilacap, a Segara Anakan Estuary is very sensitive to oil spills [22]-[23].

Based on the description above, it is necessary and essential to conduct a study and simulation of oil spill pollution due to the tsunami in Cilacap waters. The purpose of this study was to determine the distribution pattern, thickness, and arrival time of an oil spill if the tsunami hit industrial areas and damaged oil and gas facilities in Cilacap Regency. This model's study and simulation combined the tsunami simulation with the TUNAMI model and the MIKE21 hydrodynamic model. The results of the TUNAMI model are used as input for hydrodynamic modeling with the MIKE21-Flow Model FM. Furthermore, the MIKE21 hydrodynamic model results are used as the basis for modeling the oil spill distribution with the MIKE21 Spill Analysis module.

Based on this study and simulation results, we can use it to prepare contingency plans for handling oil spills if a tsunami occurs and can simplify and speed up managing the oil spill. In the end, we can minimize the negative impacts and risks due to the oil spill.

II. MATERIAL AND METHOD

A. Area of Study

The area of this study is located on the coast of Cilacap City, Central Java Province. Cilacap is on the south coast of Java Island, Indonesia and directly faces the Indian Ocean (see Fig. 1).

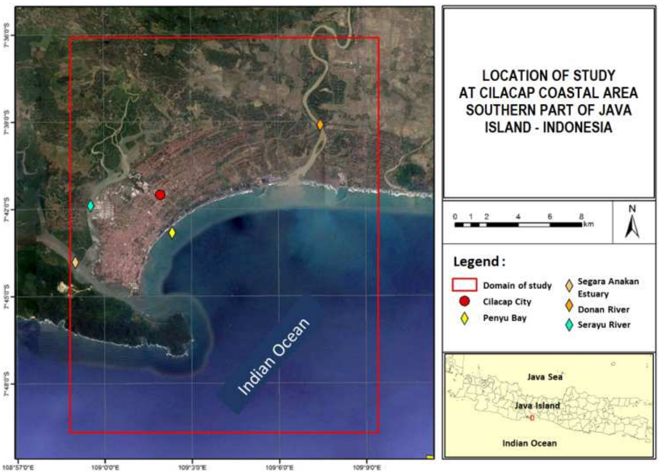


Fig. 1 Area of study

B. Modeling Scenario

1) Scenario of Tsunami Modeling: The tsunami scenario in this modeling is built based on the worst-case scenario. Research by Hanifa et al. [24] on the tectonic activity of the Australia-Eurasia plate during the 2008-2010 period revealed that the subduction area in the southern part of Java Island has the potential for a megathrust earthquake with a maximum magnitude of Mw 9.0. Based on this research, an earthquake with a magnitude of 9.0 was used as the worst scenario in this modeling. According to PUSGEN [1], an earthquake in southern Java has a magnitude of Mw 8.8 - 8.9.

The numerical model used in this study is the TUNAMI N2 Model developed by Imamura from Tohoku University. TUNAMI stands for Tohoku University's Numerical Analysis Model for Investigation. TUNAMI N2 is a tool for modeling wave propagation in linear theory in the deep sea, shallow-water theory in a shallow sea, and run-up on land with constant grids [25]. This model requires a wave input based on the determination of the fault parameters. Fault parameters such as fault length (L), fault width (W), magnitude (M), epicenter depth (H), slip (D), strike (θ), dip (δ), and slip angle (γ)) are the main parameters of the earthquake, which determine the initial tsunami wave before it propagates [25], [26]. Depth, slip, strike, dip, and slip values are determined from the slab model based on the earthquake epicenter location [27]. Fault length, width, and dislocation are determined from an empirical formula based on the magnitude [26].

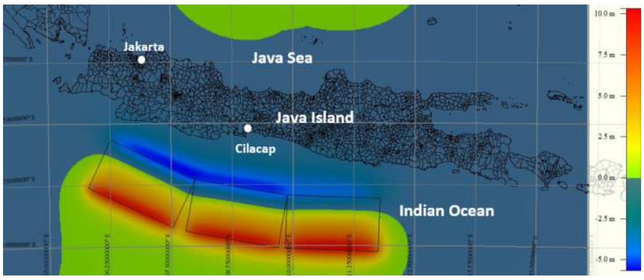


Fig. 2 Initial tsunami wave height at earthquake source

The earthquake generator's fault in southern Java was divided into three segments to produce an earthquake with a magnitude of Mw 9.0. The first segment is located at 106.8932^{O} E and 8.7168^{O} S with a depth of 19 km and a magnitude Mw of 8. 7. The second segment is at 108.8348 East Longitude and 9.3318 South Latitude with a depth of 22 km and magnitude Mw 8.7, and the third fault at 110.8100 east longitude and 9.5415 south latitude with a depth of 23 km and magnitude Mw 8.7 (see Fig. 2).

