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Muhammad Hafiz Aslami[1,a*], Oki Setyandito[1], Farell[1], Anggita Prisilia Soelistyo[1], Sarah Ananda Nabilah[1]

Department of Civil Engineering, Faculty of Engineering, Bina Nusantara University, Jakarta, Indonesia

[a] muhammad.hafiz004@binus.ac.id

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Abstract. Detached breakwaters, commonly used to mitigate coastal erosion, can lead to significant sedimentation issues when employed as protective structures near ports. These issues often result in tombolo formation, which can severely disrupt port operations. This study examines a case at a port in southern Java, where the use of a detached breakwater caused a complete operational shutdown. Through simulations conducted with GenCade, the sedimentation process was modelled to identify the conditions leading to tombolo formation. Based on these findings, alternative design solutions are proposed to prevent similar problems in the future. The results highlight the need to avoid the use of detached breakwaters for port protection, emphasising that this approach represents a fundamental error in coastal engineering. More suitable coastal structures should be encouraged to ensure the effectiveness of port operations.

Introduction

Coastal areas are ever-changing environments influenced by both natural forces, such as wave action and sediment transport, and human interventions, like the construction of coastal defence structures. To mitigate coastal erosion and protect infrastructure, coastal engineering projects often involve the installation of structures such as breakwaters, groynes, jetties, and seawalls [1, 2]. These interventions, however, can significantly alter local geomorphological processes, leading to unintended consequences that may complicate or undermine their intended functions [3]. One of the examples is using a detached breakwater to protect the port area.

Detached breakwaters are commonly used to reduce wave energy and control coastal erosion. Positioned parallel to the coastline but separated from it, they encourage sediment deposition behind them, often resulting in the formation of salients or tombolos [4]. While these landforms can be beneficial in certain contexts, such as beach stabilisation and enhancing tourism potential, they pose significant problems when constructed in front of port areas. The accumulation of sediment can obstruct navigation channels, impede port operations, and require costly dredging efforts to maintain access.

In contrast, conventional (attached) breakwaters, which extend from the shore into the sea, are designed to protect harbour basins and access channels by blocking strong wave action [5, 6]. This allows vessels to dock and manoeuvre safely within the port, ensuring the continuous operation of maritime activities. Although both conventional and detached breakwaters are often built using similar materials, their differing placements result in vastly different impacts on coastal processes and sediment transport patterns [7].

(a) November 2015 (b) May 2022

Fig. 1: Coastal zone conditions before (a) and after (b) construction of the port and detached breakwater.

Fig. 2: Field investigation photo showing the view from the eastern part of the detached breakwater towards the northwest.

A significant issue arises when detached breakwaters are used to protect port areas, as shown in Figure 1. The figure illustrates the coastal conditions before and after the construction of port infrastructure. Sediment accumulation behind these structures can eventually form a tombolo, connecting the breakwater to the shoreline. The photo from field investigation is shown in Figure 2. This landform can obstruct the navigational routes, rendering the port inoperable and requiring extensive dredging to restore access. However, such efforts are temporary, as natural sedimentation processes may cause the tombolo to reform, making long-term maintenance unsustainable [4].

This study investigates a real-world case where the construction of a detached breakwater at a port in southern Java, Indonesia, led to the formation of a tombolo, severely disrupting port operations (see Fig 1). By employing GenCade [8, 9], a numerical model that simulates shoreline changes and sediment transport, this study aims to understand the underlying mechanisms behind tombolo formation. GenCade builds on the capabilities of GENESIS [10] and Cascade [11], offering a more comprehensive tool for coastal engineering and management. It excels in simulating longshore sediment transport and predicting shoreline evolution under various conditions, including the effects of climate change and human interventions [12]

Through the application of GenCade, this study provides insights into the impact of detached breakwaters on shoreline dynamics and port operations. The findings highlight the importance of selecting appropriate coastal engineering solutions based on a thorough understanding of the interactions between coastal structures, wave dynamics, and sediment transport processes. This understanding is crucial for developing sustainable strategies that protect both coastal environments and the economic activities that depend on them.

Methodology

This section outlines the methodology of this study, starting with a description of the study area and its current conditions. Field data collected for the numerical simulations are detailed, followed by a discussion of the numerical tool GenCade, including its parameters, input data, and calibration process.

