On the investigation of vertical uncertainty of depth sounding in a shallow environment with muddy seabed: Preliminary results from a launch operation of a dual-frequency echosounder

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Abstract. Hydrographic echosounder has been the standard instrument that provides a measure of water depths. In a muddy environment, this detection is not as straightforward as it seems; low gradient of acoustic impedance presence within the water-sediment interface resulting in vertical separation of liquid-solid boundary detected by different frequencies of depth sounding system. In this study, we investigate the depths measured by a dual-frequency hydrographic echosounder in a muddy environment, coupled with a simultaneous probing of the water-seabed interface by means of a free-falling cone penetrometer. We intend to understand the extent of the uncertainty of a depth-sounding system to precisely locate the liquid-solid boundary within the water-seabed interface, specifically at Patimban coasts, situated in the north coast part of Java Island, where muddy sediments dominate the seabed. From our investigation, we found that standard high-frequency sounding (200 kHz) underestimates the physical depth by 0.26 ± 0.17 m, while standard low-frequency sounding (24 kHz) overestimates the physical depth by 0.23 ± 0.19 m and tends to give inconsistent measures. Our study suggests the importance of considering these measures of discrepancy when depth sounding is being carried out in a muddy environment.

1. Background

Hydrographic echosounder works based on the utilisation of short pulses and high-frequency propagation of acoustic waves. Depth is detected by time-stamped returning echoes from the water-sediment interface, where the liquid-solid boundary is indicated [1]. In many construction projects within the Indonesian waters, single-beam echosounders are still much preferred than other methods as many of the coastal environment is dominated by shallow water ports, low gradient coastal morphology, and wide intertidal area [2].

In the port development phase, depth detection plays a crucial role, specifically to provide the best volume estimates for dredging purposes [3]. However, the liquid-solid boundary interface in a muddy seabed is not easily detected by the acoustic waves due to its unique rheological properties and mechanical behaviours [4]. Depth observation through echo-sounding is particularly adapted to detect a sharp liquid-solid interface [5], rather than the gradual change of the rheological properties (e.g., density and yield stress) commonly observed in muddy seabed [6]. Studies on the use of standard high-frequency (100-210 kHz) and low-frequency (15-33 kHz) echosounders in this particular environment show that
the presence of fluid mud is indicated by a significant difference between the depths observed by these two standard frequencies [7]. The different sets of acoustic depth thus postulate one question: which one of the indicated depths can be defined as the navigable depth?

This study aims at investigating the depths measured by a dual-frequency hydrographic echosounder in a muddy environment. The intention is to understand the extent of the uncertainty of a depth-sounding system to precisely locate the navigable, or nautical depth, in which the navigable fluid mud ends and the non-navigable seabed begins [8]. To facilitate such an intention, simultaneous probing of the liquid-solid interface is carried out by means of a free-falling cone penetrometer. This instrument gives measures of the strength of the seabed by penetrating the water-mud column under its own weight [9].

Our study site is located in the north coast part of Java Island, specifically in Patimban, a village on the northeast coast of the Subang District of the West Java Province, where a port development phase is currently undergoing. We conduct the survey over a breakwater pre-construction site to obtain acoustic depths from a standard dual-frequency echosounder and physical depths from a free-falling cone penetrometer. In this paper, we present a general vertical discrepancy between the depths detected by a standard high- and low-frequency echosounder, as well as a general vertical discrepancy between the acoustic and physical depths. The discrepancies serve as state-of-the-art information to explore the relation between the acoustic depths, determined by the acoustic impedance observed in the water-seabed interface by echosounders and the physical depths. In this instance, the physical depth is determined by the change of acceleration and computed shear strength observed by the cone penetrometer.

