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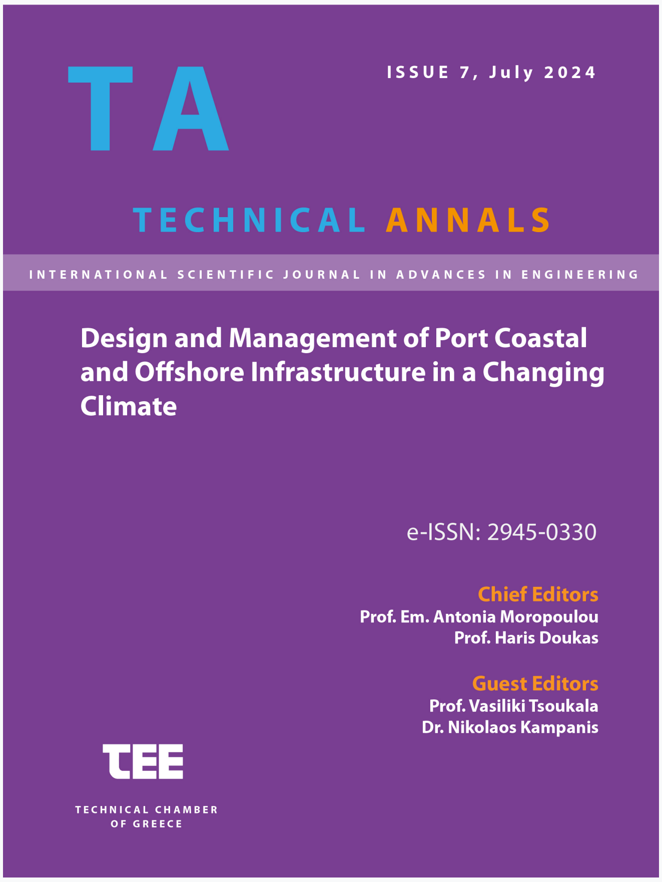

Seabed Morphology Assessment and Pockmark Detection for Port Construction and Maintenance, Using a Multibeam Echo-sounder: A Case study in Katakolo Port, Western Peloponnese, Greece

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Seabed Morphology Assessment and Pockmark Detection for Port Construction and Maintenance, Using a Multibeam Echo-sounder: A Case study in Katakolo Port, Western Peloponnese, Greece

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Abstract. The port of Katakolo is located in the Kyparissian Gulf, where the escape of natural gas is being observed. Result of this systematic leakage is the formation of circular depressions, known as pockmarks, which undermine the integrity of the seabed where port infrastructures might be established. This study investigates the current condition of pockmark formations inside the port of Katakolo, following an incident that occurred in 2009, when sections of the commercial quay sub-sided. Additionally, it studies the morphology and activity of these features and their potential influence on the structural integrity of the port. Detailed bathymetric data, using a multibeam echosounder, were collected and studied. The generated 3D model of the port indicated the presence of active pockmarks, which exhibit elongated, normal and unit shapes, primarily located near the commercial pier, that indeed impose threat to the structural integrity. By identifying the morphology and distribution of these features, this study emphasizes the significance of integrating seabed assessments into port maintenance strategies. The findings also highlight the need for continuous monitoring and adaptive engineering approaches to ensure the long-term stability and operational safety of existing and future port infrastructures.

Keywords: Port Maintenance; Port Safety, Hydrography; Bathymetry; Multibeam Echosounder; Pockmarks.

1 Introduction

The assessment of seabed morphology is a critical component of port construction and maintenance [1, 2], as it significantly influences the stability and resilience of infrastructure. Bathymetric surveys provide essential information for the management and exploitation of ports, ensuring safe navigation, optimizing dredging activities and maintaining adequate water depths for manoeuvring within the ports. However, beyond these conventional applications, a detailed understanding of seabed characteristics is crucial for assessing potential geohazards that may compromise infrastructure resilience over time.

Port construction failures related to seabed morphology are multifaceted and critically impact the stability and integrity of structures, such as breakwaters. Key factors include unfavourable seabed topography causing uneven force distribution, scour and erosion, undermining foundations [3, 4], and differential settlement resulting in tilting or sliding [3]. In particular, geological anomalies such as pockmarks—circular to elongated depressions formed by fluid escape—can present an engineering challenge [5,6] and pose significant risks by altering seabed stability and influencing sediment transport dynamics. These formations may weaken foundation soils, exacerbate erosion processes, and increase the risk of subsidence [7,8], thereby compromising the performance of critical infrastructure such as breakwaters, quay walls, and mooring facilities and require immediate intervention by conducting hydrographic and geological surveys [6,7].

