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Topographic Change Detection around Underwater Artificial Structures Using Airborne Bathymetric Light Detection and Ranging Data: Case Study of Won-Pyeong Beach

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Coastal protection structures such as submerged and detached breakwaters are increasingly being installed to prevent coastal erosion, scouring, and subsidence, which pose serious threats to the stability of these structures. In this study, we used airborne light detction and ranging (LiDAR) bathymetry (ALB) to detect precise topographic changes around artificial underwater structures. Digital surface models with a 1 m grid resolution were obtained for the Won-Pyeong Beach area from ALB data acquired in November 2020 and July 2024. We analyzed the topographical changes (erosion/deposition patterns) and bathymetric contour shifts around pre-existing submerged and newly installed detached breakwaters and groins. ALB has been validated as an effective tool for acquiring precise bathymetric data in shallow waters inaccessible to vessels, with ALB data serving as a foundational baseline for assessing structural conditions, such as scouring and subsidence, and managing coastlines.

1. Introduction

The coastal zone is not only a complex physical space where land, atmosphere, and ocean interact but also a vital area where human economic activities and habitation are concentrated.(1–3) However, recent phenomena such as sea-level rise driven by climate change, increased typhoon intensity, and accelerated coastal erosion pose serious threats to the safety of coastal infrastructure.(4) In particular, coastal protection structures such as breakwaters, detached breakwaters, and revetments are subjected to the direct impact of wave energy. Consequently, the scouring and subsidence of the seabed terrain surrounding these structures are the primary causes of structural failure.(5) To address these issues, coastal improvement projects involving the installation of various artificial structures such as submerged breakwaters, detached breakwaters, and groins are being implemented. However, the installation of these artificial structures can induce unintended sedimentation on the surrounding seabed, as well as scour or

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erosion, which may threaten their long-term stability.(6,7) In particular, beach topography, composed of unconsolidated sediments such as clay, sand, gravel, and shell fragments, is distinct from hard rocky coasts because it can undergo significant morphological changes over short periods owing to external forces such as waves, tides, and longshore currents. In general, a beach profile consists of a bar, trough, step, and berm, as shown in Fig. 1.(8) A bar is a convex sedimentary structure formed on the seabed near the surf zone, and as waves break over the bar, a significant portion of their energy is dissipated. A trough is a concave depression located between the bar and the shoreline, where longshore currents are concentrated or the active vertical movement of sediment occurs. A berm is an upper beach area affected by tides or waves that form or disappear, depending on seasonal wave characteristics. A step is a section where the sandy beach forms a steep slope under high-wave conditions and is closely related to wave run-up. Therefore, when installing structures in beach environments, precise monitoring is required, as morphological changes such as local scouring or abnormal sedimentation may occur owing to the altered effects of waves, tides, and longshore currents.

Bathymetric surveys have traditionally relied on ship-based echo-sounding technology. Although the multi-beam echo sounder (MBES) has established itself as the standard for deep waters, the surf zone, ranging from 0 to 10 m in depth, has remained a “blind spot” for surveys.(9) This zone represents the interface where the limitations of land- and vessel-based surveys converge, acoustic signals are scattered by air bubbles generated by breaking waves, and the risk of vessel grounding is ever-present owing to small depths.(9) Airborne light detction and ranging (LiDAR) bathymetry (ALB) was developed specifically to address the challenges associated with surveying these shallow waters; it utilizes laser scanners mounted on manned aircraft or unmanned aerial vehicles to emit laser pulses, which measure depth by analyzing the full waveform of the pulses reflected from the water surface and seafloor.(10) This technology is advantageous because it allows for the rapid and safe acquisition of continuous topographic data, even in hazardous waters that are inaccessible to vessels. The core of the ALB system leverages the physical properties of green lasers capable of penetrating water. Unlike conventional topographic LiDAR, which typically employs an infrared wavelength (1064 nm), ALB utilizes a green wavelength (532 nm), which exhibits the lowest absorption rate in water.(10) In general, ALB systems can construct more precise seafloor topographic data by emitting an infrared laser