2) Scenario of hydrodynamic and oil spill modeling: For the hydrodynamic tsunami model and spill analysis with MIKE21, the domain model must consider the area of the model domain, the details on the focus area, the location of the oil spill source, and the estimated simulation time required. The domain of the hydrodynamic tsunami model and spill analysis with MIKE21 has a maximum mesh area in a tsunami-prone area of 625 m^2 and consists of 227,815 mesh and 114,464 nodes.

There are two-time scenarios for this hypothetical model, namely the west monsoon and the east monsoon. For the west monsoon, modeling was carried out in December and the east monsoon in June. These times were chosen because they were considered to represent conditions in the two seasons. Modeling was carried out for 24 hours with a time step of one minute resulting in 1440-time steps.

C. *Modeling Input Data*

Modeling input data obtained from various sources. Table 1 presented the input data that we used in this study.

TABLE I
MODELING INPUT DATA

No	Data	Value	Reference
1	Bathymetry	0 to -90 m from MSL (resolution 900 meter), data at the river and nearshore from field survey, and at the offshore from GEBCO	Survey and GEBCO [28]
2	Topography	0 to 180 m from MSL (resolution 180 meter)	DEMNAS [29]
3	Bed resistance (Manning Number M)	a. Seabed 40 m$^{1/3}$/s b. Land depending on land use (sand, swamp, soil: 32; grass 28, rice field 27; shrubs 26; moorland 23; settlements 17, mangroves 11 m$^{1/3}$/s)	a. [30] b. [31]
4	Wind	Time series for either west monsoon (0,9 – 9,1 m/s with dominant from southwest) or east monsoon (2,1 – 8,1 m/s with dominant from southeast), grid 0.125 x 0.125	[32]
5	River Discharge (constant)	a. Serayu (west monsoon 550 m^3/s and east monsoon: 250 m^3/s) b. Donan (west monsoon 310 m^3/s and east monsoon 86 m^3/s) c. Segara Anakan (west monsoon 300 m^3/s and east monsoon 100 m^3/s)	[33]
6	Oil spill parameters	a. Spill Location: CIB 1, CIB 2, and SPM (see figure 3) b. Spill volume: CIB 1: 135,000 ton; CIB 2: 135,000 ton and SPM: 300,000 ton. c. Spill discharge CIB 1 and 2: 8 m^3/s for 5 hours; SPM: 10 m^3/s for 10 hours d. Oil properties: crude oil (Density 831 kg/m3; Viscosity 6 cP; Volatile 50 %; Heavy 40 %, Wax 8 %, Asphalt 2%)	a. [34] b. [34] c. [34] d. [35]

Note:

a. CIB (Crude Island Berth): is a temporary oil storage facility originating from tankers before being distributed to refineries on land.

b. SPM (Single Point Mooring): is a floating structure located offshore that functions as a mooring and interconnection for tanker cargo or unloading gas or liquid products.

D. *Boundary Condition*

There are two boundary conditions in this study: the closed and open boundary condition. The closed boundary condition is a land that does not affect hydrodynamics, while the open boundary requirements are determined based on waters with hydrodynamic influences such as river flow, wind, tides, and tsunami waves. In the tsunami's hydrodynamic model, the boundary conditions in the open sea use the flather condition type [35]. The input data for open boundary conditions for tsunami conditions are obtained from the tsunami's model output using the TUNAMI model in the form of water level, u, and v velocity. In this hydrodynamic model, there are 6 open boundaries (see Fig. 3).

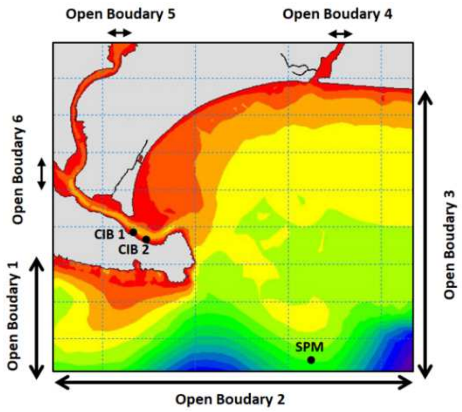


Fig. 3 The boundary condition of the domain for hydrodynamic and oil spill model with MIKE21.

Open boundaries 1, 2, and 3 use flather condition type with input in water level, u, and v velocity, while open boundaries 4, 5, and 6 represent river flow with discharge input.