Pockmarks are nearly circular depressions formed where fluids escape upward through fine-grained seafloor sediments [9, 10, 11, 12,13]. These formations are generated by the venting of gas, such as methane, which is often thermogenic [9, 10, 13]. The process as illustrated in Fig. 1, begins with gas generated at depth, migrating upward through minor reservoirs and accumulating in near-seabed sediments.

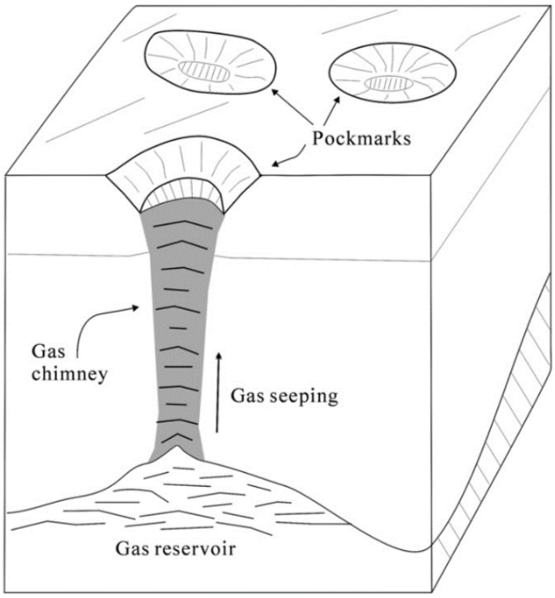


Fig. 1. Diagram illustrating gas seepage from a subsurface reservoir through a gas chimney, leading to the formation of pockmarks on the seafloor (Source: Hovland M., 1989)

This accumulation creates domes on the seafloor, and small tension fractures on these domes allow gas to escape. As the gas venting enlarges these cracks, the venting velocity and erosion increase, leading to a violent burst of escaping gas, which forms a unit pockmark. These unit pockmarks can continue to develop, cluster and coalesce to develop a fully-grown composite pockmark [9, 10].

Pockmarks exhibit diverse morphological characteristics [5,6], influenced by factors such as fluid expulsion rate, sediment composition, and hydrodynamic conditions. They are generally categorized into six morphological classes, as illustrated in Fig. 2. Unit pockmarks are small depression typically measuring 1 to 10 m across and up to 0.5 m deep, probably representing a one-time expulsion event [11, 12,13]. This type is common inside and around normal pockmarks [13]. Normal pockmarks are more common, characterized as circular depressions that range from 10 to 700 m in diameter and from 1 to 45 m deep [12]. Their cross sections can vary from low-angle basin-formed shapes to asymmetrical and steep-walled features, with some even displaying a funnel shape in the centre. Elongated pockmarks are depressions with one axis that is much longer than the other. They occur on slopes and areas of seafloor influenced by strong bottom currents. Eyed pockmarks contain an acoustically high-reflective object on region in its central part, which could either be caused by coarse material remaining after the erosive process (winnowing), from biological activity (dead and living shells) or from authigenic carbonate precipitation. [13]. Strings of pockmarks consist of unit pockmarks or small normal pockmarks arranged in curvilinear chains or strings, which may be kilometers in length. They are suspected to be a result of fluid focusing along near vertical faults, flexures, or weakness zones in the upper sedimentary layer. Complex pockmarks occur as clusters of normal pockmarks or amalgamations of large pockmarks [13].

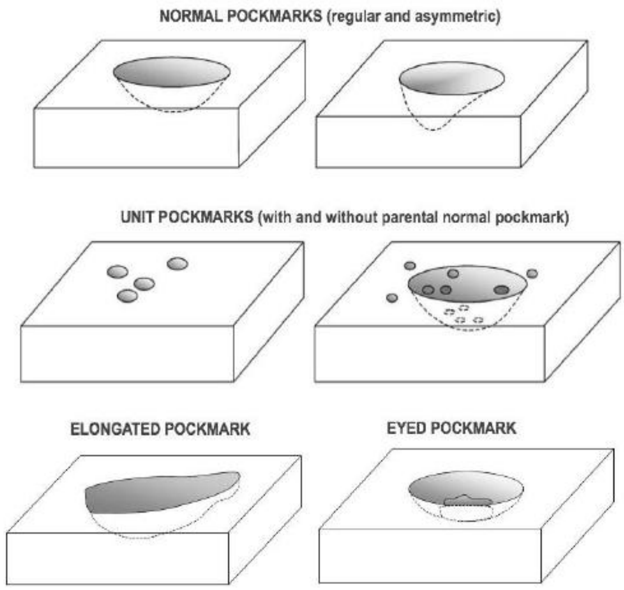


Fig. 2. Pockmark formation main morphological classes. (Source: Hovland M., et al., 2002).