Study area

The study area is located in Southern Java, Indonesia, where a new port was designed and constructed with a detached breakwater for protection from waves. This coastal region experiences strong wave action from the Indian Ocean and sediment transport processes, resulting in significant shoreline changes, particularly tombolo formation due to inappropriate coastal structure. The study focuses on the adverse effects of the detached breakwater on port operations, using a numerical tool calibrated with field data.

Field data

Field data collection involved an extensive survey of critical parameters essential for understanding shoreline changes and coastal dynamics within the study area. The primary data sets acquired include bathymetric measurements, topographic profiles, tidal observations, and sediment transport data. These measurements were fundamental in developing accurate models and calibrating them to replicate real-world conditions effectively.

Bathymetric data were collected using an echo sounder to map the underwater terrain, with the survey extending across the area surrounding the port. Additionally, topographic data were obtained to measure land elevation along the coastline, contributing to the understanding of coastal morphology and potential changes over time. Tidal measurements were carried out using tidal gauges positioned

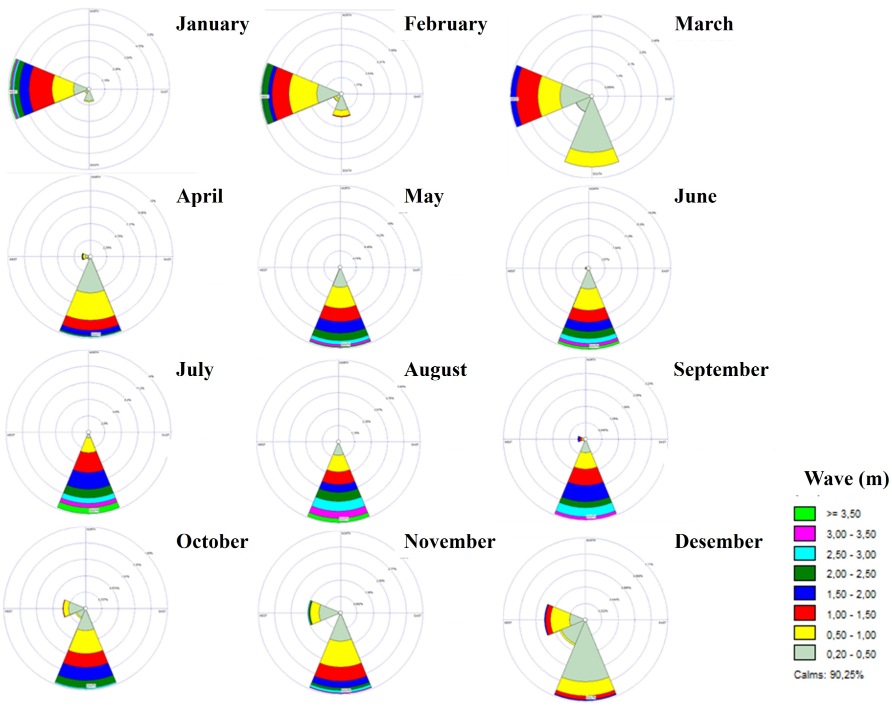


Fig. 3: Wave data after the hindcasting procedure.

at various locations within the study area. These gauges recorded water levels over a specified period, providing valuable insights into tidal ranges and patterns. The tidal data were used to calibrate the bathymetric measurements and establish key tidal elevations, such as Mean Sea Level (MSL), Mean High Water Springs (MHWS), Mean Low Water Springs (MLWS) etc. These benchmarks were crucial for the future design of coastal structures, ensuring alignment with local tidal conditions.

Current data were measured using the OSS B1 universal current meter, which provided detailed information on water movement within the study area. Suspended sediment samples were collected at different depths using water samplers, while bedload sediment data were gathered through grab sampling techniques. These sediment data sets were important in assessing sediment transport dynamics and served as key inputs for numerical models simulating shoreline changes. Collectively, these field data form the foundation for modelling efforts aimed at predicting shoreline changes due to the detached breakwaters.

Secondary data

To predict shoreline changes, historical wave data were required. However, since field wave data were unavailable, wind data were utilised as a substitute. Wind data spanning from 2013 to 2022 were obtained from the European Centre for Medium-Range Weather Forecasts (ECMWF) as secondary data. These data were employed for surface-wave hindcasting, using the Sverdrup-Munk-Bretschneider (SMB) method to estimate wave height and direction based on fetch calculations. The derived wave data were then used as input for simulating wave propagation from the deep sea to the port zone using the CGWAVE model. It should be noted that the CGWAVE simulation is beyond the scope of this paper.

