Indonesian Geotechnical Journal, April 2026, Vol 5 (1). Page 43-54
DOI: https://doi.org/ 10.56144/igj.v5i1.142
EISSN: 2829-7520
https://indonesian-geotechnical-journal.org/index.php/JGI/issue/archive

Implementation of Sludge-Filled Geotextile Tubes as a Sustainable Coastal Protection Measure in Muddy Coastline

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SUBMITTED 19 January 2026 **REVISED** 25 April 2026 **ACCEPTED** 29 April 2026

ABSTRACT Coastal erosion is one of the major challenges faced along the northern shoreline of Java Island. This phenomenon results in degradation of the coastline, threatening not only the local ecosystems but also the livelihoods of coastal communities. The soft, muddy coastal characteristics of this region make conventional hard-engineering structures less effective and unsustainable, prompting the need for alternate solutions. This study aims to evaluate the effectiveness of sludge-filled geotextile tubes (GI-Tubes) as an erosion control measure in muddy coastal areas. A field experiment was conducted using three GI-Tube units, each measuring 1.3 meters in height and 20 meters in length, installed parallel to the shoreline. The GI-Tubes were made from double-layered needle-punched staple fiber polypropylene non-woven geotextile and filled with locally sourced sludge mixed with flocculants to promote effective sediment floc formation within the tubes. The small opening size of the non-woven geotextile facilitated efficient dewatering while retaining the sludge inside. The outer layer of the GI-Tube provided high UV resistance and enhanced sediment-trapping capability, offering additional protection and extended durability. The double-layered design of the geotextile tubes enhances their overall structural integrity, enabling them to withstand hydrodynamic forces such as wave and coastal currents. After five months, a height reduction of approximately 0.4 meters was observed, likely due to settlement of the sludge filling. Monitoring conducted 2 years after installation indicated that the sludge fill remained solid and well-consolidated with no sign of damage, thereby confirming good performance of the structure. Satellite imagery analysis 40 months post installation indicated shoreline accretion accompanied by a significant expansion of mangrove growth, reaching up to 50 m beyond the initial vegetation line. These findings suggest that sludge-filled GI-Tubes can be an effective, low-cost, and sustainable solution for mitigating coastal erosion in soft-soil coastal environments.

KEYWORDS Geotextile Tube; Sludge Dewatering; Flocculant; GI-Tube; Sludge Filled Geotextile Tube; Coastal Erosion

1 INTRODUCTION

The northern coastal corridor of Java plays a pivotal role in the transportation network, logistics systems, industrial development, and the socioeconomic dynamics of coastal regions endowed with abundant natural resources. With numerous industrial complexes, aquaculture ponds, agriculture, and extensive public and transportation infrastructure, the northern coastal corridor of Java holds significant strategic value for the economic development of coastal communities. However, the sustainability of this coastal infrastructure is increasingly threatened by environmental degradation, particularly coastal erosion, which contributes to the progressive loss of shoreline and the degradation of vital coastal assets.

The coastal characteristics of the northern coast of Java can be classified into four types: sandy coast, muddy coast, gravelly coast, and areas dominated by coastal protection and infrastructure. The muddy coast, which includes mangroves, mudflats, and salt marshes, is extensively distributed across regions such as Serang, Tangerang, North Jakarta, Bekasi, Subang, Cirebon, Brebes, Semarang, Demak, and Pati. (Solihuddin, et al., 2021). The rate of shoreline changes due to erosion along this type of coastline, particularly in the Cirebon area, can reach up to 78 meters per year (Triana, et al., 2023), resulting in significant loss of coastal land. This accelerated erosion has led to the depletion of the shoreline, underscoring the urgent needs of mitigation measures to prevent further degradation and preserve coastal integrity.