Current bathymetric survey methods offer diverse capabilities, each with specific advantages and limitations, suited to varied applications [16, 17]. For instance, Single beam Echo Sounders provide a cost-effective solution for basic depth measurements but are constrained by data gaps and limited coverage compared to advanced systems [16, 17]. Multibeam Echo Sounders (MBES), significantly enhance seabed mapping accuracy (cm/mm), coverage and data density [16, 17, 18]. However, their operation involves higher costs and sensitivity to sound velocity variations, which can affect precision. LiDAR (Light Detection and Ranging) excels in shallow environments and integrates topographic and bathymetric data but is hindered by high costs and relatively lower resolution than MBES [16, 17]. Spectral Response Bathymetry is advantageous for large-area, low-cost surveys but is restricted to depths of approximately 30 meters in clear waters, with accuracy challenges in meeting rigorous standards [2, 17]. Meanwhile, Radar Altimetry is valuable for deep-water applications and addressing data scarcity, yet it struggles with spatial and temporal variability [17]. These methods collectively cater to diverse needs, balancing cost, depth, resolution, and operational challenges [1, 16, 17].

For the purposes of this study, a high-resolution bathymetric and backscatter survey was conducted, with the primary objective of investigating the distribution and sediment composition of geological formations associated with seepage activity. The port of Katakolo, located in Western Peloponnese, Greece, was selected as the study area due to the documented presence of gas seepages and geological peculiarities, which underscore the site's unique underwater characteristics. The employment of Multibeam Echosounder technology facilitated the detailed mapping of the seabed, by providing wide coverage and overlapping swaths of the investigated area, dense data which enabled the complete representation of the pockmark formations, while the backscatter data provided valuable insights into the acoustic intensity of the seabed, which will further aid in classifying sediment types within the survey area.

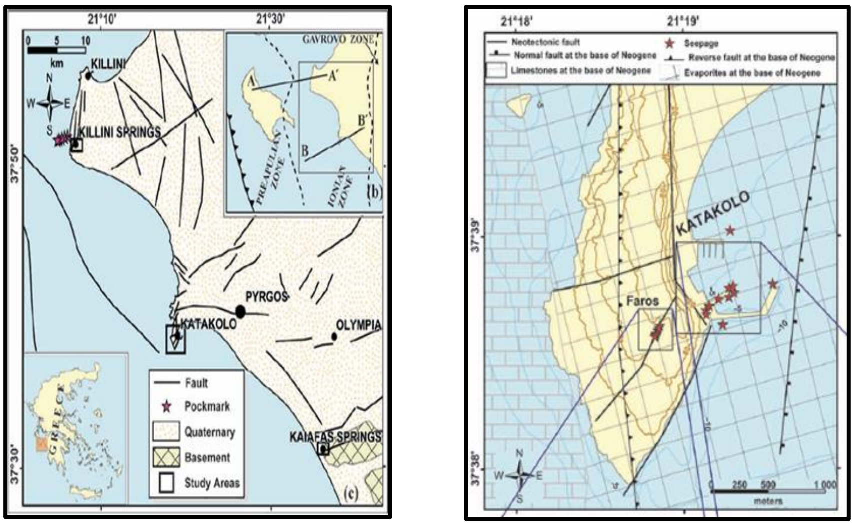
The survey method selected for investigating pockmarks in the survey site was consistent with established techniques used in previous studies on pockmark formation and gas seepage. Hydrographic surveys, particularly those utilizing multibeam echosounders, sidescan sonar, and sub-bottom profiling, have been widely employed in pockmark research. For instance, in a study conducted in 2009 and 2010 in the Katakolo Harbour [19], two main types of equipment were utilized. A side scan sonar towfish operating at dual frequencies of 100 kHz and 500 kHz, in association with a 4200 Topside processor EDGETECH for digital correction, and a 3.5 kHz sub-bottom profiling system with a Geopulse transmitter (types 5430A and 5210A) and a 4-array transducer (type O.R.E. 132B), along with a Triton Elics digital recorder. The side scan sonar system emitted high-frequency acoustic pulses to scan the seafloor and provide a plan view acoustic image, while the sub-bottom profiler emitted acoustic pulses to create a high-resolution profile of the sub-bottom beneath the towing path. Additionally, in 2010 Dandapath S. et al. [20], analysed pockmarks and sediment characteristics in the offshore area of Goa, employing a multibeam echosounder operating at a frequency of 95 kHz, for both bathymetric and backscatter data collection. Regarding more recent literature, in 2023, Hillman J. I. T. et al. [21], compiled a comprehensive dataset of pockmarks across various geological and geomorphological regions in Aotearoa New Zealand, using already existing multibeam bathymetric data, and established the first national pockmark database, providing valuable insights into regional and inter-regional trends in pockmark geometry and seabed characteristics. Similarly, Wang W. et al. [22], focused on identifying active or recently active gas leakage by employing high-resolution multibeam and seismic data (sub-bottom profiler) to reveal complex substrate structures and gas migration patterns associated with pockmarks. In another relevant study, Christodoulou D. et al. [23] investigated the pockmark field in the Gulf of Patras, Greece, employing multibeam echosounders, high-resolution sub-bottom profiles, and dual-frequency side-scan sonar to study fluid seepage and map pockmark formations. These studies collectively highlight the effectiveness of these methods in providing detailed and high-resolution data on pockmark morphology and associated fluid migration.