The results from the CGWAVE simulations were subsequently utilised as input parameters for the GenCade model. CGWAVE was chosen over direct hindcasting due to the harbour's location,

(a) Across the domain

(b) Zoomed to the area of interest

Fig. 4: Initial setup for GenCade modelling (before the new port existed).

which is somewhat sheltered within a bay, making direct hindcasting less accurate. Wave analysis was conducted monthly over one year, with the process repeated in subsequent years. The wave-rose resulting from this analysis is shown in Figure 3, with the data processed monthly.

GenCade model

The GenCade modelling process began with determining the initial shoreline. A georeferenced satellite image from Google Earth, captured in August 2017 before the construction of the new port, was imported into the software interface (see Figure 4). From this image, the initial shoreline (represented by the red line), regional contour (yellow line), and detached breakwater (orange) were delineated. The red circle indicates the location of the assigned wave data, where only one point was used. The green grid lines represent the one dimensional (1-D) computational grid, with a denser concentration near the area of interest to enhance computational efficiency. Both ends of the shoreline were assumed to remain fixed at their initial positions throughout the simulation. The effective grain size, determined from sediment samples, was 0.2 mm. It is important to note that during the simulation period, no beach nourishment, dredging, or bypassing activities were considered.

Result and discussion

We began the analysis by calibrating the parameters in the GenCade model by comparing the numerical results with actual field conditions. Once the model was calibrated, the software could then be used to design alternative solutions to restore port operations.

Model calibration

Model calibration is conducted to make sure that some assumed parameters are correctly assigned to represent the real phenomenon being studied. In this research, we modelled shoreline changes caused by a detached breakwater, closely following the actual layout of the coastal area. The simulation begins with an initial shoreline configuration that represents conditions before the construction

(a) Aug 2017: initial condition

(b) Oct 2017: after 2 months

(c) Oct 2018: after 1 year

(d) Oct 2019: after 2 years

(e) Oct 2020: after 3 years

(f) Oct 2021: after 4 years

(g) Jun 2038: after 21 years

(h) Shoreline envelope (green area)

Fig. 5: Simulation results showing the formation process of a salient and tombolo behind the detached breakwater (Red line: current shoreline, Yellow line: initial shoreline, Orange line: detached breakwater, Green line: 1-D numerical grid).

Fig. 6: The accelerated forming of tombolo due to the backfill for material access roads during the construction period (September 2018) that is not modelled in this study.

of a new port. The model was run for a period of up to 20 years, using a computational timestep of 1 hour, to capture the long-term impacts on shoreline dynamics.

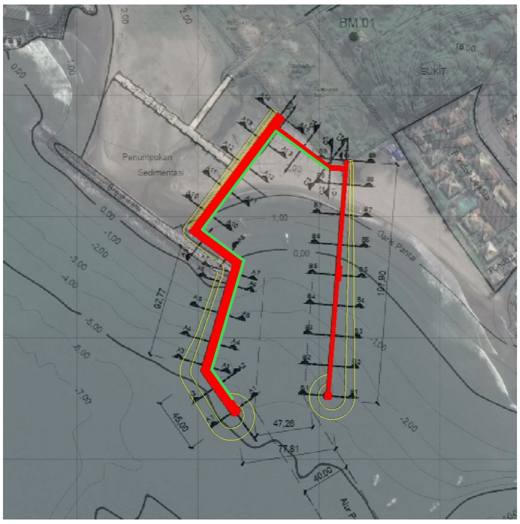
The calibration process employed a trial-and-error approach. The key parameters adjusted during calibration were the closure depth and the longshore sediment transport coefficients, K1 and K2 [10]. Other parameters, such as the berm height, were kept constant at 1 meter based on topographical data. After multiple iterations, the optimal values were determined to be K1=0.5, K2=0.25, and a closure depth of 10 meters. These values provided the best fit for simulating shoreline changes in the study area.

