Integrating Underwater Acoustic Remote Sensing and Soil Investigation Data for Sediment Volume Estimation in Gresik Jasatama Port Pool, Indonesia

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Abstract
Port is one of the transportation networks that connect sea and land transportation. Thus, it can be ensured that there are many activities closely related to port such as planning, implementation, and maintenance. One of the port maintenance activities is dredging. The sea current that is always moving carries sediment towards the port causing sedimentation in the port pool area and preventing the ship from grounding. Maintenance dredging is required to remove sediment deposits in the pool port to maintain the safety depth. Before dredging, the parameter that has to be considered is the sediment type and its thickness in the area of interest. The study utilized underwater acoustic remote sensing instruments such as Sub Bottom Profiler, Side Scan Sonar, and Multibeam Echosounder to determine the type and thickness of sediments in the port pool. The validation process for the sediment types and the Standard Penetration Test value are derived from the soil investigation data. There are six borehole points at the research location which have a Standard Penetration Test value. The research location is in a shallow water area with depth values ranging from 0.5 m to 7.0 m with respect to Low Water Spring. Based on the SSS image interpretation, the research location is dominated by sediment type of clay. The area of interest is 30541.29 m^2 and the total volume of the sediment thickness is 82326.7 m^3 with respect to the depth design. This sediment volume is dominated by the soft sediment with the volume of 79614.8 m^3. The couple of underwater acoustic remote sensing and soil investigation can provide a continuous representation of the sediment thickness and an essential reference for future research on the estimation of sediment volume in the port pool.

Keywords: Acoustic Remote Sensing, Pool Port, Sediment Volume, Soil Investigation

1. Introduction

A port is an area of water protected from waves, used as an anchorage for ships and other watercrafts used to lift passengers and goods, make repairs, refuel, and equip wharves for mooring ships and cranes. Loading and unloading goods, transporting them through warehouses and storage locations, and waiting for distribution to the destination area or the next shipment [1]. Terminal Gresik Jasatama is one of the dry bulk terminals located in Gresik Regency, East Java Province, Indonesia. This terminal provides various services such as loading and unloading of industrial materials, cargo bags, log wood, and palm oil. Due to the increasing traffic activities of ships, maintenance and inspection of the port area are required to preserve the water depth from sedimentation. As continuous sedimentation processes cause the port basin to become shallower, dredging is necessary to maintain the safety of navigation in the area. The sediment deposition process which occurs continuously will accumulate surficial sediment at the bottom of the harbor pond.

The sedimentation rate depends on how prone the area is to the effects of sedimentation. The area which is located in river mouths and estuaries have a high risk in sedimentation that may affect shipping activities as the performance of the port is very dependent on the depth of the shipping channel and the anchorage pond [2].

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This circumstance may affect shipping activities and safety. One of the activities that can be taken to overcome the accumulation of sediment in the harbor is to perform a dredging process. However, to carry out dredging effectively, it is necessary to evaluate the sediment impact on the harbor area, including the thickness and volume of hard and soft sediment layers in the waters. One of the ways to identify the thickness of the sediment in these waters is by observing the seabed using the acoustic wave. Acoustic methods are currently widely used to detect the presence of underwater objects. Seabed sediment research utilizing the acoustic method has been done by Khomsin et al., [3], by analyzing MBES data. Based on the study, the acoustic method is an effective means to inspect the seabed sediment and its environment [4]. However, to identify the layer thickness of the sediment, a Sub Bottom Profiler (SBP) survey can be used as an alternative approach. SBP is an instrument which utilizes an acoustic wave to identify sediments on the seabed sub surface [5]. As it is important to determine the type and thickness of sediment for dredging planning [6]. The study also used a Side Scan Sonar to acquire the acoustic imagery of the seabed. Combined the underwater acoustic remote sensing and the soil investigation data as a validation, this can be an innovative method to quantify the sediment volume in the port pool area.

2. Material and Methods

2.1 Study Area

The research area as shown inside a red box in Figure 1 is in the port pool area of Gresik Jasatama. The area of interest is located in Gresik Regency, East Java, Indonesia at geographical coordinates between 7° 9′ 6.23″ S 112° 39′ 37.31″ E and 7° 8′ 57.95″ S 112° 39′ 41.09″ E. The area of this study is approximately 30541.29 m^2.

2.2 Research Methodology

2.2.1 Sub-bottom profiler data processing

The SBP data results the acoustic intensity based on the interaction between the acoustic wave and features on the seabed surface and the layers below. These intensities are then digitized as sediment layers and converted into XYZ data to calculate the sediment volume and to produce a three-dimensional image of sediment layers. The first step of SBP processing is filtering the SBP data to remove the water column effect and retrieve the seabed surface line. SBP is an acoustic instrument used to obtain information on the sediment and rock layers below the seabed surface. This underwater acoustic remote sensing technique emits acoustic waves that have a single channel wave system and is used to display the seismic profile of the shallow seabed [7]. This underwater acoustic system uses a low frequency that operates between 2 kHz to 12 kHz to penetrate sediment layers below the seabed surface.