This paper is organized as follows: Section 2 reviews the background and key studies relevant to the seismic activity and the existence of pockmark formations inside the port of Katakolo and vicinity. Section 3 introduces the case study and outlines the data collection process. In Section 4, we analyse the results, highlighting implications for [specific field]. Finally, Section 5 discusses the findings and provides concluding remarks.

2 Background Literature

A series of geological and geophysical surveys conducted in the Kyparissian Gulf in 2004, 2009, 2010 and 2018 have provided substantial insights into the dynamics of natural gas seepages in the regions of Killini, Katakolo, and Kaiafas, igniting interest in surveying the seabed to better understand and visualise the morphology of these formations. Notably, studies conducted in Katakolo, considered one of Europe's largest natural gas seepage sites [24], have significantly advanced the understanding of gas seepage phenomena and the resulting formation of pockmarks on the seabed.

The 2004 surveys [25] aimed to investigate the origin, mechanisms, and environmental impacts of gas seepage in the region. The study, which involved measuring methane microseepage and analysing gas concentrations in the atmospheric air above soil in both offshore and onshore vents, revealed that the gas migration is strongly influenced by local brittle tectonics and stratigraphy. This was corroborated by isotopic analysis of methane, which indicated a connection between gas seepage and the structural elements of the area, including faults and diapiric movements. These geological features facilitate the migration of gas from deeper carbonate reservoirs to the surface, forming pockmarks on the seabed. Additionally, the survey underscored the potential hazards of methane and hydrogen sulphide emissions, as these gases can reach dangerous concentrations in seepage areas, posing significant risks to both the environment and human health due to their explosive and toxic properties.



(a) (b)

Fig. 3. (a) Pockmark Distribution Along the Kyparissiakos Gulf, (b) Structural map illustrating onshore and offshore Gas seepages within the study area along with existing faults. (Source: Etiope et al., 2006)

In 2009 and 2010 [24], a more focused investigation was conducted in Katakolo Bay, one of the largest offshore-onshore gas seepage zones in Europe. The aim was to build upon previous surveys and gather comprehensive data on the gas seepage phenomena. Using side-scan sonar and sub-bottom profiling, along with molecular and isotopic analyses of the seeping gases, the survey identified over 523 active gas plumes across the area (Fig. 3). These plumes were primarily composed of thermogenic methane (CH_4) and hydrogen sulphide (H_2S), with the latter believed to form through thermo-chemical sulphate reduction in deep anhydrites. The survey estimated offshore methane emissions to range from 33 to 120 tons per year, while onshore emissions were approximately 89 tons per year. These results solidified Katakolo's reputation as one of Europe's largest thermogenic gas seepage areas, highlighting both the scale of the emissions and the potential environmental and safety hazards posed by such large-scale seepage activity.

A comparative study conducted in 2018 [15], analysing data from 2010, sought to investigate changes in methane emissions from natural gas seepage over time. The study revealed a significant increase in methane emissions, rising from 57 kg per day in 2010 to 225 kg per day in 2018. Additionally, the number of gas release points, such as cracks and fissures, increased by a factor of 5.5, suggesting that subsurface gas flow had intensified over the eight-year period. The study attributed this increase primarily to natural variations in gas seepage rather than chemical corrosion of the pavement. It was also noted that diffuse methane emissions from unfractured asphalt were negligible compared to those from cracks and fissures. These findings highlighted the substantial variability of geological gas sources over time and emphasized the need for periodic re-evaluation of emission factors in atmospheric methane budget models, challenging the previous assumption of constant methane emissions.

3 Case Study

The port of Katakolo is located on the western coast of the Peloponnese in Greece, within the region of Ilia prefecture (Fig. 4). Katakolo comprises a port of considerable importance to the Greek economy, serving as a prominent tourism hub that attracts hundreds of thousands of visitors each year. As one of Greece's largest ports dedicated to tourism, it functions as a principal gateway for international arrivals, underscoring its strategic role in the nation's tourism infrastructure [26].