There are many methods to prevent coastal erosion, one of which involves the use of geotextile tubes functioning as low-crested breakwaters. On sandy coastlines, the primary concern is the prevention of further erosion, whereas on muddy coasts, the focus shifts toward mangrove rehabilitation and ecosystem conservation (Lee et al., 2014). Numerous studies on the use of geotextile tubes for coastal protection have demonstrated promising results, indicating their potential as an effective and sustainable erosion mitigation strategy (Alvarez et al., 2007, Ashis, 2015, Lee et al., 2010, Lee et al., 2014, Lim & Siew, 2022, Nugroho et al., 2021, Shin & Oh, 2007, Shin & Kim, 2018).

One of the common constraints encountered in the construction of geotextile tubes is the selection and availability of suitable filling material. Sand has been demonstrated to be an effective infill due to its fast-filling process, its rapid settling characteristics, and its minimal dimensional reduction upon consolidation. However, in muddy coastal environments, the availability of sand is often limited, requiring its transportation from external sources, which can increase project costs, logistical complexity, and increase carbon footprint. One viable solution to the sand shortage is utilizing locally available mud through sludge dewatering techniques.

Sludge dewatering involves the pressurized pumping of liquid slurry into geotextile tubes, allowing the contained slurry to undergo dewatering over time. This process is repeated in multiple cycles until it settles to the desired dimensions (Lawson, 2008). This method requires geotextile materials with sufficient tensile strength to withstand the internal pressures generated during pumping. This technique has been widely adopted globally, not only for hydraulic and marine applications but also for the containment of contaminated sludge.

This study aims to assess the performance of an innovative coastal erosion mitigation approach employing double-layered geotextile tubes filled with flocculated sludge. The evaluation will focus on assessing structural durability, sediment trapping capacity for shoreline accretion, and the role of the system in facilitating mangrove growth.

2 PROJECT AREA

A pilot project was conducted to evaluate the effectiveness of sludge-filled geotextile tubes in mitigating coastal erosion in muddy coastlines. The project site was located at Mundu Beach, Cirebon, Central Java, an area characterized by muddy coastal conditions (Figure 1). Three geotextile tubes—hereafter referred to as GI-Tubes—were installed, each with a designed circumference of 5 meters, a length of 20 meters, and a target height of 1.3 meters. The tubes were arranged in a continuous row, with overlapping ends to ensure no gaps between individual GI-Tubes. The total installed length of the structure was approximately 60 meters.

Figure 1. Satellite image of project area

The performance of the tubes was evaluated based on these primary aspects: settlement of the GI-Tube structure, changes in shoreline accretion and mangrove growth post installation, as well as structural and material durability over the monitoring period. Structural settlement was evaluated through direct field measurement of the GI-Tubes. The effects of GI-Tubes on shoreline morphology and mangrove growth were assessed through periodic site inspections and satellite imagery. Durability of the double-layered geotextile material was evaluated through regular visual inspections throughout the monitoring period.

3 MATERIALS

When dewatering high water content materials using geotextile tubes, the primary performance criterion is dewatering capacity, which includes both dewatering efficiency—defined as the ability to achieve a high final solids content—and dewatering rate, referring to the time required to complete the dewatering process (Berilgen et al., 2016). The geotextile tube material should demonstrate sufficient dewatering capacity to accelerate the installation process. Furthermore, it must exhibit adequate durability and retention performance to ensure that the contained sludge remains stable and securely enclosed throughout the operational lifespan of the geotextile tube structure.

The material used for the GI-Tube is a double-layered needle-punched staple fiber polypropylene geotextile, with a beige color as the top layer (Figure 2). The geotextile has a mass per unit area of 1300 g/m² and a thickness of 9 ± 3 mm. Its tensile strength is 60 kN/m in the machine direction (MD) and 70 kN/m in the cross-machine direction (CD). The material features an opening size (O_{90}) of 60 ± 20 µm, which is smaller than the fine sludge particles, thereby ensuring effective containment of the sludge within the GI-Tube structure. The permeability of this material reached 25 x 10^{-3} m/s, which facilitates efficient water discharge from the interior to the exterior of the GI-Tube, thereby enhancing the dewatering performance.