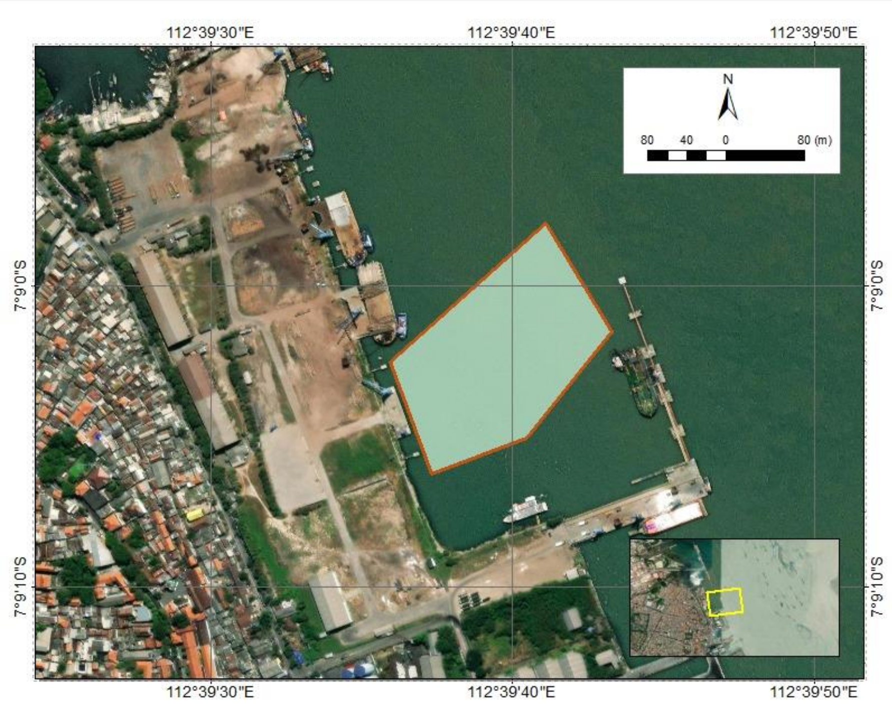

Figure 1: The area of interest in Gresik Jasatama Port pool

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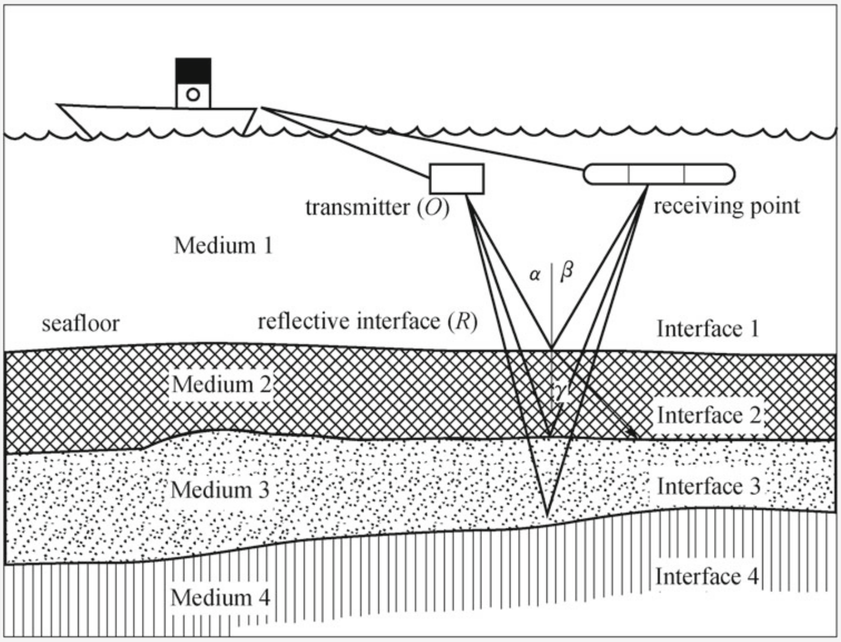

Figure 2: Geometric kinematic model of acoustic signal for SBP [8]

The SBP utilizes a sound source that sends an acoustic signal vertically downward through the water. The receiver will receive the signal reflected by the seabed and the layers below. Some of the acoustic signals will penetrate the seabed layer and will be reflected when it meets the boundary between the two layers which have different acoustic characteristics, known as acoustic impedance [6].