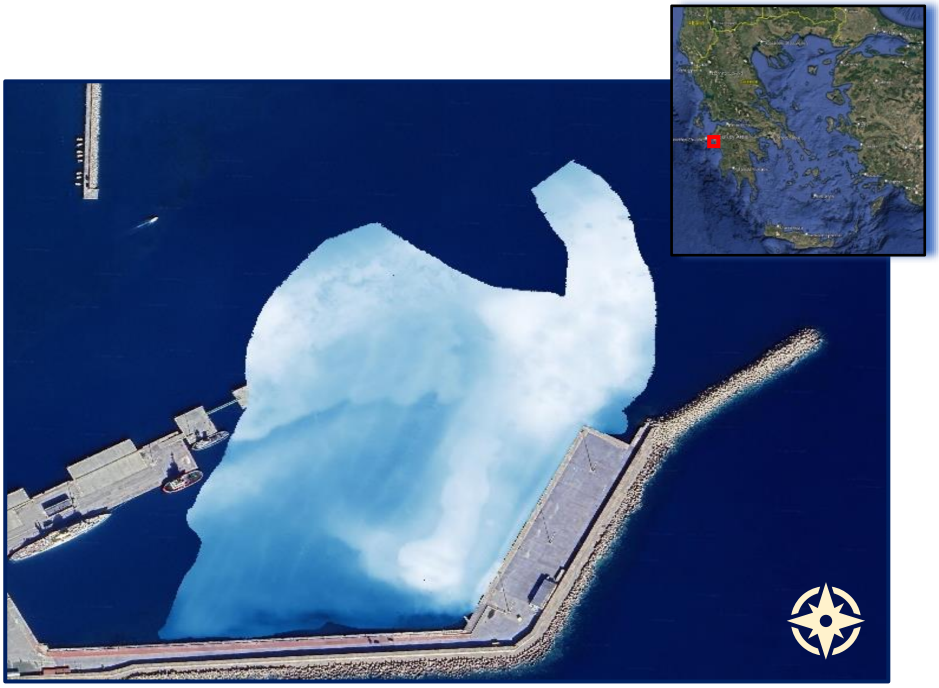


Fig. 4. Illustration of Survey Area. (Source: Google Earth)

At the port of Katakolo, a significant incident occurred in 2009 attributed to pockmark formations, provoked the subsidence of sections of the commercial mooring quay (Fig. 5). In addition, during the survey conducted in 2018 [14], related to the impact of gas seepages on the port and surrounding infrastructure, it was observed that gas accumulation beneath asphalt and concrete surfaces led to mechanical deformation, swelling, and the formation of cracks. The study particularly noted significant increases in asphalt swelling and the opening of linear fissures after 2010, highlighting the deteriorating ground conditions due to intensified subsurface gas flow. Given the port's considerable annual traffic, which encompasses numerous cruise ships and yachts, the hazards posed by these depressions to both the seafloor and marine infrastructure presents serious risks to human life and vessel safety. Thus, recognising the presence of pockmarks and their distribution on the seabed and in relation to the infrastructure, is crucial for improving our understanding of the current local seabed morphology. Detailed analysis of survey data can reveal even minor anomalies in the underwater seabed profiles that might have otherwise gone undetected. Modern sonar systems provide a reliable method for detecting pockmark formations by generating high-resolution images of cold seep features and their acoustic characteristics.

Fig. 5. Subsidence of sections of the commercial quay of Katakolo Port in 2009, circled in red. (Kiousi et al., 2023)

3.1 Materials and Methods

The bathymetric survey was executed using a multibeam echosounder, along with a Differential Global Positioning System (D-GPS) Real Time Kinematic (RTK) antenna and an Inertial Measurement Unit (IMU), all integrated on a 2m stainless steel bar, affixed on the portside of an 8m vessel of convenience (VOC).

The multibeam echosounder utilized in the survey, provided a swath coverage of up to 120°, with 224 beams per sounding, operating at a frequency of 220 kHz. The GNSS RTK system, received positional corrections from a nearby established base station, via Network Transport of RTCM via Internet Protocol (NTRIP), delivering accurate horizontal positioning, while the IMU measured the angular movements of the multibeam head with regard to its 3 vertical axes (roll, pitch, yaw), ensuring the reliability of the collected data. Tidal observations were derived by utilizing the RTK tides method, which automatically reduced the depths to the Chart Datum (CD) surface.

A total area of 124.400 m^2 and average depth of 20m was surveyed for the purpose of this research.