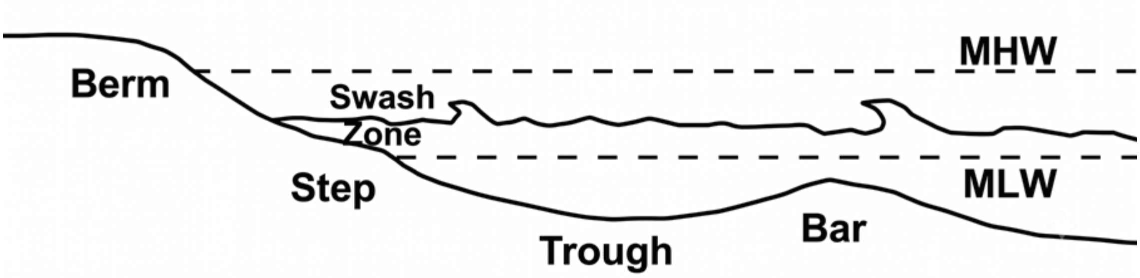

Fig. 1. Profile of coastal area.(8)

for water surface detection and a green laser for seafloor detection, either simultaneously or sequentially.[11]

In Korea, the "Guidelines for Post-Construction Management and Effectiveness Evaluation of Coastal Improvement Facilities", established in 2017 by the government, mandate that safety inspection methods and procedures adhere to the "Detailed Guidelines for Safety Inspection of Port Facilities". Furthermore, condition assessments are required to evaluate factors such as structural subsidence, foundation scour, and baseline displacement. However, conducting high-precision hydrographic surveys under actual field conditions is challenging because of the physical characteristics of the coastal zone, including small depths (0–10 m), strong wave action, and the presence of underwater vegetation. Consequently, cases in which post-construction management projects failed to adhere to the prescribed hydrographic survey procedures have been reported. In these instances, even MBES can only operate at a limited capacity by tilting the detection sensor, resulting in failure to secure basic seafloor topographic data (e.g., digital elevation models) surrounding the structures. Furthermore, the "Detailed Guidelines for Safety Inspection of Port Facilities" establish quantitative criteria for identifying critical defects in coastal structures as part of the condition assessment process. Specifically, the guidelines define thresholds for structural subsidence (≥16 cm for non-progressive and ≥12 cm for progressive) and foundation scour (≥90 cm). Consequently, high-precision survey data must be acquired and managed with centimeter-level accuracy to meet these standards. Therefore, in this study, we used ALB data to establish a dataset that satisfies facility management standards that require high precision. Furthermore, we compared the changes in seafloor topography before and after the installation of coastal defense structures designed to prevent coastal erosion.

2. Data and Methods

2.1 Study area and data

This study area is located at the site of a coastal improvement project implemented at Won-Pyeong Beach in Samcheok-si, Gangwon Special Self-Governing Province. The beach features a sandy coastline spanning approximately 2 km. Following the construction of a nearby port and tourism development in the vicinity, a coastal improvement project was initiated with the primary objective of restoring and protecting sandy beaches. As a result of the project, which was executed from 2017 to 2023, in addition to the three submerged breakwaters previously installed in 2016 [Fig. 2(a)], two detached breakwaters and two groins have recently been installed, as shown in Fig. 2(b). Annual coastal erosion monitoring surveys have been conducted in the study area since 2015. Although the area received the lowest safety rating of Grade D from the initial survey for 2015–2021, it has maintained a moderate rating of Grade B since 2022.