E. Study scheme

The study begins by validating the data and models used. Validation is divided into two methods: validation of elevation with the NRMSE test and inundation validation with an overlay. The validation data uses data from the 2006 Pangandaran tsunami, which consists of elevation data measured at the Cilacap station [36] and maximum inundation data from a field survey [37], [38]. After the model was validated, tsunami modeling was carried out with TUNAMI, hydrodynamic tsunami modeling, and oil spill with MIKE21 using the specified scenario (see Fig. 4).

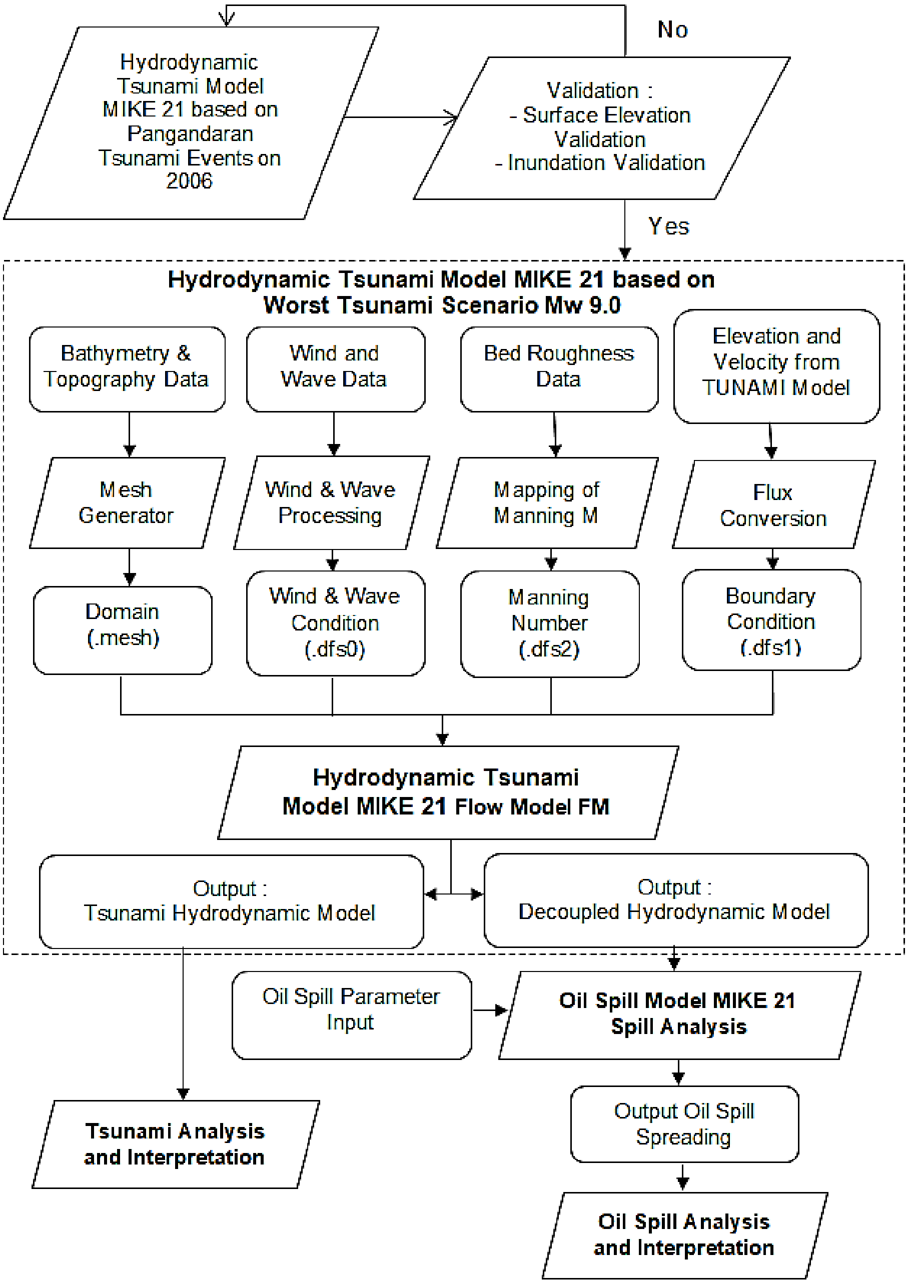


Fig. 4 Scheme of study

III. Results and Discussion

A. Validation of Sea Level for the 2006 Pangandaran Tsunami

The sea level comparison between the MIKE21, TUNAMI model results, and field data is shown in Fig. 5.