As shown in Figure 2, the acoustic signal emitted by the O generator propagates through the water column and the seabed. According to the principle of seismic reflection geometry, when touching different shapes, the incident wave will create a reflected wave with angle β equal to the incident angle α at the interface. The propagation angle γ is determined by the sound wave propagation speed in the upper and lower layers at the interface. If the speed of the sound wave in medium 2 below the seabed interface is greater than the speed of the sound wave in medium 1 above the interface, the transmission angle γ will be larger than the incidence angle α and vice versa. As the transmitted wave continues to travel down, new reflected and transmitted waves continue to be created at subsequent acoustic impedance intersections until the energy of the transmitted wave is too low to produce a reflected echo of any energy. To produce a strong reflected echo at a surface, there must be a clear difference in the acoustic impedance state at that surface. Therefore, the reflection coefficient R at the surface is non-zero if the sound wave is excited by detecting a flat plate at an angle approximately perpendicular to the reflecting surface. The equation can be expressed as Equation 1 [9].

$$R = \frac{Z_2 - Z_1}{Z_2 + Z_1} = \frac{\rho_2 v_2 - \rho_1 v_1}{\rho_2 v_2 + \rho_1 v_1} \neq 0$$

Equation 1

Where Z_1 is the characteristic impedance or wave impedance that refers to the first medium or the first side in a transmission and Z_2 is the impedance that refers to the second medium or the second side in a transmission. ρ and v are the density of the sediment layer and the speed of sound wave propagation in the layer, respectively, and their product is called the wave impedance. Subscripts 1 and 2 designate the layers above and below the interface, respectively. According to the above equation, the condition that means the reflecting interface can form a reflected echo is that $\rho_2 v_2$ is not equal to $\rho_1 v_1$; The larger the difference between $\rho_2 v_2$ and $\rho_1 v_1$, the stronger the reflected energy. The larger the amplitude of the reflected signal received by the transducer, the larger the gray value of the in-phase sound reflection axis displayed by the recording section, and the clearer the interface of the reflection layers. Therefore, the reflection interface is also called the wave impedance interface, which matches the lithological interface of real strata and represents different lithological horizons [8].

By examining areas with a soil test using drill or borehole samples, it is possible to extend the usefulness of these samples by identifying subsurface structures in the images that match the structures shown in the borehole samples.

Furthermore, digitization is done to obtain an overview of the seabed surface and sediment layers. Validation is done by comparing the results of digitization with soil investigation data to identify the characteristics of the type of sedimentation. Soil investigation is the first activity which is related to the planning of the substructure structure [10]. Overall, the aim of a soil investigation is to obtain technical data or soil parameters that are representative of the local soil conditions. This activity is expected to provide information on soil conditions, soil types, groundwater levels, layers of soil structure, and soil characteristics for foundation planning [11]. In this study, sediments are classified into two types based on their Standard Penetration Test (SPT) value: soft sediment has an SPT less than or equal to 20 and hard sediments which has an SPT more than 20. A three-dimensional visualization of sediment thickness is used to clarify the distribution of sediments and display a comparison between soft and hard sediment layers. Finally, analysis of the sediment volume is retrieved by calculating the layer above the surface design and the sediment that needs to be dredged.

2.2.2 Side Scan Sonar Data processing

The Side Scan Sonar (SSS) survey aims to collect the depiction image of the seabed. This instrument uses the emission of acoustic waves to determine the sediment type and features present on the seabed. SSS records backscatter values reflected from the seabed as an electrical energy. This instrument can distinguish the size of particles that make up the seabed surface such as rocks, mud, sand, gravel, or other types of seabed sediment [12].

Seabed sediments can be classified based on their acoustic backscatter strength, where each type of sediment usually has a different intensity level. This can be used to investigate the type and spatial distribution of seabed sediment morphology [13]. One approach to analyze the relationship between sediment type, incident angle of the acoustic wave and received backscatter is Angular Range Analysis (ARA) [14]. The backscatter data is generated and classified using machine learning. The color distribution is represented using an 8-bit digital number. Values within the range are assigned to a specific color class. A larger range value will result in a smaller number of colors. Specifying a small range will produce a variety of colors. However, color diversity is not the main factor determining the classification of seabed types. The multiple images of SSS are merged into a mosaic imagery. This image makes it possible to classify or segment several layers of the seafloor based on the texture and properties of each layer. The mosaic is an image of the seafloor that preserves information about seafloor characteristics such as intensity over time and ray averages. The mosaic can be used as a starting point to examine the distribution of intensity values and results [15].

This research classified a seabed sediment type into three categories based on its backscatter strength: sand, silt, and clay. To determine the type of seabed, the ARA method applies the half-scan uniformity principle and estimates the average backscatter value of the measurements obtained from the scanned area. Angular reactions will create sedimentary boundaries that give rise to sediments with different compositions. Because sand is hard and dense, the backscatter value of sand is higher than that of silt and clay. When acoustic signals were obtained on sand, the acoustic signal response was still relatively high compared to other types, and the graph obtained by backscatter intensity was also higher. Because silt is physically finer than sand, alluvial sediments tend to be weaker than sand. Signals related to sediment type are more likely to be absorbed than signals related to litter. Sediments with low resistivity are clay. The structure of these sediments is finer than that of sand or silt. Clay is the most sensitive of all sediment types according to the Wenworth classification scale. Almost all the energy emitted from the transmitter is absorbed by the sediment. Due to this condition, the strength of this type of sediment is very low [15]. Illustration of measurements using SSS can be seen in Figure 3.