An ALB survey was conducted following the "Regulations on Hydrographic Survey". These included compliance with system performance standards, ground control point surveys, global navigational satellite system base station installation, and system calibration during the preparatory phase. During the actual survey flight, the operation adhered to the planned optimal flight altitude and speed as well as relevant regulations for data supplementation and feature

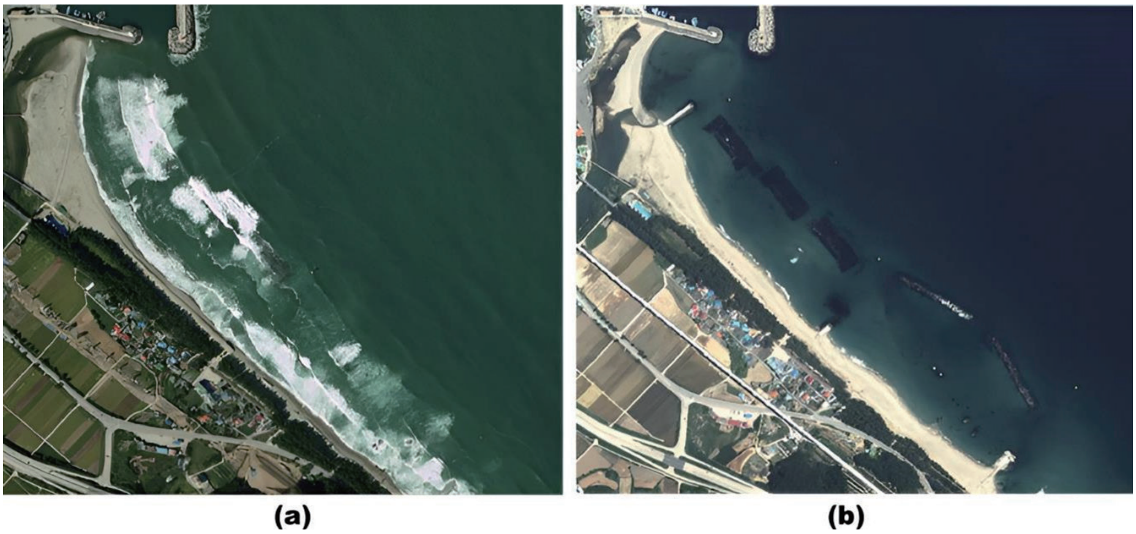

Fig. 2. (Color online) Aerial images of the study area taken in (a) 2019 and (b) 2024.

identification. The processing of the acquired data followed established standard processes, including the removal of noise caused by atmospheric particles and waves and the verification of data voids and point density adequacy. An accuracy assessment conducted through comparison with MBES data yielded a mean error of 0.179 m and a root mean square error of 0.224 m. These results confirmed that the data satisfied the requirements for "Order 1b", which is a hydrographic survey classification for areas where under-keel clearance is not an issue and a general depiction of the seafloor is adequate as defined by the International Hydrographic Organization Standards for Hydrographic Surveys.[12–14]

2.2 Methods

ALB is an active remote-sensing technique used to measure the depth of relatively shallow coastal waters. This technique is based on the simultaneous use of two lasers in the light range: infrared and green. The infrared pulse reflects off the surface of water or land, whereas the green pulse penetrates the water and reflects off the bottom of the water body. The depth is determined on the basis of the difference in registration time between the beam reflected from the water surface and that reflected from the bottom, as shown in Fig. 3. To calculate the precise coordinates and depth of a point on the seafloor, the geometry of the scan, speed of light changes between media, and light refraction must be mathematically modeled and calculated. More detailed information can be found in previous publications.[10,11]

3. Results

In this study, digital surface model data with a 1×1 m^2 grid resolution were constructed using ALB data acquired in November 2020 and July 2024. On the basis of these results,