The results of the NRMS (Normalized Root Mean Square) test between the field data and the result of the MIKE21 model show the error percentage is 18.17%, the field data, and the TUNAMI model are 17.20%, and the MIKE21 and TUNAMI models are 6.39%. Based on this value, the MIKE21 and TUNAMI models' results can be accepted because the

NRMSE per cent error meets the requirements is below 20% [39].

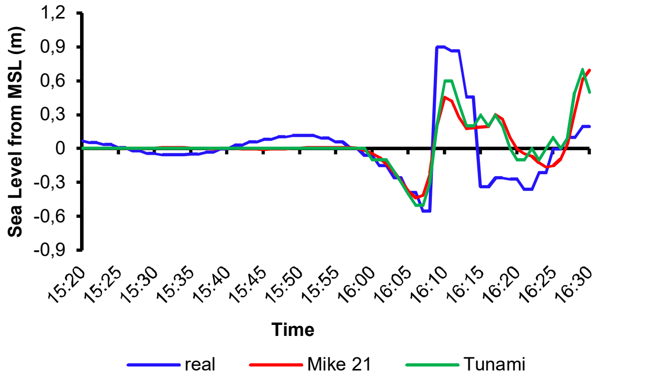


Fig. 5 Graph of comparison of sea level between field survey (blue), MIKE21 model (red), and TUNAMI model (green)

B. Validation of Maximum Inundation

Based on the results of the Agency for Assessment and Application of Technology Indonesia (BPPT) tsunami maximum inundation survey in 2006, there are several locations of maximum inundation that occurred in the Cilacap area (see Fig. 6).

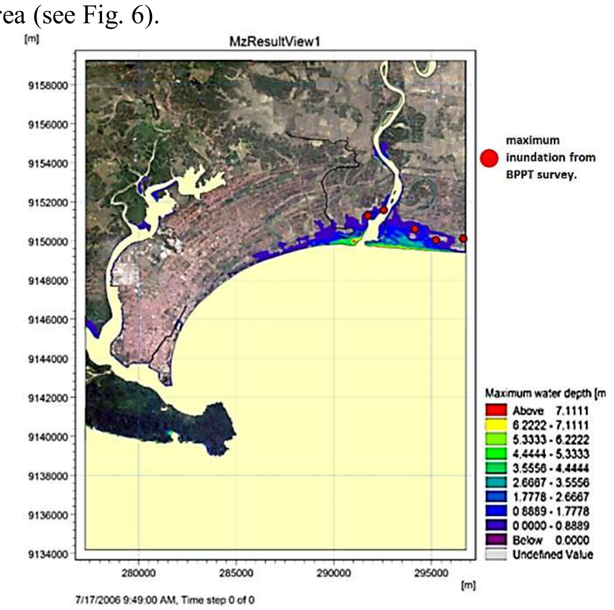


Fig. 6 Comparison between results of MIKE21 inundation model and BPPT survey

These locations are located in the eastern part of Cilacap around the Serayu River's mouth, to be precise in Baru Village, Wlahar Village, and Adipala Village [37]. The results of the MIKE21 tsunami run-up model for a deep inundation along the East Coast of Cilacap. Based on these results, it is known that between the maximum tsunami inundation point, the model results with MIKE21 are similar to the BPPT survey results (see Fig. 6).

C. Result of Modeling Tsunami Height and Maximum Inundation

From the TUNAMI model, the tsunami reached the boundary of the hydrodynamic model MIKE 21 for about 40 minutes. It reached the SPM location for about 43 minutes with a wave height of about 5.7 m. The maximum height of the tsunami waves when approaching the shoreline reaches approximately 8 meters to 32 meters. The area that experiences the maximum wave height is in the southern part of Nusakambangan Island. In this area, the height of the tsunami waves reaches more than 32 meters on the shoreline. For Cilacap and its surroundings, the wave height when it reaches the shoreline is between 8 to 16 meters. The maximum wave height is shown in Fig. 7.

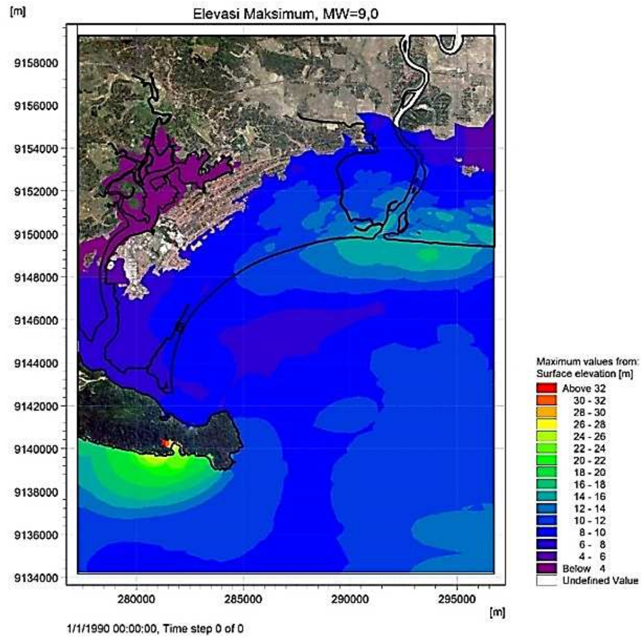


Fig. 7 Maximum wave height from the tsunami model with earthquake magnitude Mw 9.0