2. Materials and method

2.1. Investigation domain

The domain of investigation is situated in the north coast part of Java Island. Patimban is a village on the northeast coast of the Subang District of the West Java Province. The area is located in the west end of the Eretan Bay, a stretch of coastline embayment enclosed by Cipunagara and Cimanuk River outlets, respectively, in the west and east parts (Figure 1). The approximate slope of the beach profile is 0.2%. The planned navigation entry channel of the Patimban port elongates to the north-northeast direction.

Earlier studies suggest that the deltaic promontory in the west and east of Eretan Bay, i.e., Cipunagara and Cimanuk River outlets, have experienced extensive deposition resulting in coastline advancement [10]. In particular, the selected site for the study presented in this paper is connected mainly to the Cipunagara River basin, where massive ‘new land’ is developed due to deposition of sediment in the order of several tens of hectares per year [11]. The hinterland region, i.e., the Cipunagara watershed, is a catchments area with an approximate size of 1,203 km². Information on the yield of sediment produced by the Cipunagara watershed is least known. Nevertheless, simulation on sediment yields from nearby watersheds having comparable size indicates an annual magnitude of within the order of one to two million tons [12].

Several works related to physical coastal processes in the domain in question have been recently published. Among others, data on the sedimentation rate in the port development area has been reported. By means of an ad-hoc numerical simulation, the rate of sedimentation in the west of Eretan bay is approximated as in the order of 0.6 m/year and up to 0.8 m/year near the coastline on the west side of the port development area [13]. It turns out that official publications by the Indonesian hydrographic authority confirmed rapid changes of coastline expansion in the Cipunagara River outlet, as it is reflected by an updated version of nautical charts of the area. In this instance, the nautical chart for the region in question from 2010 is updated by the 2013 version to take into account the change of coastline. In this paper, we will be focusing on a breakwater pre-construction site bordered by an area of approximately 500 and 400 m.
Figure 1 Patimban port area development in the Eretan bay NW Java coast. Contoured depths are after [2] and presented in metres. The Cipunagara and Cimanuk River outlets enclosing the Eretan Bay are shown as blue lines in the insets (top-left and bottom-right corner). The study area is located at the NE breakwater pre-construction site, covering four breakwater points (red circles).
2.2. Experimental design

We design a field experiment to test the detection capability of both acoustic and physical methods in muddy coastal waters. An illustration of this experimental design can be seen in Figure 2. We design several surveys transects over a breakwater pre-construction site the study area (Figure 3), hereinafter considered as dynamic sounding. For the sake of compactness of the presentation in this paper, we present observations from four survey transects perpendicular to the NE breakwater line with nine probing points at each survey line. The survey is comparable to 1b order of IHO S-44 Standard. The launch operation is executed by the Category A Hydrographic Surveyor Profession Education Program of Institut Teknologi Bandung in January 2020 as part of the Complex Multidisciplinary Field Project [14].

![Figure 2 Experimental design](image-url)

**Figure 2** Experimental design [15]. Acoustic depths obtained from dual frequency single beam echosounder are compared to physical depths obtained from GraviProbe 2.0 free-falling cone penetrometer. Conceptually, high-frequency echosounder (200 kHz) will indicate the water-soft sediment boundary, while the low-frequency echosounder (24 kHz) will indicate the soft-hard sediment boundary. This concept is tested using a physical measurement using the free-falling cone penetrometer.
Figure 3 Survey design and data procurement. Dynamic SBES survey is carried out perpendicular to the breakwater line. Probing points are named after the corresponding breakwater points with an additional A to H from the northernmost to the southernmost points and ø for the central points. Acoustic and physical depths at points marked by blue squares will be studied in Figure 4.

The echo-sounding employs Odom Teledyne Echotrac MK III dual frequency echosounder, with standard high frequency (200 kHz) and low frequency (24 kHz) signals. It detects the time arrival of returning echo from the seabed based on the gradient of acoustic impedance observed over the boundary of the water and sediment layers [1]. We define the speed of sound for the echosounder by deploying a sound velocity profiler in the water column at the beginning and end of the survey. We compute the harmonic mean to define the sound speed throughout the echo-sounding operation. Vertical separation between the seabed and surface is calculated by involving the speed of sound observed during the survey as profiled by a sound velocity profiler. The higher frequency sound is expected to detect the interface between the water and soft sediment layers, while the lower frequency sound shall penetrate further and detects the interface between the softer and denser sediment layers [4].