Offset Measurement

Accurate offset measurements are essential for ensuring the spatial precision of multibeam bathymetric data. These offsets were determined manually using a measuring tape to quantify the precise distances between the GNSS antenna, IMU, and the multibeam transducer head. Such measurements are fundamental as they define the relative positioning of each sensor on the survey vessel, thereby enabling the rectification of positional discrepancies arising from sensor misalignments.

The measured depths were referred to the Centre of Gravity (GoG), located at the multibeam head, which was also the reference point for the aforementioned offsets.

Patch Test

A Patch Test was conducted to identify and rectify systematic biases within the survey system, prior the beginning of the survey. Specifically, the Patch Test procedure, erases the angular misalignments between the multibeam head and the motion reference sensor. This consisted of the run of a configuration of three survey lines over specific seabed type.

Sound Velocity Profile Measurement

The acquisition of accurate velocity profile in the vicinity was imperative due to the principles of Snell's law, which governs the refraction of acoustic waves as they propagate through the water layers of varying densities and temperatures. A sound velocity profiler (SVP) was deployed at the beginning of the survey at a deep point close to the survey area (~ -28m). This dataset was essential for correcting beam angle refraction effects and ensuring the accuracy of depth measurements across the multibeam swath.

3.2 Data Collection

The survey was in compliance with the "Exclusive Order" specification of the International Hydrographic Organisation (IHO) Standards for Hydrographic Surveys (S-44, 6th Edition), which mandates 200% coverage in shallow water areas, such as ports and berthing zones, as illustrated in Table 1. The overlapping among the neighbour survey swaths was achieved by implementing the boustrophedon cellular decomposition survey method [27]. Additionally, the Total Vertical Uncertainty (TVU) of the survey, was computed using the IHO TVU equation, provided also in S-44 IHO Standards edition [28]. Additionally, to correct the measured depths from refraction errors, a sound velocity (SV) profile was collected in the vicinity [Fig. 6], using a sound velocity profiler, along with a sound velocity sensor mounted on the multibeam head, intended for the correct beam steering. The SV profile was imported in the acquisition software at the beginning of the survey.

Table 1. Minimum Bathymetry Standards for Safety of Navigation Hydrographic Surveys (IHO,2022)

Criteria	Order 2	Order 1b	Order 1a	Special Order	Exclusive Order
Area description (Generally)	Areas where a general description of the sea floor is considered adequate.	Areas where underkeel clearance is not considered to be an issue for the type of surface shipping expected to transit the area.	Areas where underkeel clearance is considered not to be critical but features of concern to surface shipping may exist.	Areas where underkeel clearance is critical	Areas where there is strict minimum underkeel clearance and manoeuvrability criteria
Depth THU [m] + [% of Depth]	20 m + 10% of depth *Ba5, Bb2	5 m + 5% of depth *Ba8, Bb3	5 m + 5% of depth *Ba8, Bb3	2 m *Ba9	1 m *Ba10
Depth TVU (a) [m] and (b)	a = 1.0 m b = 0.023 *Bc7, Bd4	a = 0.5 m b = 0.013 *Bc8, Bd6	a = 0.5 m b = 0.013 *Bc8, Bd6	a = 0.25 m b = 0.0075 *Bc10, Bd8	a = 0.15 m b = 0.0075 *Bc12, Bd8
Feature Detection [m] or [% of Depth]	Not Specified	Not Specified	Cubic features > 2 m, in depths down to 40 m; 10% of depth beyond 40 m *Be5, Bf3 beyond 40m	Cubic features > 1 m *Be6	Cubic features > 0.5 m *Be9
Feature Search [%]	Recommended but Not Required	Recommended but Not Required	100% *Bg9	100% *Bg9	200% *Bg12
Bathymetric Coverage [%]	5% *Bh3	5% *Bh3	≤ 100% *≤ Bh9	100% *Bh9	200% *Bh12

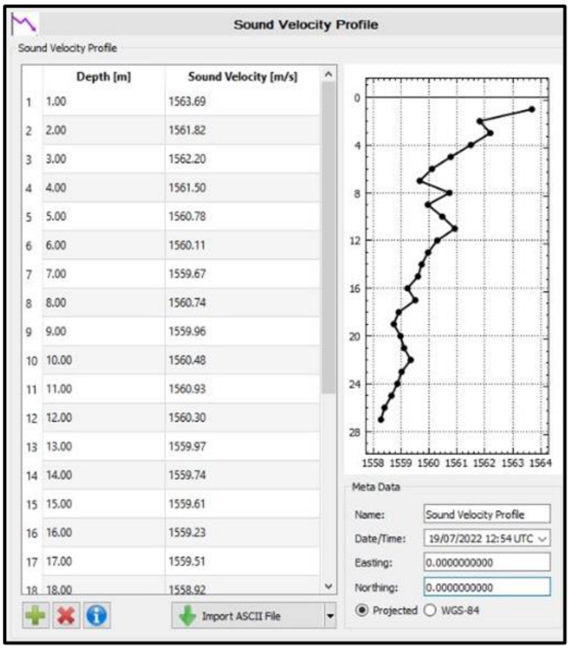


Fig. 6. Sound velocity profile collected in Katakolo, Greece, showing how acoustic speed varies with water depth