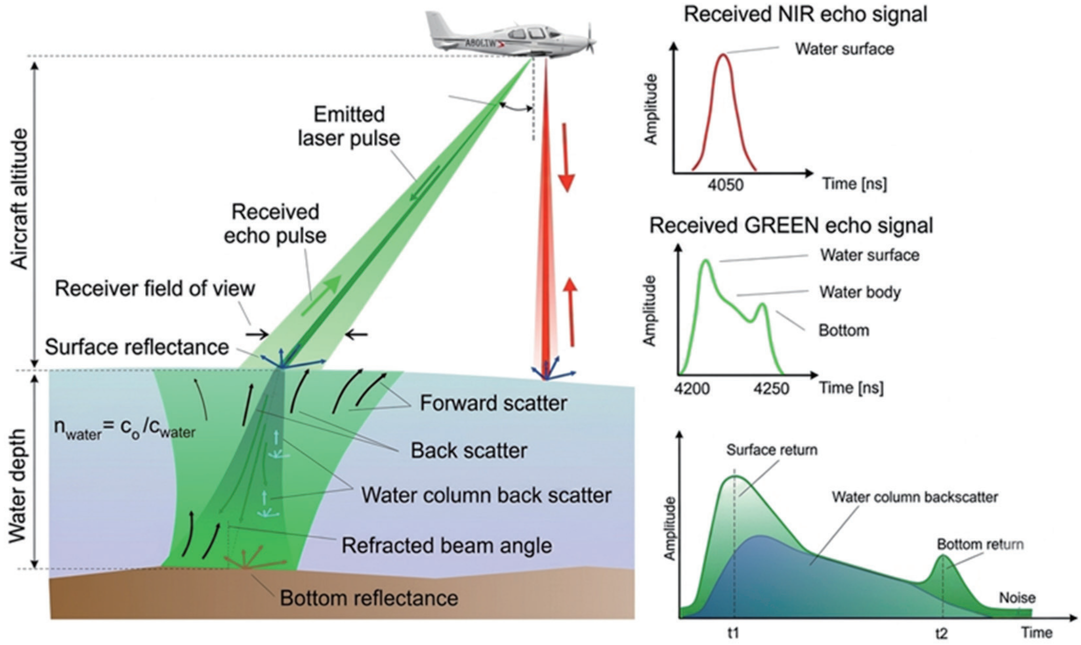

Fig. 3. (Color online) Operating principle of ALB with topographic (NIR) and bathymetric (green) laser scanners mounted on the same airborne platform.(10)

bathymetric maps of the study area were generated for both years (Fig. 4). The changes in the underwater topography surrounding the structures between 2020 and 2024 were analyzed by categorizing them into morphological changes (related to sediment transport around the structures) and bathymetric contour shifts (related to the closure depth). The year 2020 corresponds to the period following the installation of the three submerged breakwaters on the west side. Regarding the characteristics of the topographic changes, a pattern of gentle sedimentation relative to the surrounding seabed was observed around pre-existing submerged breakwaters extending from the offshore side toward the coast, as shown in Fig. 4(a).

In the intermediate section, approximately 100 m between the three submerged breakwaters and the detached breakwater on the right, a trough (indicating an erosional trend) developed and was predominantly concentrated toward the submerged breakwaters, as shown in Fig. 4(a). This trough is characterized by the formation of a 7 m depth contour, which is approximately 2 m deeper than the surrounding 5 m contour. In contrast, a round shoal (circular nearshore bar) with a diameter of approximately 100 m formed in the direction in which the detached breakwater was scheduled for installation in 2023. In Fig. 4(b), the installation of two detached breakwaters to the right of the three pre-existing submerged breakwaters and one groin located near the shoreline, as well as their neighboring underwater topography, are presented as bathymetric maps. Regarding the topographic characteristics, erosion (scouring) was observed near the newly installed detached breakwaters and groins. Conversely, a sedimentation (accretion) trend was observed on the shoreward side of the detached breakwaters. Furthermore, depth contours ranging from approximately 7 to 9 m developed near both ends of the detached breakwaters.