Fig. 8 shows the maximum inundation of the tsunami under a hypothetical scenario of magnitude 9.0. The inundation due to the tsunami waves reach approximately 2 to 6 km from the shoreline. The areas with the furthest inundation are the Serayu River Estuary and Donan River. In this area, the inundation reaches 6.2 km.

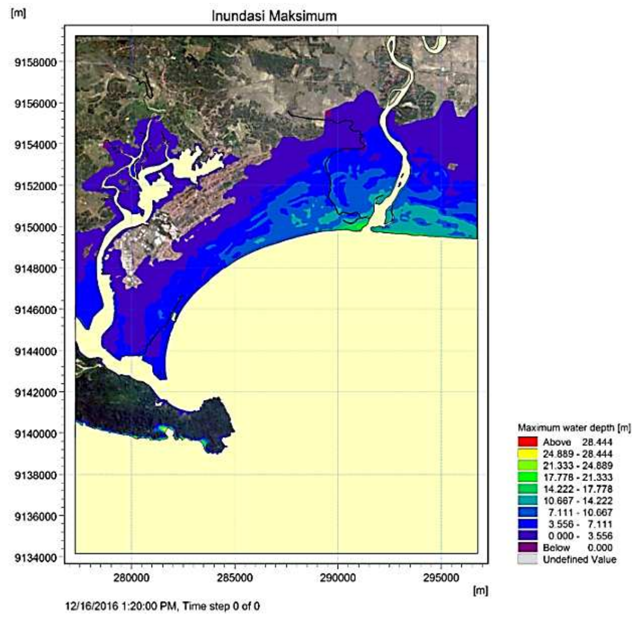


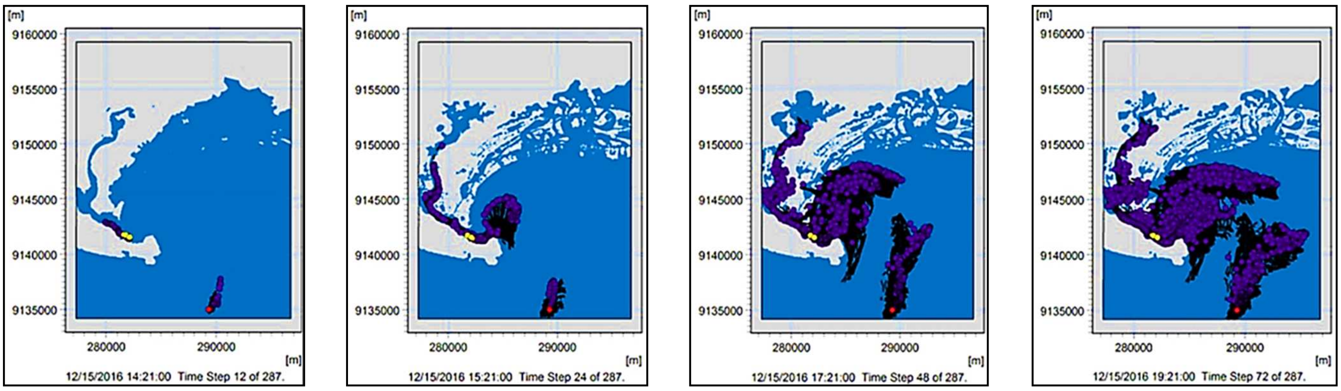
Fig. 8 Maximum tsunami inundation from tsunami model with earthquake magnitude Mw 9.0

D. Results of Oil Spill Modeling

The modeling of the oil spill distribution due to the tsunami is divided into two scenarios of wind conditions: the west monsoon, which was modeled on December 15, 2016, and the east monsoon, which was modeled on June 26, 2017. This division of wind conditions aims to see the difference in the direction of the distribution of the oil spill that occurred between the conditions of the west monsoon winds and the east monsoons are due to the two scenarios that the wind conditions are very different. The following figure shows the pattern of oil spill distribution at the 1st, 3rd, and 6th hours after the earthquake in both the west monsoon (see Fig. 9) and the east monsoon (see Fig. 10). Fig.11 show the comparison of the scheme of oil spill spreading pattern between west and east monsoon.