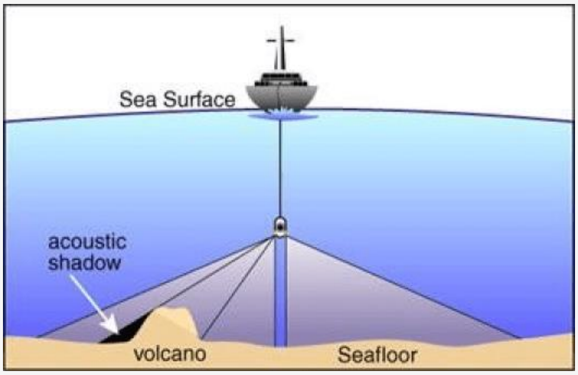

Figure 3: Side scan sonar survey illustration [16]

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When conducting a field survey using SSS, the scanning method, width, resolution, speed, towing height, and transmission line length must be determined based on the environment and scanning requirements. Based on these parameters, the direction and distance of the lines should be designed. Effective towing speed is an important parameter in field operations using side scan sonar with respect to acquisition range and image resolution. Theoretically, the pulling speed can be calculated according to Equation 2 [8].

$$V = 0.97\frac{LC}{RH}$$

Equation 2

Where L refers to the mass or load of the conveyed material, C is the coefficient of friction between the material and the underside of the conveyor belt, which affects the amount of frictional force that the conveyor system will need to overcome. R represents all other resistances that affect the movement of the belt and H denotes horsepower, a unit of power.

Additionally, if high-resolution images are required, the range of the target's acoustic signal must be dense, thus requiring a slower tow speed. Therefore, in field detection, it is necessary to consider the relationship between detection efficiency and work efficiency. In general, when the target is sighted, the ship must slow down, and the tow body must be as close to the seabed as possible to ensure the safety of the tow fish [8].

Processing SSS data begins with Slant Range Correction (SRC) to remove blind spots from images on each survey line. Furthermore, a time varying gain correction is taken to balance the brightness of the image even though the object is far from the nadir and to compensate for the characteristics of the detected seabed features. The third stage involves creating an image mosaic to combine images between data segments to produce processed image visualizations that display the surface appearance of the seabed which can be interpreted and classified based on its texture to obtain sediment characteristics. Furthermore, analysis of sediment distribution patterns is carried out based on their characteristics to get sediment distribution patterns. Interpretation of SSS images can be carried out qualitatively to obtain the physical properties of the seabed material and determine the shape of objects or quantitatively to define the relationship between ship position, to fish position, and object position. The features in SSS imagery can be classified based on texture observations to recognize the characteristics of the seabed [17].

3. Results and Discussion

3.1 Sub-Bottom Profiler Analysis

The sediment data obtained from the SBP is used to determine the type of sediment and the hardness of the layers below the seabed surface. The study used a pinger system to collect 14 SBP survey lines with an interval of 10.0m. The Pinger system has a low frequency and is suitable for shallow water areas. This system provides high resolution but has low penetration. Thus, the pinger type is often used to detect relatively shallow objects, for example in the form of a pipe tracker for the detection of pipes and cables. SBP pinger and chirp are sometimes combined with side scan sonar (SSS) in a single towing fish, allowing surface and sub-bottom data to be collected simultaneously [18].

In the early stages of data processing, a filtering process is performed to remove the water column which is located above the seabed. The filtering process used the Dynamic Range and Bottom Tracking corrections. In the Bottom Tracking process, correction due to waves (Swell Correction), Median Filter Seabed, and water column correction to obtain accurate seabed measurements [6]. An overview of the seabed surface and the surface of the sediment layers from SBP datagram can be seen in Figure 4(a). The seabed surface is represented by a yellow line and the vertical distance between the sea surface and seabed is the water column. The Bottom Tracking and water column process removal result is shown in Figure 4(b).

A Dynamic Range process was taken to obtain an image with optimal light intensity. In the process, the display was adjusted by modifying the color and the density so that differences between sediment layers can be clearly discriminated. Different color contrasts are used to indicate the thickness of the sediment layers. The interpretation and digitization processes of the seabed and the layers with difference acoustic intensities provide the geospatial information of subsurface geological layers' boundaries. This can be used to measure the thickness of the sediment layers.

In order to validate the SBP data, a soil investigation was performed in six locations with a depth of 10m below the seabed surface. Based on the soil investigation results, the types of sediments in this study are divided into two categories, namely soft and hard sediments. Soft sediments have an SPT value of less than 20, while hard sediments have an SPT value greater than or equal to 20. Figure 5(b) shows the overlay of an SBP image, and the boreholes performed in the same location.