In addition to the echo-sounding, a physical method for the detection of the seabed is carried out by deploying a GraviProbe 2.0 free-fall cone penetrometer (8 kg, 5 cm diameter) provided within a collaborative work of PT Geotronix Indonesia, dotOcean, and the Patimban project management team. The probing is intended to assess the physical profile of the sediment layers, particularly within the liquid-solid boundary around the seabed, in terms of shear strength [5]. Such a physical profile is observed according to the gradient of the acceleration, in which the penetrometer will start to decelerate at the interface of a solid bottom [9]. In this study, we use the penetrometer to give an indication of the shear strength gradient of sediment layers within the interface of water column and sediments. The penetrometer is deployed over the designated probing points except for the TAW-43B, TAW-43C, TAW-43D, and TAW-43E stations for safety reasons. The deployments rely on a manual winch, where the weight connected to the probing rope is deployed first to ensure that the penetrometer will not be drifted at a great distance from the target points. In addition, an anchor is lowered to ensure that the vessel’s drift is approximately within a 10 m range from the designated probing points.
Continuous sounding is carried out simultaneously with the probing operation to obtain a direct comparison between the instantaneous acoustic/echo-sounding and physical depths probing while the vessel is nearly static, hereinafter considered as static sounding. Water level correction due to tides is obtained from a tide station installed by the Patimban project management team.

2.3. Assessment of agreement
Having the acoustic depths defined by standard high- and low-frequency sounding, we conduct a direct comparison between the two instantaneous acoustic depths to see their general discrepancy in our study area. Firstly, the comparison is carried out at each probing station, where depth observation through echo-sounding is carried out simultaneously with gravity probing, denoted as the physical measurement. In this first step, we intend to compare acoustic and physical depths over a point in which the vehicle remains relatively static, denoted as the static measurement. Quality control over the acoustic data set is carried out by visualising the acoustic depths and setting a specific depth limit from the visual observation to define and remove data outliers. We decide to set the depth limits visually, as we obtain a proportionate number of data outliers from low-frequency sounding in several locations compared to the data points with ‘true’ average values, which are reasonably closer to the depths obtained from high-frequency sounding (e.g., Figure 4b and h). Having the outliers eliminated, we compute a 95% confidence interval to check if our data set complies with the 1b order of IHO S-44 Standard.

Subsequently, we define the instantaneous physical depths at each probing point by visually delimiting a depth value in which the GraviProbe acceleration profile decreases by a significant gradient. In addition, we compute the effective shear strength limits [5]:

\[ \sigma = K_{\text{sigma}} \cdot \rho^n \]

where \( K_{\text{sigma}} = 7 \cdot 10^7 \) and \( n = 6.67 \) [5,16] to check whether the defined physical depth falls within a definitive liquid-soil boundary. In this regard, we consider a safety term, namely the nautical depth, defined as a solid seabed interface with the density of \( \rho = 1.2 \text{ t/m}^3 \) [4,8]. The instantaneous physical depths are compared to the two instantaneous acoustic depths at each probing station to observe their vertical discrepancy. Having the discrepancies computed in each station, we define probing stations with extreme vertical discrepancy values as outliers and remove them for further processes.

Finally, we investigate the depth comparison over four survey lines to observe the consistency of the vertical discrepancy when the vehicle is moving, denoted as dynamic measurement. Similar steps of quality control are carried out to the depths obtained from this dynamic measurement. We remove data outliers, mostly from the low-frequency sounding, by visualising the acoustic depths and setting a specific depth limit from the visual observation. As the dynamic measurement is carried out several days before the physical measurement, a tidal correction is performed to both types of measurement using the water level observation from a tide station installed by the Patimban port authority. The average discrepancy presented in this study is obtained from the comparison between the tidal-corrected acoustic depths from the dynamic measurement and the tidal-corrected physical depths, as depth sounding surveys are commonly carried out using a constantly moving vehicle.