Figure 2. GI-Tube material

This material was selected based on its small opening size, ultraviolet (UV) resistance, and high durability. The fine pore size effectively prevents the escape of smaller sludge particles, ensuring optimal retention within the GI-Tube structure. Additionally, the material possesses strong UV resistance, enhancing its longevity under prolonged exposure to sunlight. The beige outer layer is also capable of entrapping external materials such as sand or mud, which may adhere to the surface and provide an additional protective layer, further improving the durability of the structure.

GI-Tubes are commonly fabricated with dimensions ranging from 1.3 to 1.5 meters in height and approximately 20 meters in length. Depending on site-specific design requirements, they may be installed either longitudinally or in stacked arrangements. However, in coastal environments characterized by muddy or soft soil conditions, the use of stacked GI-Tubes requires careful evaluation of the subsoil's bearing capacity. This consideration is essential due to the substantial weight of individual tubes, which can range from 100 to 150 metric tons or more, depending on the type and density of the filling material. Failure to account for the bearing capacity may lead to structural instability.

4 DESIGN

The GI-Tube employed in this project was designed with a circumference of 5 meters and an initial height of 1.3 meters. The tube is intended to be filled with flocculated sludge, which may result in consolidation and subsequent settlement of the structure. Preliminary assessments estimate a vertical settlement of approximately 0.4 meters, resulting in a final stabilized height of around 0.9 meters. Figure 3 shows the schematic diagram of the GI-Tube design.

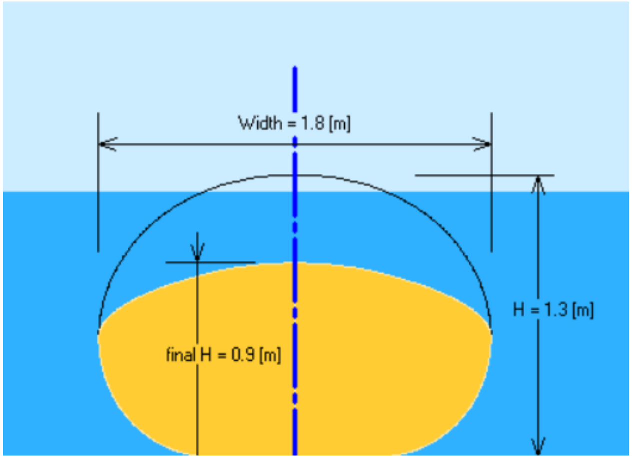


Figure 3. GI-Tube design and expected deformation

The existing seabed at the project site was classified as soft alluvial deposit, necessitating reinforcement of the foundation soil prior to the installation of GI-Tubes. To enhance bearing capacity and mitigate settlement, a ground reinforcement system comprising bamboo piles and a bamboo mattress were chosen as a basal support layer (shown in Figure 4). However, the placement of bamboo piles must be carefully considered, as improper positioning could result in the piles puncturing the GI-Tubes over time, particularly due to the substantial weight of the tubes which are estimated to be around 49.4 tons/tube and the potential differential settlement.