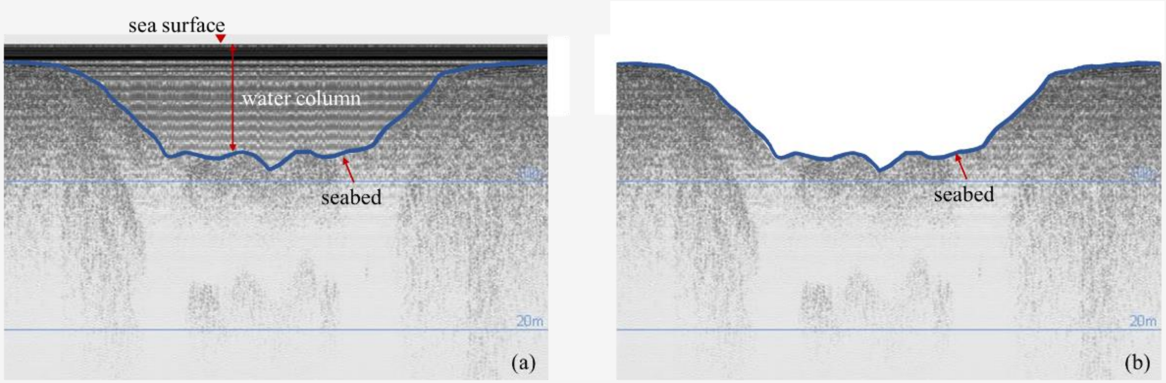

Figure 4: (a) The sub bottom profiler datagram which includes the sea surface, the water column, the seabed, and its subsurface layers
(b) The SBP image after applying the bottom tracking and water column removal process

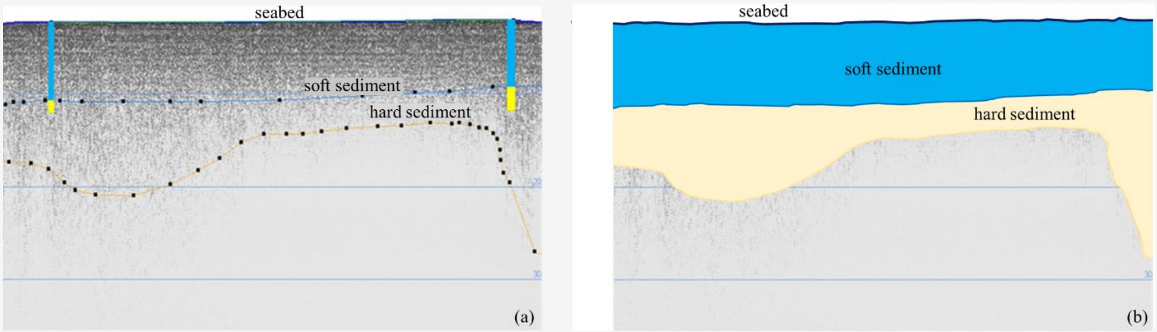

Figure 5: (a) The digitation process of the SBP acoustic intensity image which is verified by soil investigation data (b) The sediment thickness layers image which is resulted from the digitation process

In this figure, two soil investigations is located in the SBP line. The blue bar is the soft sediment, and the yellow bar is the hard sediment. The digitation of the boundary of the difference acoustic intensities in SBP data is shown in blue line and orange line. This shows that the soil investigation test in two points is dominated with the soft sediment.

Figure 5(a) shows the data collected by the SBP indicates the presence of two layers of different sediments beneath the seabed. To determine the boundaries of the two layers, on screen digitation was carried out with respect to the result of soil investigation in the area. After successfully digitizing, the XYZ coordinates of the two layers are converted into *.txt file format and corrected to the vertical reference of Low Water Spring (LWS), which is 1.216m.

3.2 Sediment Type Analysis

In this study, the soil investigation data were taken from six different points which are scattered in the area of study. Soft sediments layer (SPT $\leq$ 20) includes of clay and mud, while hard sediments layer (SPT > 20) consists of silty clay to loamy silt. Clay is the smallest particle with a diameter of less than 0.004 mm, while silt particles have a diameter between 0.004 mm - 0.625 mm [19]. The thickness of each layer varies in each sample. Figure 5b is the result of digitization of soft and hard sediment layers. The soft layer shown in blue area, and the hard layer shown in a yellow area. The soft layer in this area consists brownish-gray clay, very soft, with high plasticity. Whereas the hard layer is in the form of silt clay, yellowish brown to light brown in color, hard, moderate plasticity, there are sandstone inserts, very fine to fine in size, in the form of gravel to boulder with a maximum diameter of 5.0cm.

3.3 Three-Dimensional Sediment Visualization

A three-dimensional sediment surface was created using geospatial data from the SBP which has been verified with soil investigation. The main objective of this three-dimensional visualization is to obtain a clear picture of the sediment types and their distribution at the study site. In developing the surface model, the research used bathymetric data from a Multi Beam Echo Sounder (MBES) as the depth reference for the sediment surfaces.