3. Results and discussion
3.1. Seabed detection from dual frequency echoshounder
From the static sounding, we found an average vertical discrepancy of \( 0.34 \pm 0.07 \) m between the depths obtained by high- and low-frequency sounding. In the dynamic sounding, the average vertical discrepancy increases up to \( 0.48 \pm 0.09 \) m. The values are comparable to the echo-sounding criteria [1], where typical values for the difference between the high- and low-frequency signals vary from 0.3 to several metres. In both measurements, we found that the depths obtained by high-frequency sounding are consistently shallower compared to those obtained by low-frequency sounding (Figure 4 and 5). In
addition, the high-frequency reflectance is typically consistent and exhibits a stable contrasted line in the recorded acoustic signals, while the low-frequency often appears as trembled lines. Such a trembled line might occur due to a weak density gradient within the mud layer having various densities [1]. As the lower frequency sound penetrates further to detect the interface between the softer and harder sediment layers, the muddy environment does not allow this interface to be easily detected, compared to an environment with a more distinctive rheology.

3.2. Seabed detection from probing
The instantaneous physical depths are defined at each probing station by visually delimiting a depth value in which the GraviProbe acceleration profile decreases by a significant gradient (Figure 4). To see how the physical depth detection relates to the change of rheology within the seabed, we observe the change of the computed static shear strength at the physical depth defined from the visual delimitation. In general, we found that the significant gradient of deceleration coincides with the start of a deviation in the static shear strength profile. The deviation roughly matches with the effective shear strength limits \( \sigma \) (Equation 1) of \( \pm 23.62 \) Pa, shown in Figure 4a, c, e, and g as a couple of vertical dashed lines. From our field measurement, we found that the deviation of the static shear strength profile starts off as a decrease in the shear strength values that continues to oscillate approximately within the effective shear strength limits \( \sigma \) until a significant increase is observed. This significant increase might be marking the limit of a ‘fluid mud’ layer [5], but this hypothesis will not be observed further in this paper.

Having the instantaneous physical depths at each probing station defined, we compare them with the instantaneous acoustic depths observed by the high- and low-frequency sounding. From the comparison, we found that the instantaneous physical depths defined at TAW-46ø, EBD-2F, and TAW-43H stations shall be excluded from further analyses as they return instantaneous physical depths with extreme vertical discrepancy to the acoustic depths compared to those observed in other probing stations. With this knowledge, we can proceed to compare the physical depths with the acoustic depths obtained from the dynamic sounding.

3.3. Vertical discrepancy between acoustic and physical depths
As the dynamic sounding is carried out several days before the physical measurement, a tidal correction is performed to both types of measurement using the water level observation from a tide station installed by the Patimban project management team. The results are shown in Figure 5. In general, we can see that the high-frequency echosounder (HF-SBES) tends to underestimate the physical depths (GP) while the lower frequency (LF-SBES) tends to overestimate it. We can also see an extreme discrepancy between the physical and acoustic depths is observed over the TAW-46ø and EBD-2F stations. Although it is not evident in the figures, we also found an extreme discrepancy over the TAW-43H station during the quality control of the static measurement. Hence, the physical depths observed in these stations are removed from the dataset before we compute the average vertical discrepancy as they seem to return outlier measurements which will disrupt the averaging process.
Figure 4 Instantaneous depth profiles at the four bounding survey points, depicted in Figure 3. Physical depths defined by gravity probing (GP) are depicted in (a), (c), (e), and (g). GP is defined when the acceleration profile ($a$) decreases by a significant gradient and the static shear strength ($\tau$) reaches the effective stress range ($\sigma$) for $\rho = 1.2$ t/m$^3$ (dashed lines) described in [5]. Acoustic depths defined by high- and low-frequency sounding (HF-SBES and LF-SBES, respectively) are depicted in (b), (d), (f), and (h). Data outliers and 95% confidence interval have not been removed and defined in the plots, respectively. GP is plotted over the acoustic depths to observe the general discrepancy.
Figure 5 Acoustic profiles over survey lines with physical depths defined at probing stations. Data outliers and 95% confidence interval of the acoustic and physical depths have not been removed and defined in the plots, respectively. In the calculation of general vertical discrepancy, depths by probing at TAW-46a, EBD-2F, and TAW-43H stations have been removed. All depths have been corrected to the tides occurring at the study area during the survey period. HF-SBES: Acoustic depths measured by high-frequency SBES. LF-SBES: Acoustic depths measured by low-frequency SBES. GP: Physical depths measured by gravity probing. The average discrepancy diagram is shown in Figure 6.