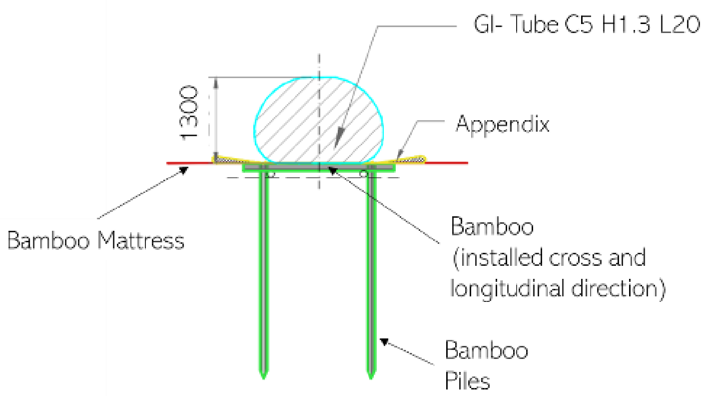


Figure 4. GI-Tube cross section

Bamboo piles with diameters approximately 10 cm and 3 meters depth were installed every 1 m in longitudinal direction, followed by the placement of a bamboo mattress. Positioned above the mattress, geotextile appendices—designed to provide scour protection at the base of the GI-Tubes—were installed to improve structural stability. These appendices, fabricated from the same geotextile material as the GI-Tubes, were installed adjacent to the tubes and were approximately 0.5 meters wide. The appendices were filled using the same sludge filling method with the GI-Tubes.

5 LABORATORY TEST OF THE SLUDGE

The in-situ slurry in the project area consists predominantly of very fine particles. Directly pumping this untreated slurry into the GI-Tubes could prolong the installation period and increase the risk of dewatering failure due to the formation of a slurry cake on the geotextile material. Therefore, a flocculation process was applied to the slurry prior to GI-Tube pumping process.

Laboratory jar tests were conducted to determine the optimal dosage of flocculant before GI-Tube installation. Slurry samples with consistency of 20%, 50%, and 75% were evaluated. An anionic polymer (R-1001; properties detailed in Table 1) at a concentration of 0.2% was employed, with dosages varied at 50, 100, 150, and 200 ppm. The polymer solution was prepared by dissolving 1 gram of polymer in 500 mL of seawater collected from Mundu Beach.

Table 1. Physical and chemical properties of R-1001 polymer

Properties	Value
Appearance	Granul, Powder
Solid content (%)	≥ 87.0
Residual AMD (ppm)	≤ 500
Anionic product charge (% Mole)	10.1 – 18.4
Fines (% weight)	≤ 4.0
Oversize (%weight)	≤ 1.0
Specific gravity (25°C)	0.78
Viscosity (25°C) (cp/m Pa Sec)	4.9 – 6.1
Freezing point	-18°C
Flash point (closed up)	> 93°C

Based on the laboratory tests as can be seen in Table 2, it was concluded that the optimal formulation consists of a 20% slurry concentration combined with a polymer dosage in the range of 150 to 200 ppm. The recommended polymer dosage for achieving optimal results is 175 ppm. The jar test was also conducted on-site prior to pumping the slurry into the GI-Tubes to ensure that the appropriate polymer dosage was applied.

Table 2. Result of laboratory jar test

Slurry (%)	Polymer	Result	Slurry (%)	Polymer	Result
20	50 ppm		50	50 ppm	
20	100 ppm		50	100 ppm	
20	150 ppm		50	150 ppm	
20	200 ppm		50	200 ppm	

6 CONSTRUCTION PROCESS

6.1 Site Preparation

The construction process began with the installation of bamboo piles and bamboo mattresses to form the foundation and platform for the GI-Tubes. The bamboo piles, with an approximate depth of 3 meters, were installed outside the alignment of the GI-Tubes and driven manually. To ensure stability and maintain the intended positioning, bamboo members were arranged in both longitudinal and transverse directions. Following the bamboo pile installation, bamboo mattresses were placed on top of the bamboo grid, serving as the platform for both the geotextile appendices and the GI-Tubes. Figure 5 shows a photograph of the bamboo piles installation.

Figure 5. Bamboo piles installation

Two auxiliary systems were constructed on either side of the installation area: a slurry holding container and a flocculant mixing tank. These setups were designed to facilitate the conditioning and handling of slurry and flocculants prior to the pumping into the GI-Tube. The slurry holding container serves as the primary conditioning unit for achieving the target slurry concentration, which is standardized at 20% solids by weight. This container was constructed using geomembrane sheets, constructed on-site into a temporary containment structure. Flocculants mixing tank was deployed to dilute the flocculant with seawater, achieving a final solution concentration of 0.2%. Figure 6 shows the photograph of construction layout.