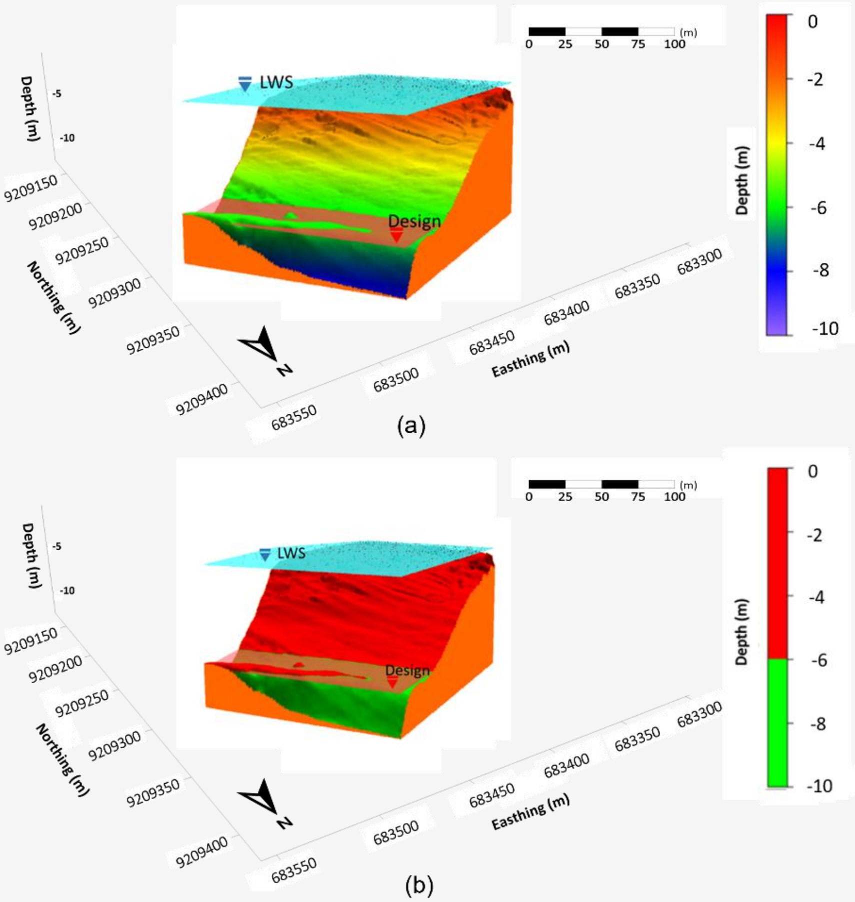

Figure 6: (a) Three-dimensional visualization of the seabed surface in Gresik Jasatama Port pool and its corresponding dredging depth design with respect to the LWS. (b) The superimposed of the dredge design and the seabed surface, red color represents the area above the depth design, whereas the green color has the depths below the design

The sediment surface model is developed using the Kriging interpolation method. This method is one of geostatistical data analysis techniques which estimates the representative value of a point which is not sampled by utilizing the surrounding sampled points based on the semi variogram structural model [20].

Based on the three-dimensional surface analysis, the soft sediment layer has a maximum thickness of 10.0m, while the thinnest is approximately 1.0m. The thickness of the hard sediment has a range from 2.5m to 13.0m from the seabed surface. As the port pool area has to meet the requirements of the safety of navigation, the depth in this area should be maintained so that ships can navigate safely. The shallowest depth that should be preserved is 6.0m below LAT. However, it is apparent that depths in the area range from 0.5m to 7.0m. Therefore, dredging is necessary to be done to have a minimum depth requirement.

Figure 6(a) represents the three-dimensional seabed surface and the depth design for dredging. The area that has to be cut is shown in red color in Figure 6(b). While the area deeper than the depth design is shown in green color (Figure 6(b)). In the area that has to be dredged (red color) has two sediment types as the thickness of soft sediment and hard sediment are in the depth range that has to be dredged. Figure 7 shows the hard sediment surface and the surface design. The surface above the design has to be cut whereas the surface below the design is not necessary to be dredged as it has exceeded the predetermined depth.