Figure 5a, we can see that most of the physical depths across the TAW-46 line lie close to the low-frequency acoustic depths, except over the TAW-46B station. A similar finding is observed across the EBD-2 line, except over the EBD-2G station (Figure 5b). These findings confirm the echo-sounding criteria by PIANC [8], which states that nautical depths are often determined by low-frequency sounding. Although many of the physical depths also lie close to the low-frequency acoustic depths across the TAW-43 and EB-2 lines (Figure 5c and d), the phenomenon is less consistent along these two lines. The inconsistency might occur as the area along these lines are relatively deeper than those in the
TAW-46 and EBD-2 lines. Despite the sub-meter difference, we observe a greater deal of inconsistency in the depths measured by the low-frequency echosounder compared to those in the shallower area. The inconsistency of the low-frequency depths is also observed towards the northernmost part of each line, where the seabed is gradually deeper. Based on this finding, we suggest that the determination of nautical depth from low-frequency sounding needs to be accompanied by a general knowledge on the behaviour of the acoustic wave compared to the average water depth.

From the vertical comparison, we compute an average vertical discrepancy of around 0.26 ± 0.17 m between the tide corrected physical and high-frequency depths, and around 0.23 ± 0.19 m between the tide corrected physical and low-frequency depths (Figure 6). The high-frequency depths tend to overestimate the physical depth, while the low-frequency depths tend to underestimate it. The quantification of vertical discrepancies between the physical and acoustic depths serves as a piece of important preliminary information on the behaviour of acoustic waves within the liquid-solid boundary and how it compares to a subsequent physical-based depth measurement.

![Figure 6 Diagram of average discrepancies. HF-SBES: Average depth measured by high-frequency SBES. GP: Average depth measured by gravity probing. LF-SBES: Average depth measured by low-frequency SBES.](image)

4. Conclusions

From this study, we conclude that in a muddy environment of the studied area in question, the high- and low-frequency echosounders give distinctive acoustic depth measurements with a vertical discrepancy of 0.49 ± 0.25 m when performed with a moving vehicle. Compared to the depths measured by probing, the high-frequency echosounder tends to underestimate the physical depth by 0.26 ± 0.17 m, while the low-frequency echosounder tends to overestimate the value by 0.23 ± 0.19 m. The quantification of vertical discrepancies between the physical and acoustic depths provides state-of-the-art knowledge on the uncertainty of depth observation by acoustic echo-sounding, specifically in a muddy environment. Further studies on the comparison between the defined depths and a measure of nautical depth will advance the knowledge and have the potential to be turned into a standardised procedure on depth sounding at environments dominated by fine-sized sediments. Our study hence suggests the importance of taking into account considerable measures of discrepancy when depth sounding is being carried out in a muddy environment. We also suggest that a procedure must be made available to understand the extent of the uncertainty of a depth-sounding system to precisely locate the liquid-solid boundary within the water-seabed interface, particularly where muddy sediments dominate the seabed.
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