Figure 6. Layout of the construction area

6.2 Construction Process

Polymer and slurry were prepared in separate containers to ensure proper conditioning prior to dewatering. The polymer (flocculant) was first diluted to a working concentration of 0.2% using a mixing tank equipped with mechanical agitation to ensure homogeneity. The prepared flocculant solution was then delivered via a dosing pump into a static mixing pipe, allowing for precise control of the dosing rate.

Slurry is first conditioned by mixing it with sea water to form a homogeneous 20% solids slurry. This operation is performed in a dedicated slurry holding container. The pre-conditioned slurry is mixed with the flocculant solution within a static in-line mixer prior to being pumped into the GI-Tube. The hydraulic turbulence and pressure induced during the pumping phase enhance particle-flocculant interactions, thereby promoting the in-situ formation of floc aggregates within the GI-Tubes. Figure 7 shows the flowchart of GI-Tube filling process.

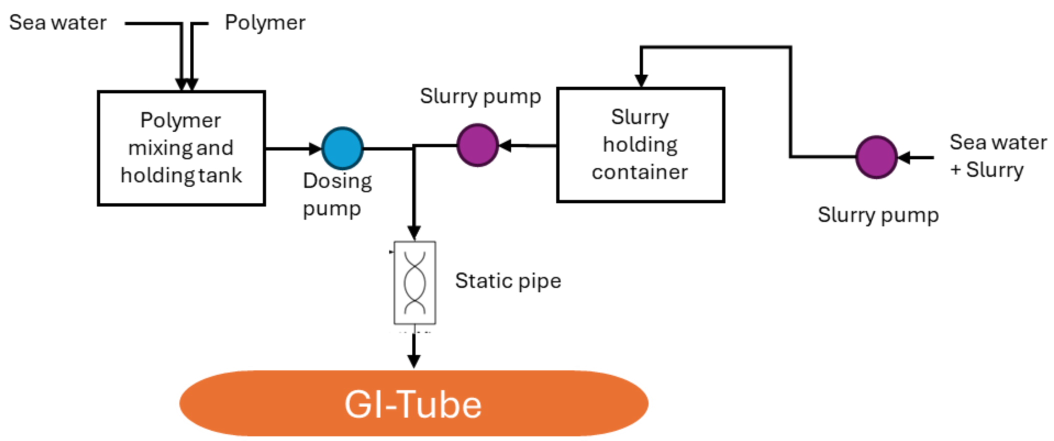
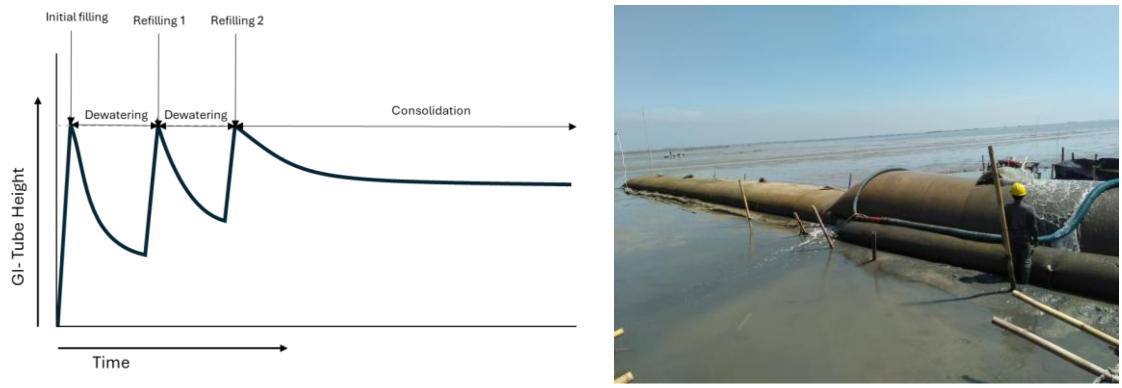


Figure 7. Schematic of GI-Tube filling process

The GI-Tube were filled in three sequential stages (Figure 8a) to reach the design height. Following each filling stage, a dewatering interval was permitted, during which excess water was discharged through the permeable fabric, while the solid sludge was retained within the GI-Tube. Figure 8b shows a photograph of GI-Tube being filled.