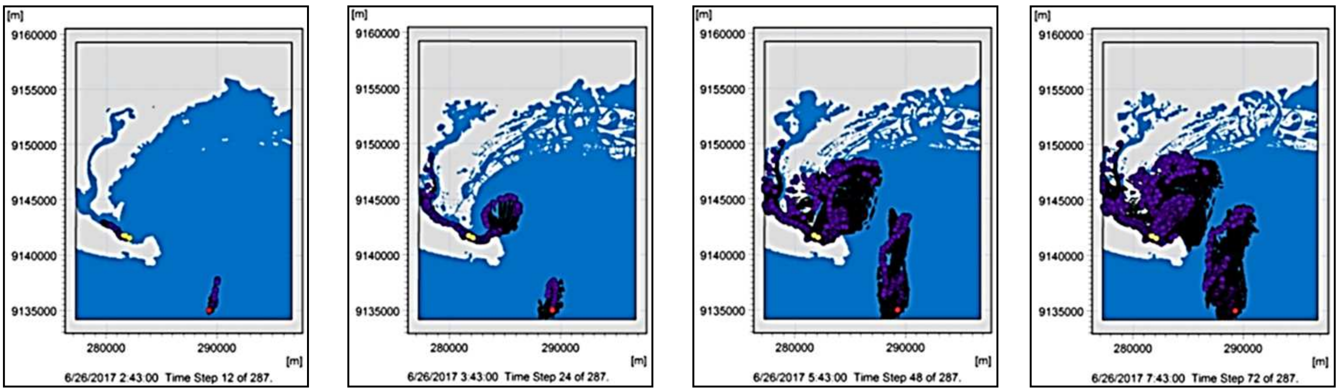
In general, the distribution of oil spills in the west and east monsoon scenarios has a similar distribution pattern. The oil spill in two scenarios is carried along the currents generated by the tsunami waves towards the shoreline. This result is different from another research, which states that oil spills' distribution in east and west monsoon is significantly different. In the west monsoon, the oil spills spread to the southeast and east monsoon to the west [3], [4]. The oil spill distribution due to the tsunami is also less affected by tidal conditions, unlike the results of Widhayanti's study [20], which states that tidal conditions significantly affect oil distribution spills.

The maximum current velocity generated by the tsunami waves reaches 6.4 m/s. This velocity has a significant effect on the spread of oil spills. According to Fingas, the spread of the oil layer at sea level is greatly influenced by surface currents. If the oil layer is close to land where the wind speed is less than 2.8 m/s, it will spread 100% with the surface currents. The wind's influence on the oil layer under these conditions is not more than 3% [40].



(a) 1 hour after the earthquake (b) 2 hours after the earthquake (c) 4 hours after the earthquake (c) 6 hours after the earthquake

Fig. 9 Pattern of oil spill distribution during the west monsoon



(a) 1 hour after the earthquake (b) 2 hours after the earthquake (c) 4 hours after the earthquake (c) 6 hours after the earthquake

Fig. 10 Pattern of oil spill distribution during the east monsoon

Although the oil spill between the two wind scenarios is equally carried by the currents approaching the shoreline, there is a slight difference in the distribution of the oil layer caused by the wind. This slight difference occurs because the wind also contributes to the spread of the oil layer on the surface [35]. According to Fingas [40], wind affects the spread of the oil spill only about 1% - 6% of the actual wind speed, and the rest is influenced by surface current conditions. In the west monsoon, wind conditions predominantly blow from the southwest to the east and northeast with speeds reaching 9.1 m/s causing the oil spill carried by the tsunami wave in the west wind scenario to spread slightly to the east. Meanwhile, in the east monsoon, the wind is blowing from the southeast to the west and southwest at 8.1 m/s. This wind causes the tsunami wave's oil spill in the east wind to spread slightly to the west.

The west monsoon occurs from December to February. When the west monsoon occurs, winter in Asia causes the area's pressure to increase so that the wind moves from Asia to Australia. The east monsoon occurs from June to August due to winter in Australia. The pressure increases in the area and causes the wind to move from Australia to Asia, while the transitional season occurs between the two seasons [41].