3.3 Data Processing

The data processing and analysis were conducted using specialised hydrographic software, designed for high-precision bathymetric result data. The final point coordinates were referenced to the Greek Geodetic Reference System 1987 (GGRS87). However, prior to analysis, the raw data underwent a cleaning process to remove noise generated by external factors, such as marine life, debris and gas seeps. This noise was mitigated through the application of both automated and manual editing techniques, depending on the nature and extent of the interference.

A critical step in this process was the careful evaluation and interpretation of the raw data before the application of any filtering methods. This was especially important, given the unique characteristics of the survey site, where the presence of pockmarks, necessitated the selective preservation of certain anomalies. In surveys of this type, indiscriminate filtering could inadvertently remove important data points linked to the very phenomena under investigation, such as gas seeps. In the present analysis of the raw data, the data points that were significantly below the seafloor level, were attributed to gas leakage, re-leased as bubbles that interfered with the echosounder beams. This interference helped delineate the locations of pockmarks. This noise was preserved, while geolocational markers were also added, to highlight the location of the pockmarks in the survey area.

The backscatter data was processed through a series of automated cleaning and normalization steps to ensure high data quality and accuracy. Initially, noise and artifacts caused by water column interference, transducer side lobes, and beam pattern distortions were removed. Geometric corrections were applied to account for variations in sonar beam angles, ensuring consistent backscatter intensities across the dataset. The data was then normalized to correct for transmission losses, including sound absorption and spreading in the water column. These processing steps resulted in a refined dataset, facilitating more precise analysis of seabed composition and seafloor features.

The methodology for pockmark measurement and validation involved manually measuring the average dimensions and depth of each pockmark. This was done using the slice editor tool provided by the processing software, allowing precise measurement and validation of the features in the dataset.

4 Results

4.1 Bathymetric Map

The outcome of the survey was a bathymetric map [Fig. 7] that visually represented the distribution of pockmarks in relation to the port structures and a backscatter intensity visualisation of the area. Seven pockmarks were detected, exhibiting a variety of morphologies, including normal, elongated and unit shapes [Fig. 8].

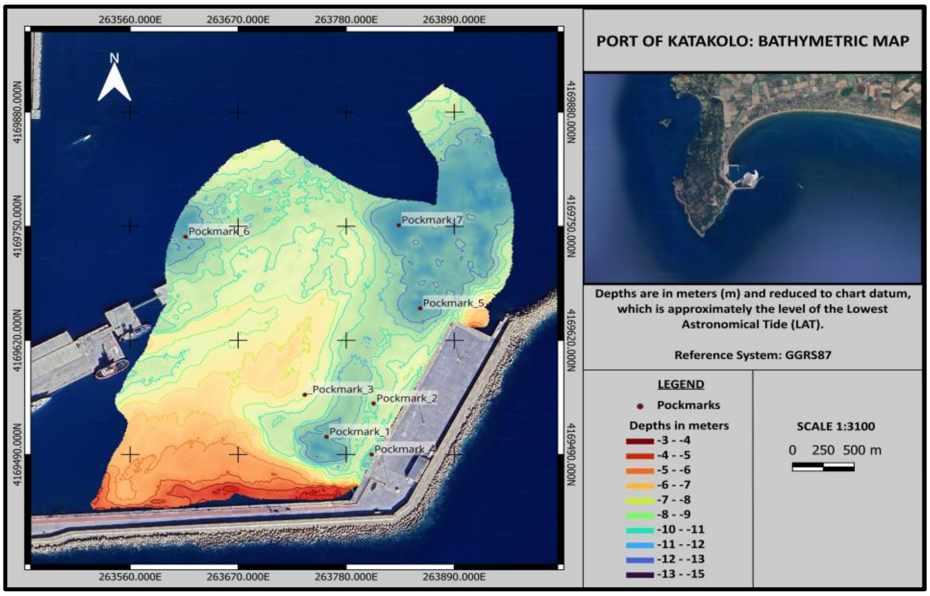
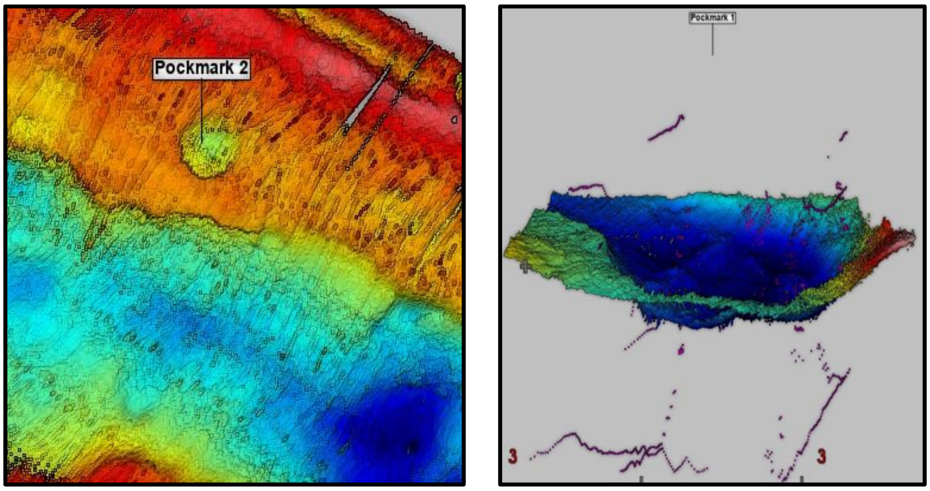