Figure 5 presents the simulation results of shoreline changes behind a detached breakwater over 20 years. The initial condition in August 2017 shows an undisturbed shoreline before the breakwater was constructed. Two months after construction, a salient begins to form as sediment accumulates in the sheltered zone behind the breakwater. By October 2018, after one year, this salient becomes more pronounced, and after two years, a tombolo starts to develop, indicating significant sediment deposition connecting the shoreline to the breakwater. By the fourth year, the tombolo is well established, altering the coastal landscape. The long-term simulation, shown in June 2038, demonstrates that the shoreline continues to stabilise, with the tombolo firmly in place. The final image highlights the shoreline envelope, showing the range of shoreline positions over the simulation period. These results emphasise how the detached breakwater influences sediment transport and shoreline morphology, leading to significant shoreline changes and highlighting the need to consider the long-term impacts of such structures in coastal management.

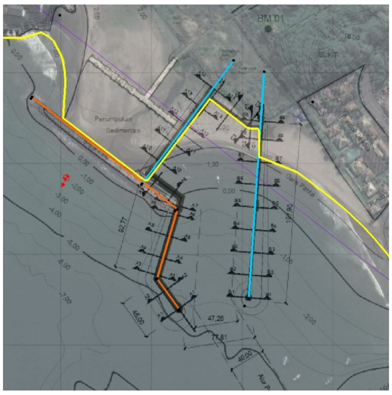
An important note is that, in reality, a tombolo formed within just one year, which is faster than the predictions made using numerical methods. This accelerated formation can be attributed to the construction fill used for the road that transported breakwater armour materials to their designated location during the construction phase (see Figure 6). Furthermore, the actual wave conditions are more dynamic, whereas the GenCade model simulates these with a simplified monthly variation.

Alternative engineering solutions

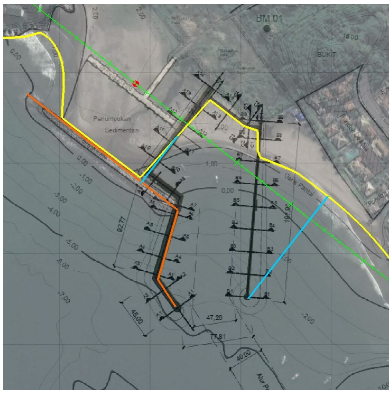
In this study, we present a single alternative from several proposed designs, which we believe is the best option given the constraints of cost and the urgency of starting port operations. Although this



(a) Additional structures

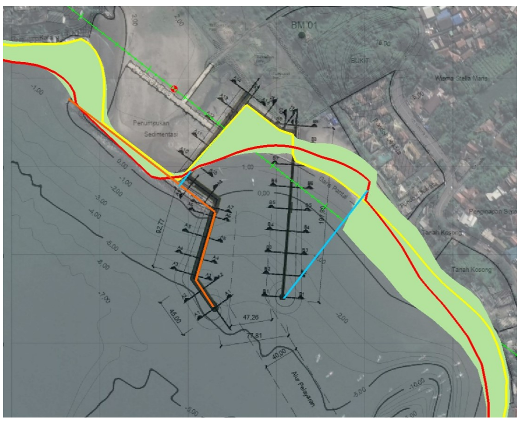


(b) Schematic design

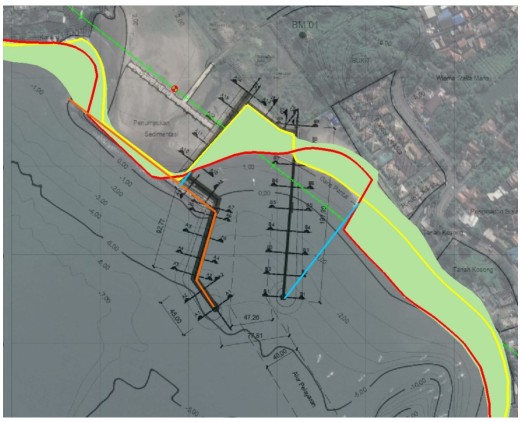


(c) Schematic design projected onto 1-D grid

Fig. 7: Initial setup of GenCade modelling for the proposed alternative design.



(a) Dominant wave from West



(b) Dominant wave from South

Fig. 8: Shoreline prediction after 20 years for the proposed alternative design.

design may not be the ideal choice from an engineering perspective, it is essential to consider the limitations imposed by funding constraints.

The new design, as depicted in Figure 7a, extends the eastern section of the original breakwater by 138 meters towards the open sea, with the endpoint positioned at a seabed elevation of -5 meters. Additionally, a connecting structure is introduced to link the breakwater to the mainland. To further protect the port from wave action and sediment transport, a 198-meter-long groyne is constructed on the opposite side. In this design, the old pier is no longer operational but can still be utilised as part of the port's land facilities. The new docking area is located inside the newly extended breakwater and stretches to the shoreline, marked by a green line in Figure 7a. Dredging of sediment in the basin and docking areas will also be necessary to ensure the port's operability.