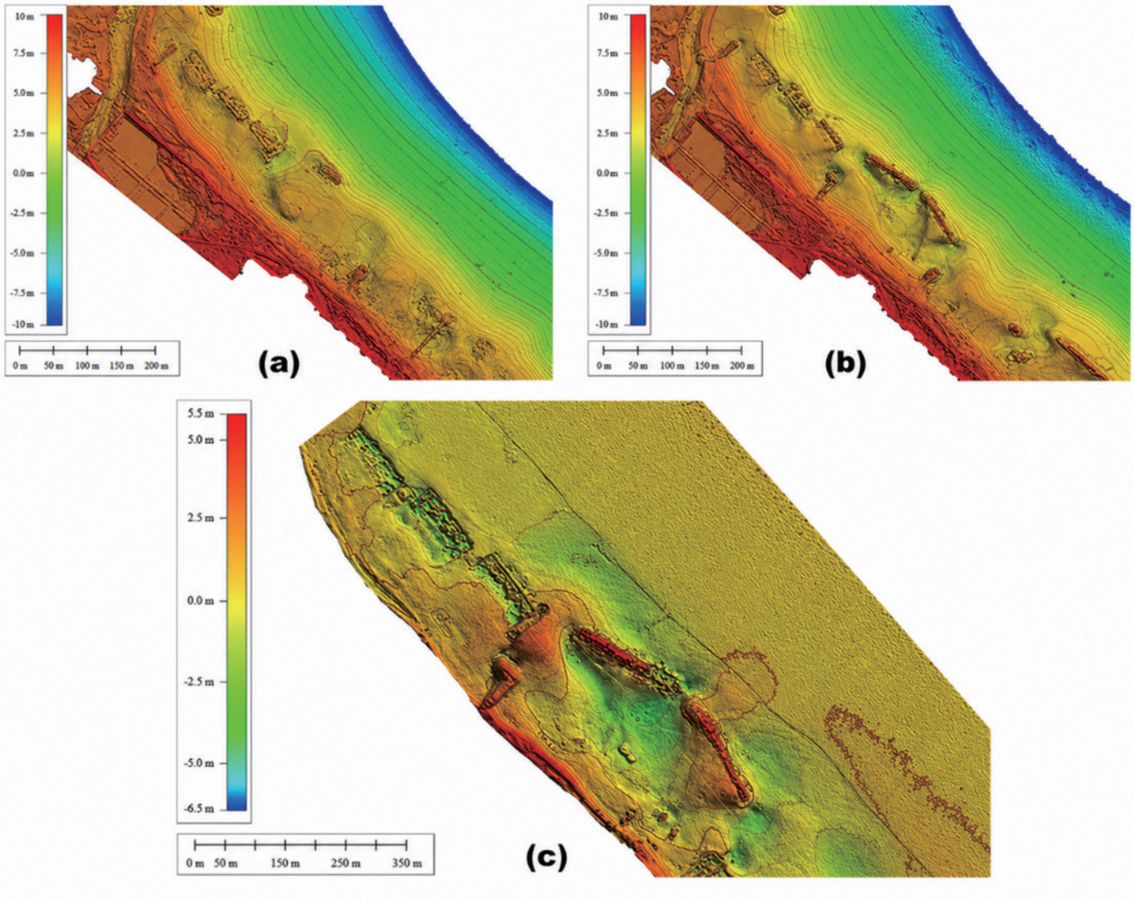

Fig. 4. (Color online) Bathymetric maps of the study area for (a) 2020 and (b) 2024, and (c) underwater topography changes in erosion and deposition.

This indicates an erosional (scouring) trend, with depths increasing by approximately 2–4 m compared with the surrounding depth of approximately 5 m, as shown in Fig. 5.