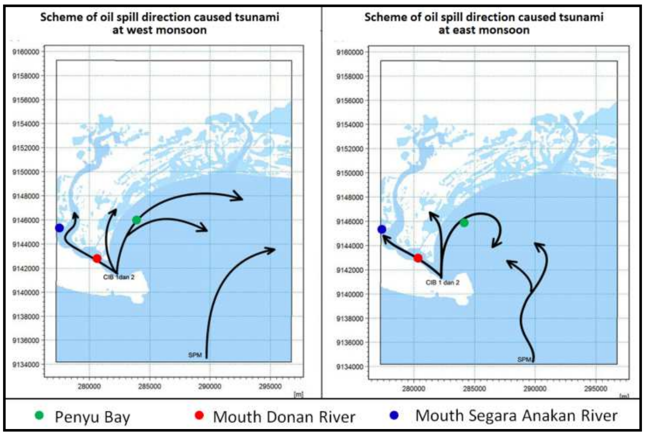


Fig. 11 Comparison of the oil spill distribution due to tsunami between west and east monsoon

The thickness of the oil spill spread for 6 hours after the earthquake ranged from 0.001 mm to 0.26 mm. In the spill source's vicinity, the thickness of the oil spill has a higher value, reaching 700 mm. The thickness of the oil layer is related to the process of spreading. The occurrence of the spreading process is influenced by several factors, including the type of oil, volume, oil viscosity, temperature, surface turbulence, wind, and currents [35], [40], [42]. In the case of oil spills common in Cilacap waters, the spread of oil spills tends to be slower than when the tsunami occurred. At 5 hours after the spill in normal conditions, the thickness of the oil layer ranged from 0.052 - 0.1561 mm [4]. This result is due to hydrodynamic factors such as wave height, current velocity, and turbulence when normal conditions are not as large as during tsunami conditions.

In the west monsoon scenario, the oil spill reaches the Teluk Penyu coast 121 minutes after the earthquake (or 78 minutes after the oil starts spilling). Oil spill reaches the Donan River at 80 minutes after the earthquake (or 37 minutes after the oil starts spilling) and reaches Segara Anakan Estuary at 170 minutes after the earthquake (or 137 minutes after the oil started spilling). The oil layer reaches Teluk Penyu coast at 121 minutes after the earthquake or 78 minutes after the oil starts spilling in the east monsoon scenario. Oil spill reaches the Donan River at 190 minutes after the earthquake or 147 minutes after the oil starts spilling and reaches Segara Anakan Estuary at 70 minutes after the earthquake or 27 minutes after the oil started to spill.

This finding is different from other researchers' results, where the oil spill from SPM will reach Teluk Penyu coast and the mouth of the Donan River after more than 5 hours after the oil starts to spill [4].

The graph of the arrival time comparison of the oil spill in the west monsoon and east monsoon scenarios is shown in Fig. 12 and Fig. 13.