Figure 7b illustrates the schematic design of the new structure, depicted as lines within the model, while Figure 7c presents the schematic design after it has been projected onto the 1-D computational grid (indicated in green). Although this projection process may introduce some inaccuracies, especially for the groyne structure, it is nevertheless a more practical and viable approach for long-term simulations, such as the 20-year duration considered in this study. The yellow line represents the initial shoreline following the implementation of the new design and subsequent dredging activities. With these preparations complete, the setup is now ready for simulation.

The simulation results are shown in Figure 8, where the red line represents the current shoreline and the green area indicates the shoreline envelope over the 20-year simulation period. After 20 years, assuming no maintenance dredging, the shoreline has remained dynamically stable. Throughout the year, the wave direction is predominantly from the south and west. When the dominant wave direction is from the west, the shoreline appears as in Figure 8a, whereas when the dominant wave direction is from the south, the shoreline resembles Figure 8b. This condition repeats annually, following the wave patterns. Most importantly, sedimentation in the port operational area is negligible. With regular maintenance dredging, sedimentation can be minimised.

There are several other considerations for the coastal environment outside the port area. To the east of the groyne, there is a possibility of beach erosion, which could threaten the local residential area. Therefore, coastal reinforcement or revetment is necessary. Additionally, on the western side of the tombolo, the shoreline is also dynamically stable, meaning it will continuously advance and retreat. This will not affect the tombolo area, which is planned to be used as a supporting facility for the port on land.

Conclusion

In this study, we have analysed the impact of detached breakwaters on coastal erosion and sedimentation processes, particularly their effects when implemented near port areas. The use of detached breakwaters, while effective in promoting land formation through salient or tombolo creation, has proven to be a flawed design choice for port protection. A case study from southern Java illustrates how such structures can lead to significant sediment accumulation, rendering ports inoperable and necessitating extensive dredging operations to maintain navigational access.

Using the GenCade software, we successfully simulated the formation processes of tombolos and calibrated our model to reflect real-world conditions. Our findings underscore the urgent need for alternative designs that mitigate sedimentation while ensuring the operability of port facilities. The proposed design layout demonstrates a more sustainable approach, utilising both extended breakwaters and groynes to manage wave action and sediment transport effectively.

Based on this study, our recommendations for future coastal engineering projects include:

- Avoid detached breakwaters near ports: As demonstrated, these structures can lead to severe operational disruptions due to sedimentation.
- Implement regular dredging practices: While some sedimentation is normal, regular dredging can maintain navigational channels and prevent build-up.
- Utilise advanced modelling tools: Tools like GenCade can help predict sediment transport and shoreline changes, aiding in better design decisions.
- Conduct comprehensive site assessments: Prior to construction, thorough assessments of local wave dynamics and sediment transport processes are essential.
- Consider alternative structures: Instead of detached breakwaters, look into conventional breakwaters or hybrid systems that may offer better protection for ports.
- Engage in continuous monitoring: After implementation, ongoing monitoring of the coastal environment can identify emerging issues before they escalate.
- Incorporate community feedback: Local stakeholders can provide valuable insights into historical coastal dynamics, informing future designs.
- Prioritise sustainable practices: Designs should consider long-term environmental impacts and promote ecological health alongside infrastructural development.

By adopting these insights and recommendations, future coastal engineering projects can avoid selecting inappropriate coastal structures that do not fulfil their intended functions, thereby preventing significant losses and ensuring effective and sustainable infrastructure development.

Authorship contribution statement

Muhammad Hafiz Aslami: Conceptualisation, Methodology, Software, Formal analysis, Visualisation, Writing - Original Draft. **Oki Setyandito:** Investigation, Supervision, Writing - Review & Editing. **Farell:** Software, Writing - Review & Editing. **Anggita Prisilia Soelistyo:** Software, Writing - Review & Editing. **Sarah Ananda Nabilah:** Software, Writing - Review & Editing.

Data availability

M. H. Aslami and . oki . setyandito, 'Topographic and Bathymetric Map of Pelabuhanratu - LWS Elevation Reference'. Zenodo, Sep. 09, 2024. doi: 10.5281/zenodo.13733776.

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