A sedimentation zone with a scale of approximately 100 m (Fig. 6) was observed between the submerged and detached breakwaters. In addition, a trough-shaped erosion zone was identified between the two detached breakwaters, and an extensive erosion area approximately 200–300 m in scale was observed on the shoreward side of these two structures. Erosion zones spanning approximately 100–300 m were detected on the seaward sides of the submerged and detached breakwaters. A detailed examination of the ridge-shaped sedimentation section formed between the submerged and detached breakwaters revealed that the section had a height of approximately 3 m, a width of approximately 50 m, and a length of approximately 100 m. In contrast, erosion was observed across most sections of the three submerged breakwaters installed in 2016, as shown in Fig. 7. This is either caused by the stabilization process of offshore structures under load or indicative of a subsidence trend; therefore, the continuous monitoring of these changes is necessary.

The depth contours (isobaths) were compared for 2020 and 2024. The concept of “closure depth” was utilized to determine the seaward boundary of a littoral (or sand transport) cell. This

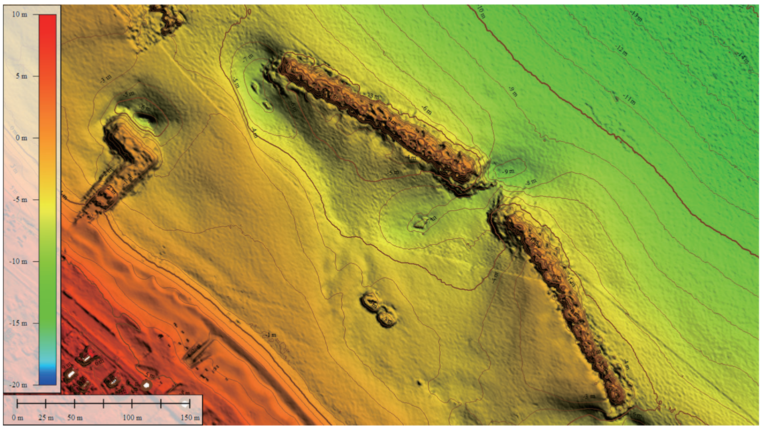

Fig. 5. (Color online) Bathymetric map of the right side for 2024.

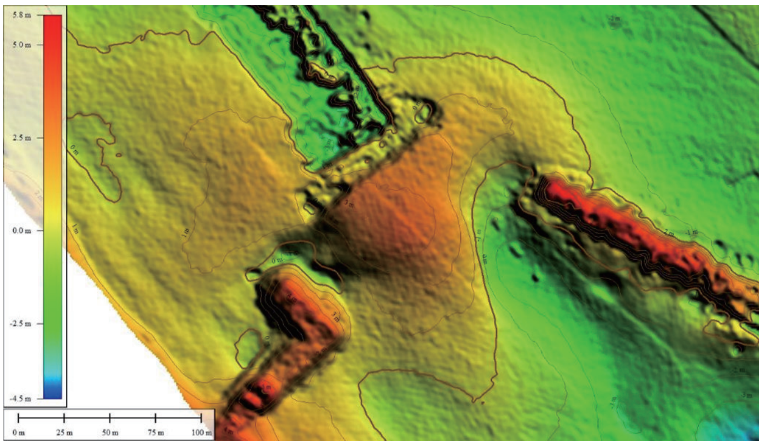

Fig. 6. (Color online) Underwater topographic changes between the submerged and detached breakwaters.

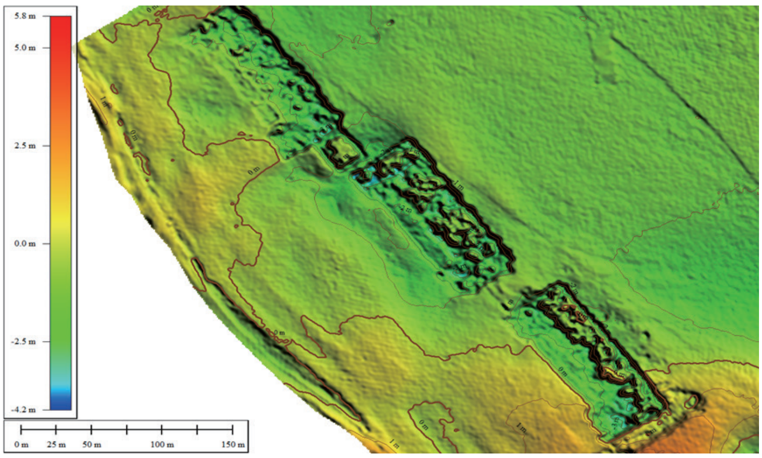

Fig. 7. (Color online) Underwater topographic changes of the submerged breakwaters.