(a) (b)

Figure 8. (a) Typical cycles of GI-Tube filling process, (b) GI-Tube filling process

7 RESULT

7.1 Settlement of GI-Tubes

The final installed height of the GI-Tubes ranged between 1.3 and 1.4 meters. Post-installation, the tubes underwent gradual settlement due to ongoing dewatering and consolidation processes. To evaluate this behavior, settlement was recorded at two reference points on each GI-Tube over a 100-day monitoring period, enabling the assessment of total vertical displacement over time. The location of monitoring points is shown in Figure 9.

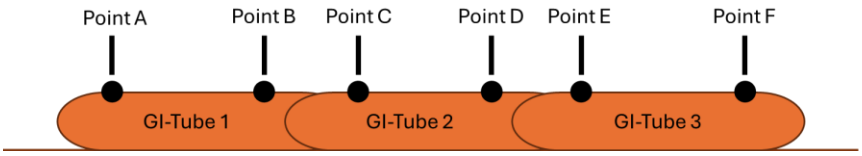


Figure 9. GI-Tube settlement monitoring point

Settlement monitoring was performed using an L-shaped measuring pole, which measure the height of the GI-Tubes from base of the mattress. Figure 10 shows the settlement of GI-Tube with time. The monitoring data indicated a progressive increase in vertical displacement of the GI-Tubes throughout the monitoring period. At 30 days post-installation, the tube heights decreased to a range of 1.1 to 1.15 meters, corresponding to approximately 84% of the initial installed height. By 60 days, further consolidation led to a reduction in height to between 0.9 and 1.0 meters, representing 69% of the original height. After 100 days, the height stabilized within the range of 0.8 to 0.9 meters, equivalent to 61% of the initial height, reflecting significant settlement due to ongoing dewatering and consolidation processes. Figure 11 shows a photograph of the GI-Tube 100 days post construction.

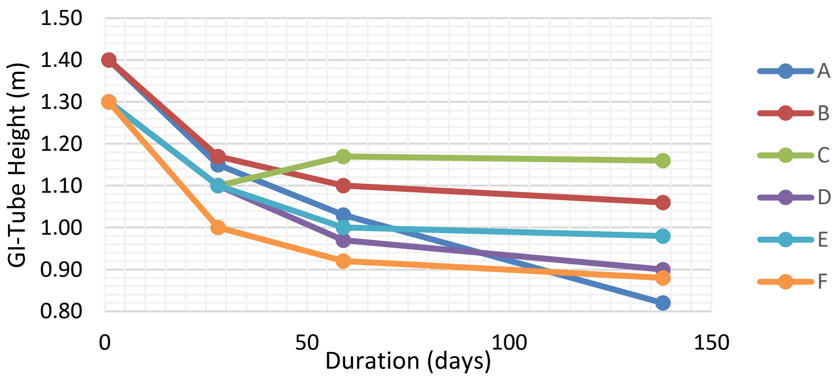


Figure 10. GI-Tubes settlement graph

The appendices, similar to the GI-Tubes, exhibited settlement behavior. In certain locations, the appendices experienced flattening as a result of sludge consolidation and subsequent volume reduction within the structure.

Figure 11. GI-Tube condition after 100 days

7.2 Performance of the GI-Tube Material

This study presents evidence that the double-layered geotextile material demonstrates efficient performance in the dewatering of sludge within the GI-Tubes. Featuring a pore size of approximately 60 microns—substantially smaller than the typical sludge particle size—the material effectively retains sludge solids within the tubes. This retention capability is confirmed by the observation that only clear water is discharged during the dewatering process (Figure 12).