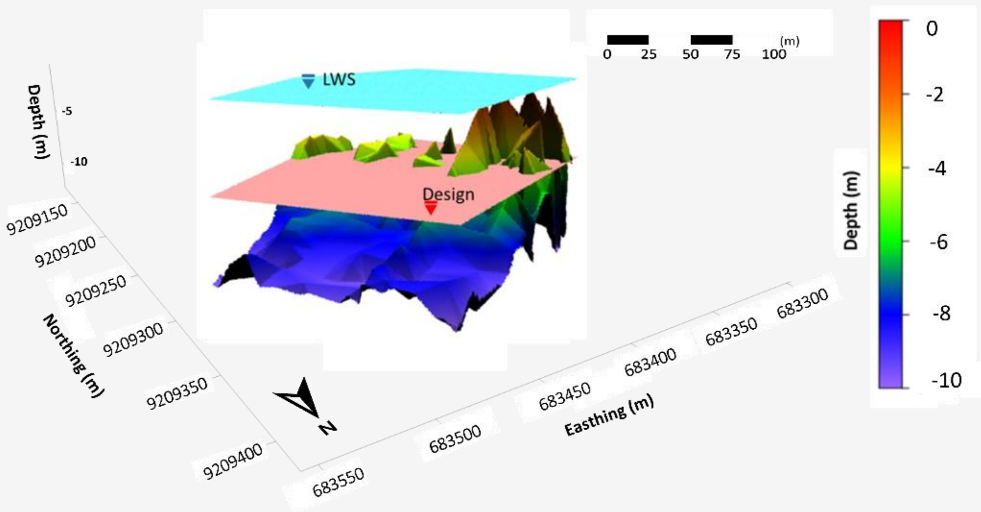

Figure 7: Hard sediments layer over the surface of depth design

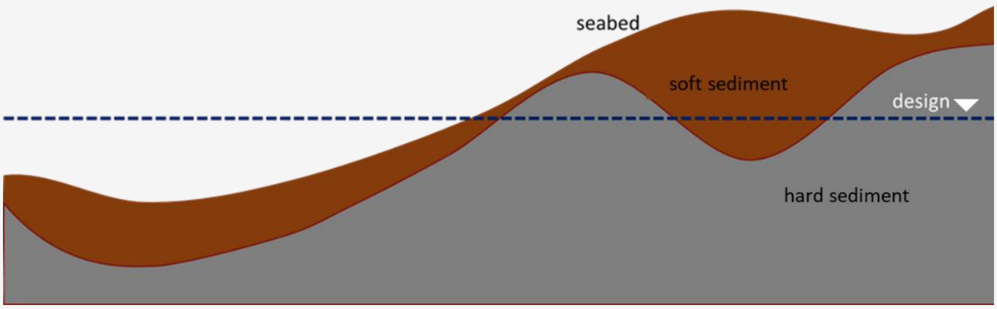

Figure 8: Illustration of hard and soft sediment layers

Table 1: Sediment volume calculation results

Sediment Surface	Volume (m^3)
Seabed (MBES)	82326.7
Soft Sediment Layer (SBP)	79614.8
Hard Sediment Layer (SBP	2711.9

3.4 Sediment Volume Calculation

In this study, the bathymetric data from MBES becomes the surface of the first layer. Whereas the SBP data is used to derive the second surface layer. The first sediment layer is referred to as soft sediment layer, while the second sediment layer is referred to as hard sediment layer. Based on bore sample, it was determined that the characteristics of the first (soft) sedimentary layer consisted of brownish gray clay, very soft and had high plasticity, while the second (hard) sedimentary layer consisted of light brown (yellowish) silt clay, hard and has moderate plasticity. Figure 8 represents the illustration on calculating the sediment volume both soft and hard sediments. Only the areas above the design line (blue line in Figure 8) are calculated.

The sediment volume of the second layer or hard sediment is calculated based on the second layer and the dredging depth design. The volume calculation uses the Triangulated Irregular Network (TIN) method, which is a vector-based topological data model used to describe the earth's surface in the form of a relationship between interconnected irregular triangles. Tabel 1 shows the results of volume calculation of each layer. Based on the volume calculation results shown in Table 1, the total dredging volume of the port pool is 82326.7 m^3. This volume consists of the soft sediment layer which has a volume of 79614.8 m^3 and 2711.9 m^3 of the hard sediment volume.

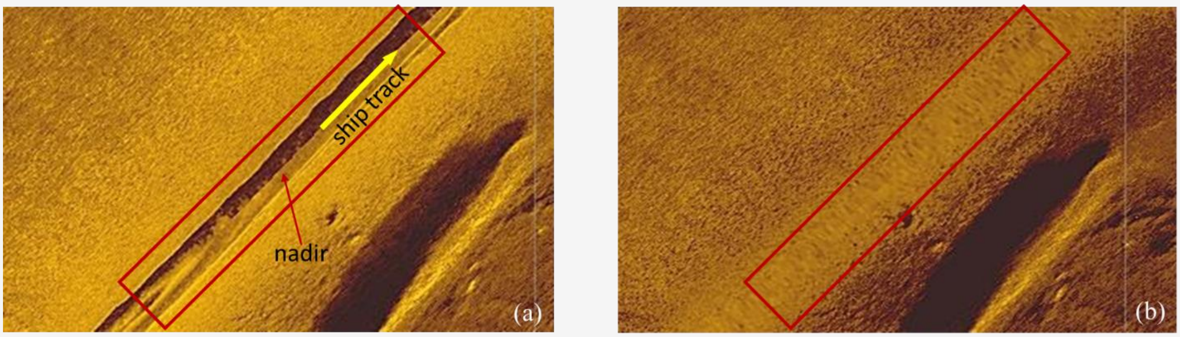

Figure 9: (a) The SSS image with water column track at the Nadir (inside the red box)
(b) The SSS image after removing the water column effect by applying slant range corrections