refers to the depth at which no significant change occurs over time within beach profiles measured at regular intervals. Morphologically, the changes in depth contours within the study area exhibited significant variations near the 5 m contour, where underwater structures were installed, as shown in Fig. 8. Conversely, areas deeper than the 8 m contour showed similar trends. However, at the 10 m contour on the seaward side of the detached breakwaters, the northwestern section shifted landward by approximately 20 m, although the southeastern section exhibited minimal change.

4. Discussion

In this study, ALB data were collected to observe changes in seafloor topography around coastal structures at Won-Pyeong Beach, and diverse morphological changes were observed in the seabed surrounding underwater structures. First, significant topographical changes were detected around the two newly installed detached breakwaters. A large trough (erosion) formed in the central section between the structures and erosion zones, with depths of approximately 2–3 m at the outer and inner ends of the breakwaters. Second, the three existing submerged breakwaters showed a tendency toward subsidence compared with their status in 2020. Third, the observation of the 10 m isobath revealed a shift of approximately 28 m toward the coastline in the submerged breakwater section and a shift of approximately 0–20 m inward (toward the coastline) in the detached breakwater section. These data are considered valuable baseline information for estimating closure depth.

Note that the ALB datasets used in this study were acquired in November 2020 (Autumn/Winter transition) and July 2024 (Summer). Generally, beach profiles are subject to seasonal variations. However, several lines of evidence suggest that the morphological changes observed between 2020 and 2024 are predominantly governed by the newly installed artificial structures

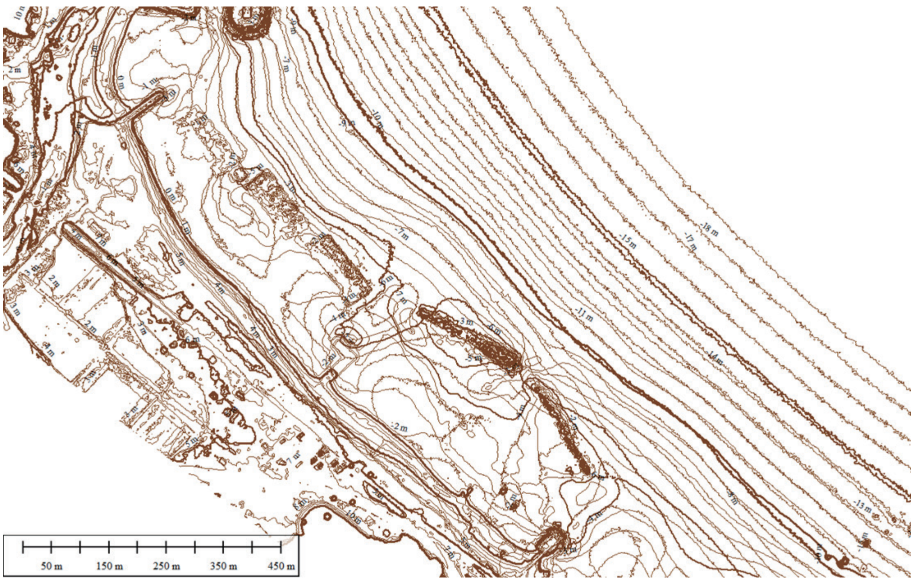

Fig. 8. (Color online) Depth contour change in the study area.

rather than seasonal variations. The spatial distribution of erosion and deposition patterns is strictly localized around the detached breakwaters. Specifically, the formation of a prominent ridge-shaped sedimentation section on the shoreward side of the detached breakwaters and the severe localized scouring at the structure tips are classic hydrodynamics responses to artificial barriers. Nevertheless, to completely discriminate seasonal variations from structure-induced morphodynamics, continuous multi-seasonal monitoring is required in future studies.