Figure 12. Clear water discharged from the GI-Tubes

This GI-Tube material has also been previously demonstrated to be effective as a low-crested breakwater (Sulaiman et al., 2015) and Nugroho et al., 2021). Both studies employed sand as the fill material and verified the structural durability of the GI-Tubes. Importantly, Nugroho et al. (2021) documented that approximately 80% of the GI-Tube surfaces were colonized by marine organisms within one year, highlighting the structure's capacity to support marine biodiversity and thereby underscoring its sustainability as a coastal protection solution.

Since installation, no damage to the GI-Tube material were observed, with inspections continuing through 2024 (installation was on December 2022). While marine organisms have colonized almost 60% of the surface of the GI-Tubes, their presence has not resulted in any material degradation. Figure 13 shows a photograph of the GI-Tube 2 years post-installation.

Figure 13. GI-Tube 2 years post-installation

7.3 Increase of Shoreline and Mangrove

The installation of GI-Tubes as low-crested breakwaters was intended to enhance sediment deposition along the shoreline. The design allowed wave energy to partially pass through the permeable structure, enabling suspended sediments to be transported into the sheltered area behind the GI-Tubes. As wave energy dissipated upon passing through the tubes, sediment was deposited and retained landward of the structure. Changes in shoreline conditions before and after GI-tube installation are presented in Figure 14. Based on the satellite imagery shown in Figure 14(b), sediment deposition is observed to have developed behind the GI-tube approximately seven months after installation. Additionally, wave conditions in the back of the GI-tube appeared to be significantly attenuated, resulting in relatively calmer hydrodynamic conditions. Field observation was also conducted seven months post-installation which revealed a significant accumulation of sediment behind the GI-Tubes, thereby confirming their effectiveness in attenuating wave energy and promoting shoreline accretion.