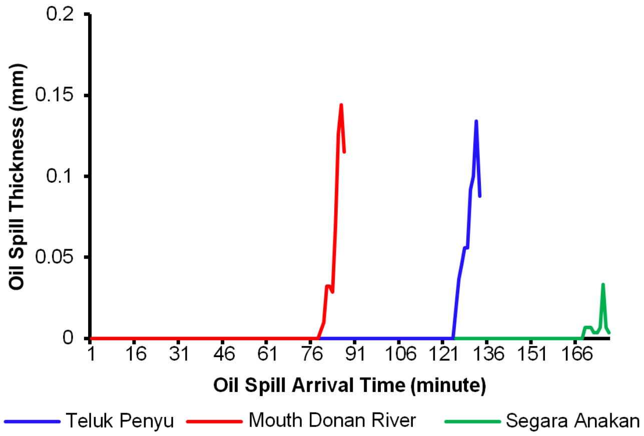


Fig. 12 Comparison of oil spill arrival times in the west monsoon scenario

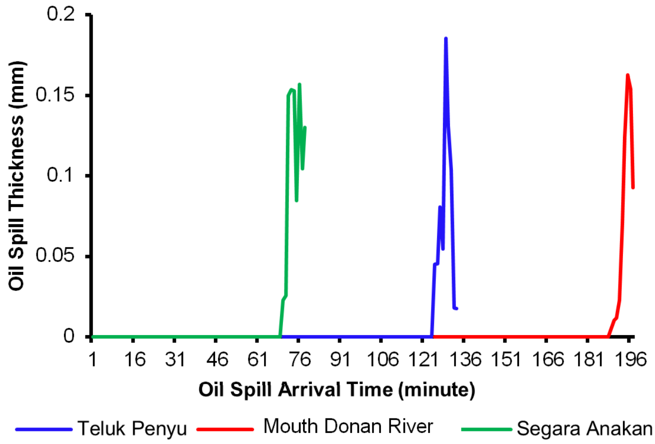
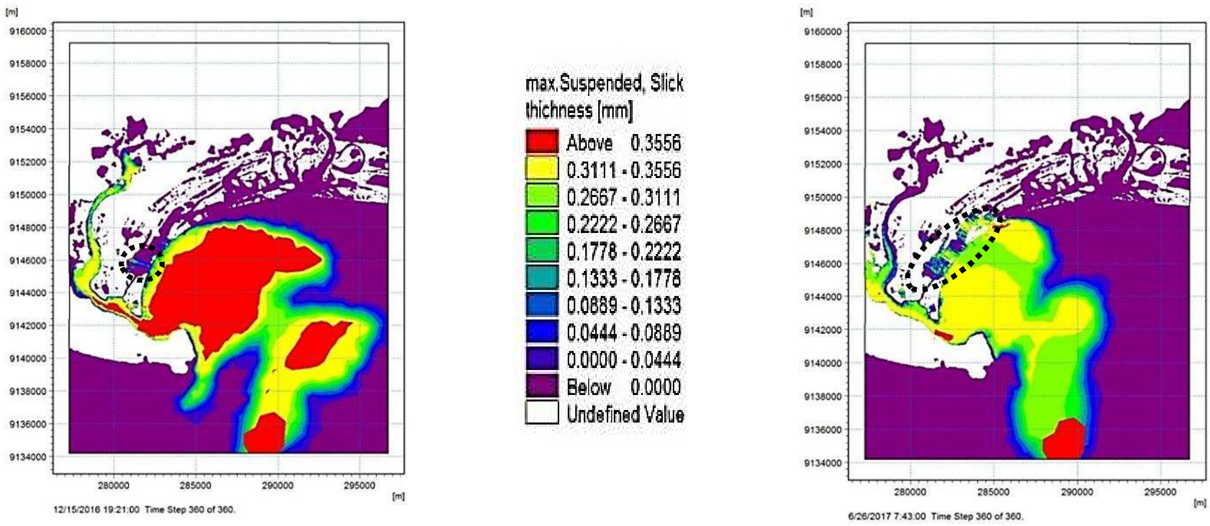


Fig.13 Comparison of oil spill arrival times in the east monsoon scenario

Differences in wind direction cause the difference in arrival time between the two scenarios. In the west monsoon scenario, the wind blows from the west so that the oil spill is blocked from entering Segara Anakan Estuary, which is located in the west. The oil spill tends to turn towards the mouth of the Donan River to the north. In the east monsoon scenario, the wind that comes from the east pushes the oil spill directly into Segara Anakan Estuary. The resultant between the tsunami wave currents and the east wind causes the oil to tend to the west and enter the waters of Segara Anakan Estuary.

Meanwhile, the arrival time of the oil spill in Teluk Penyu between the two scenarios does not experience a significant difference because the waters of Teluk Penyu are close to the open seas. The influence of the wind on the direction of oil distribution tends to be small.

Based on the West monsoon's modeling results, it is known that oil spreads to fill the Teluk Penyu waters, and some are even carried over to the mainland for more than 1 km, especially on the north coast of Teluk Penyu. Besides, oil also spreads far upstream of the Donan River. The overall average spill thickness of the spill was 0.35 mm meters (see Fig. 14a). Meanwhile, the distribution is relatively the same in the eastern monsoon, but the oil carried to the mainland is much broader in scope. Besides, oil also spreads to the mouth of the Donan River and into Segara Anakan Estuary. The overall average spill thickness of the spill was 0.32 mm.



(a) (b)

: indicate an oil spill that has entered the land

Fig. 14 Area affected by oil spill during 6 hours after an earthquake in (a) west monsoons scenario, (b) east monsoons scenario

IV. Conclusion

The direction of the oil spill spread in both the west monsoon and the east monsoon due to the tsunami is dominated by the tsunami waves' current caused; the wind has little effect. The broader and farther the oil spill spread, the thickness of the oil spill was getting thinner. The arrival time of the oil spill on the Cilacap coast due to the tsunami was faster than ordinary oil spills. The oil spill caused by the tsunami can reach the mainland as far as 1 km, especially on the north coast of Teluk Penyu. The oil spill can also reach and pollute the Donan River's upstream and the coastline along Nusakambangan Island. When combined with the map of the environmental sensitivity index to oil spills, the results of this study can be used by the government as a consideration for making contingency plans for oil spill response in Cilacap. The next potential study is the impact of the tsunami force on the oil storage tank.

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Author's Contributions

The author(s) declare(s) that there is no conflict of interest regarding the publication of this article. The authors confirmed that the data and the paper are free of plagiarism. In carry out this study and write this paper, **all the authors are the main contributor.** R.H. preprocessed data, set up and run model, and analyzed data; M.W. provided data, made scenarios modeling, analyzed data; A.S. analyzed data. All authors reviewed this manuscript.

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