To evaluate these structural risks from a practical maintenance perspective, the observed topographic changes were directly compared with the quantitative safety thresholds specified in the "Detailed Guidelines for Safety Inspection of Port Facilities". The ALB-derived differential terrain analysis revealed that the localized scouring depths near both ends of the newly installed detached breakwaters reached approximately 2.0 to 4.0 m. This significantly exceeds the critical safety threshold for foundation scour (90 cm) by a factor of two to four, indicating a high potential risk to the structural stability of the breakwater foundations, which mandates immediate maintenance attention. Regarding subsidence, although the absolute structural displacement of the three pre-existing submerged breakwaters cannot be perfectly isolated from the surrounding seabed movement, the widespread erosional/lowering trend observed over these structures (Fig. 7) strongly indicates a potential exceedance of the progressive or non-progressive subsidence threshold. These findings quantitatively demonstrate that the high-precision ALB dataset can effectively screen for critical defects that exceed structural safety margins.

On the basis of these results, meaningful possibilities were identified regarding the prediction of seafloor topographic changes within the Marine Utilization Impact Assessment system. First, ALB can replace echo-sounding systems in shallow-water areas. Second, ALB can provide validation by delivering precise seafloor topography change data as a supplement to the numerical modeling experiments. Third, in the case of offshore wind power projects that require a detailed presentation of the erosion and deposition patterns around foundation structures, this technology can be utilized to provide the necessary baseline data.

5. Conclusion

Coastal facilities are structures installed along a coast that utilize, develop, or conserve marine resources. When such facilities are constructed on beaches, potential impacts such as coastal erosion must be carefully considered. South Korea is currently investing a significant portion of the national budget in coastal improvement projects aimed at mitigating coastal erosion. However, because these facilities are typically located in shallow waters with depths of less than 10 m, it is difficult to conduct assessments such as safety inspections required for post-construction maintenance. In this study, the ABL was used to acquire bathymetric data for the Won-Pyeong Beach area. The results confirmed that these data can be effectively utilized for not only the precise detection of topographic changes, but also shoreline management by generating critical information, such as the depth of closure, for analyzing changes in active sediment transport zones and coastal erosion-accretion patterns.

The post-installation management of coastal facilities requires safety inspections, condition assessments, and effectiveness evaluations. Specifically, assessments of the structural subsidence and foundation scouring must be conducted on the basis of field survey data from safety inspections. First, phenomena such as subsidence and inclination can be identified by three-dimensionally detecting changes in the seabed topography surrounding underwater structures. Furthermore, because foundation scouring is closely correlated with the characteristics of erosion and sedimentation changes around structures (e.g., scouring characteristics at the front of a breakwater), these data can serve as a foundational basis for inferring these processes. In this study, detailed depth contours were obtained using the ABL data. On the basis of these results, the data can be used to track closure depth. Furthermore, by accumulating future data, threshold values that define significant depth changes can be derived. However, as the slope becomes extremely gentle at greater depths, an integrated analysis with the MBES data is likely to yield superior results. To achieve this seamless integration, implementing a rigorous methodology for vertical reference harmonization (datum matching) between the two sensors is essential. While ALB data are typically acquired on the basis of an ellipsoidal datum, MBES data rely on a local hydrographic datum. Therefore, data fusion requires transforming both datasets into a unified vertical coordinate system by harmonizing the vertical data. This will minimize systematic biases in the overlapping surf zone, thereby significantly enhancing the accuracy of the joint ALB-MBES terrain analysis of wider coastal areas.

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