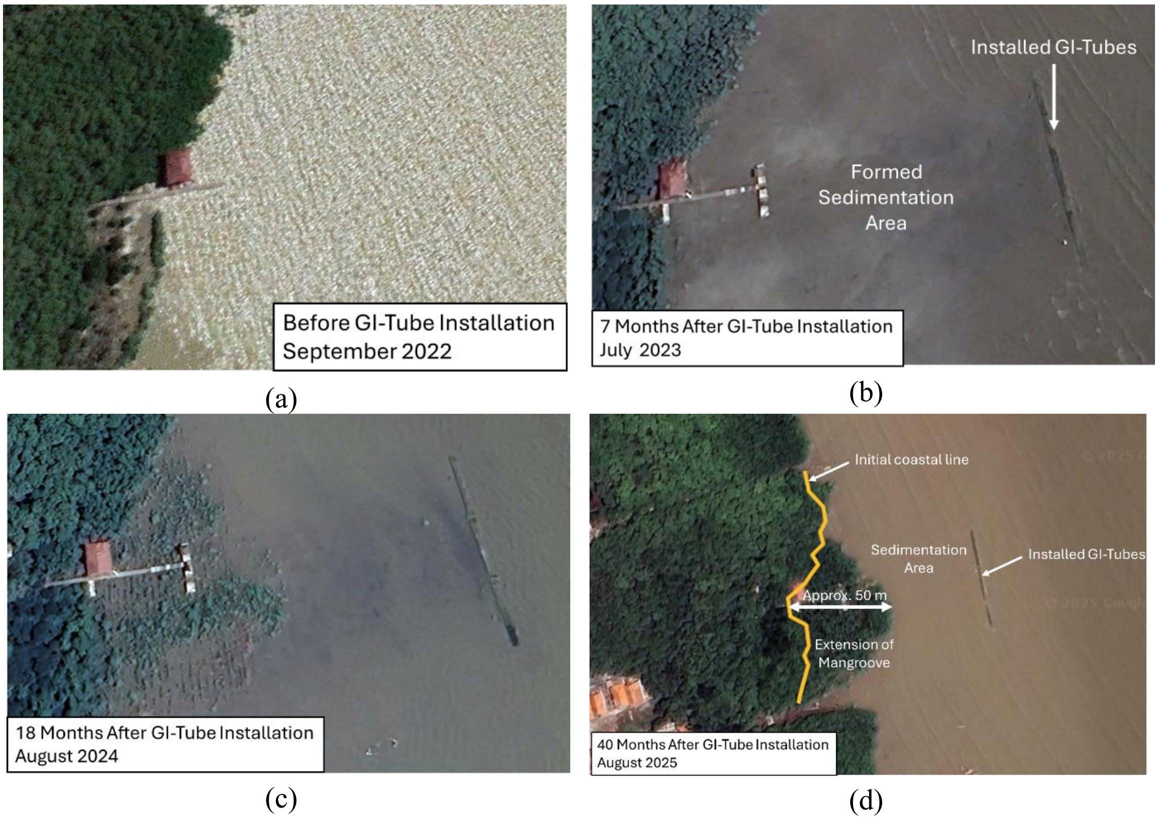


Figure 14. (a) Before GI-Tube installation, (b) Site condition 7 months after GI-Tube installation, (c) 18 months after GI-Tube installation, and (d) Coastline conditions from satellite imaging in August 2025
Source: Google earth imaging

Due to dissipation of wave energy by the GI-Tubes, the area behind the GI-Tube becomes calmer and hydrodynamically stable. These conditions are highly favorable for the establishment, growth, and long-term survival of mangrove vegetation. In addition, the progressive accumulation of sediment and fine particulate matter behind the GI-Tubes improves substrate stability, which not only supports natural mangrove colonization but also facilitates successful manual planting efforts as can be seen in Figure 14(c). Collectively, these factors have contributed to a significant expansion of mangrove coverage along the protected coastline.

Physical monitoring conducted in August 2024—approximately 18 months after the installation of the GI-Tubes—confirmed that the sludge encapsulated within the structures remained solid and exhibited good consolidation. Additionally, notable sediment accumulation was observed on the landward side of the GI-Tubes, contributing to a measurable extension of the mangrove boundary by more than 30 meters.

To clearly determine changes in the mangrove line, the initial shoreline was delineated using satellite imagery acquired prior to GI-tube installation and subsequently compared with post-installation imagery. Analysis of satellite imagery from August 2025 (approximately 40 months post-installation), as shown in Figure 14(d), indicates a continued seaward expansion of the mangrove line, reaching approximately 50 m from its original position. These observations underscore the long-term effectiveness of the GI-Tube structures in promoting sediment accretion and facilitating coastal ecosystem recovery.

GI-Tubes have demonstrated considerable effectiveness as low-crested breakwaters for mitigating coastal erosion in soft, muddy coastal environments. Their functionality is primarily attributed to their ability to attenuate wave energy, thereby enhancing sediment deposition and creating favorable conditions for mangrove establishment and growth. This integrated approach supports both physical shoreline stabilization and ecological restoration.

8 CONCLUSIONS

The integration of the double-layered GI-Tube material with well-consolidated sludge resulted in the formation of a highly effective low-crested breakwater structure. The success of this system is largely attributed to the use of a double-layered non-woven geotextile and flocculation process of the slurry. The double-layered geotextile material features fine pore sizes that effectively retain sludge particles while permitting sufficient water permeability. This dual functionality enables efficient containment of the fill material and facilitates rapid drainage, thereby enhancing the overall dewatering performance. Meanwhile, the flocculation process promotes the formation of larger flocs, thereby preventing the development of slurry cake on the geotextile material, which can hinder or prolong the dewatering process.

In addition, utilizing locally sourced sludge as the fill material not only improves technical efficiency but also represents a cost-effective and environmentally sustainable approach to coastal erosion mitigation. By promoting sediment accumulation and creating favorable conditions for mangrove establishment, this method supports both shoreline stabilization and long-term ecological restoration, positioning it as a viable and sustainable solution for erosion control in muddy coastal zones.

ACKNOWLEDGEMENTS

The author gratefully acknowledges the support provided by PT. Geoforce Indonesia and the National Research and Innovation Agency (BRIN).

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