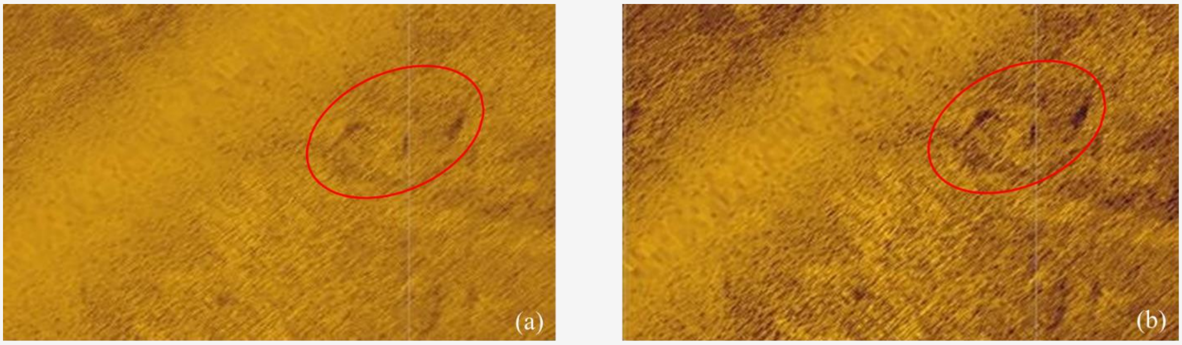

Figure 10: (a) Seabed Features in the SSS image before applying TVG corrections
(b) The SSS image after TVG corrections

3.5 Side Scan Sonar Analysis

In the SSS processing stage, geometric and radiometric corrections have to be carried out. These corrections include the Slant Range and the Time Varying Gain. Slant range correction is a geometry correction in the image that aims to eliminate the blind zone or first return to the SSS tow fish at nadir which represents the actual position of the object. While the Time Varying Gain (TVG) is a radiometric correction related to the improvement of SSS images which aimed at compensating for the characteristic of the recorded seabed features in SSS imagery. In Figure 9(a), the appearance of the SSS image before removing water column effect using Slant Range Correction. The result after applying this correction, can be seen in Figure 9(b). Figure 10(a) shows that seabed features in the SSS image cannot be clearly seen. However, after implementing the Time Varying Gain correction by increasing the amplification of the acoustic signal intensity, the feature on the seabed surface can be obviously identified on the SSS image (see inside the red circle in Figure 10(b)).

The image interpretation of SSS data is performed based on the seabed texture and the gray level. The roughness level of the seabed features affects the backscattered strength of the acoustic signal. Sediment with coarse textures have a stronger backscatter signal and brighter color intensity compared to finer textures which appear to have a lower backscattered strength. Table 2 represents the visual appearance of six samples in the SSS image. These samples are located at the same position of the boreholes. The sediment is divided into two types, namely soft and rough as shown in Table 2.

Based on the existing borehole data, it can be recognized that the seabed surface is dominated by sediment type of clay. There is unsignificant difference between hard and soft sediments layer on the seabed surface because they are dominated by silt. This is possible as the particle size of clay is less than 0.004 mm while the particle size of silt ranges between 0.004 mm and 0.625 mm.

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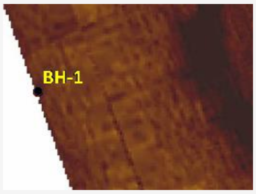
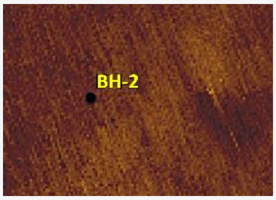
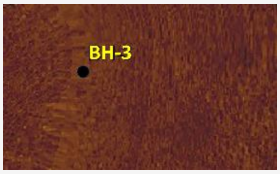
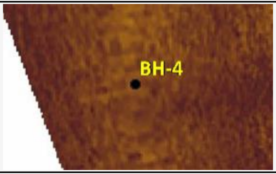
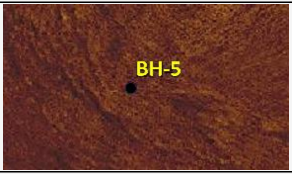
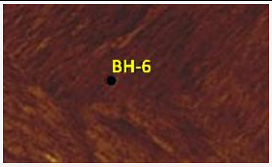
Table 1: Image interpretation results and characteristics

No.	Borehole	Sediment Type	Image Interpretation Results and Characteristics
1.	BH-1	Soft Layer (Clay)	
2.	BH-2	Soft Layer (Clay)	
3.	BH-3	Soft Layer (Clay)	
4.	BH-4	Hard Layer (Silty Clay)	
5.	BH-5	Hard Layer (Silty Clay)	
6.	BH-6	Hard Layer (Silty Clay)	

4. Conclusion

The research combines underwater acoustic remote sensing methods and soil investigation to estimate the sediment volume for the purpose of dredging in a port pool. The area of interest is shallow water with depth ranges from 0.5 m - 7.0 m with respect to LWS. The seabed surface is dominated with a soft sediment (clay) composition. Based on the SBP results, the soft sediment depths range from 1.0 m - 7.0 m from LWS. Whereas hard sediment layers are located at depths of 2.5 m - 12.0 m with reference to LWS. The results of the sediment volume calculation show the total sediment volume that has to be dredged in the area is 79614.8 m^3 (96.71%) for soft sediments layer and 2711.9 m^3 (3.29%) for hard sediments layer. This research provides a continuous representation of the sediment thickness and an essential reference for future research on the estimation of sediment volume in the port pool.

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