Fig. 7. Bathymetric map of the Port of Katakolo, Greece, highlighting depth variations and the presence of seafloor pockmarks



(a) (b)

Fig. 8. (a) Illustration of unit-shaped pockmark formation (Pockmark 2), (b) Illustration of elongated shaped pockmark (Pockmark 1)

The pockmarks were distributed both inside and outside the port area, raising concerns about potential structural implications. Of particular importance is Pockmark 4, located directly beneath the quay structure. This feature presents a significant safety risk due to its potential impact on the structural integrity of the quay. The formation's presence in close proximity to the quay suggests a possible reduction in load-bearing capacity, which may compromise the stability of port infrastructure and affect its ability to safely support vessels, cargo, and personnel. The variability in pockmark morphology and size indicates differing formation mechanisms, likely influenced by sediment composition, fluid dynamics, and localized geological conditions.

4.2 Pockmark Characteristics

The average depth of these formations is approximately 2.5 meters, indicating relatively shallow depressions in the seabed. Geolocators were employed to precisely determine the positions of the pockmarks, ensuring accurate spatial mapping and facilitating further analysis of their distribution and potential geological significance.

A detailed assessment of the pockmark dimensions revealed considerable variability in depth, width, and length [Fig.9 – Fig.13].

More specifically: Pockmark 1 [Fig. 9.], comprises an elongated pockmark and is the most prominent feature, reaching a depth of -14.8 meters with a 5-meter depression from the seabed and extending 180 meters in length, suggesting a well-developed erosional feature likely influenced by prolonged fluid seepage or sediment displacement. Pockmark 5 [Fig. 12.] exhibits similar depth characteristics (-14.7 meters) but is notably broader, with a width of 80 meters, indicating lateral expansion potentially due to subsurface gas migration or sediment instability.

In contrast, Pockmarks 2 and 3 [Fig. 10,11], constitute unit pockmark formations and are significantly smaller, with depths of -11.8 meters and -9.5 meters, respectively. These formations show less pronounced seabed depressions (1 meter and 0.6 meters, respectively) and relatively limited spatial extent (Pockmark 3 being only 4 meters in length). These smaller pockmarks suggest either early-stage formation processes or reduced erosional influence compared to their larger counterparts.

Pockmark 4 [Fig. 13.], located in close proximity to the pier, presents a unique challenge in terms of morphological interpretation. Its geometry remains ambiguous, as its spatial extent is partially obscured by the presence of the pier structure, making it difficult to ascertain whether the pockmark extends beneath it. Unlike the other formations, where depth and lateral dimensions could be clearly delineated, the precise characteristics of Pockmark 4 require further investigation. The use of sub-bottom profiler data is essential to resolve this uncertainty, as it would allow for the detection of underlying gas migration pathways and the potential presence of a gas chimney morphology.

Pockmarks 6 and 7 were excluded from the analysis as their full extent was not adequately captured during the survey. Due to the incomplete mapping of their shape and dimensions, any interpretation would lack sufficient accuracy and reliability. A more comprehensive survey would be required to properly assess their morphology and geological significance.

The following figures [Fig. 9, 10, 11, 12, 13] provide a detailed visualization of the pockmarks under investigation, the designated inspection areas, and the corresponding slice-view profiles, highlighting the deepest sections of these formations for a comprehensive morphological assessment.

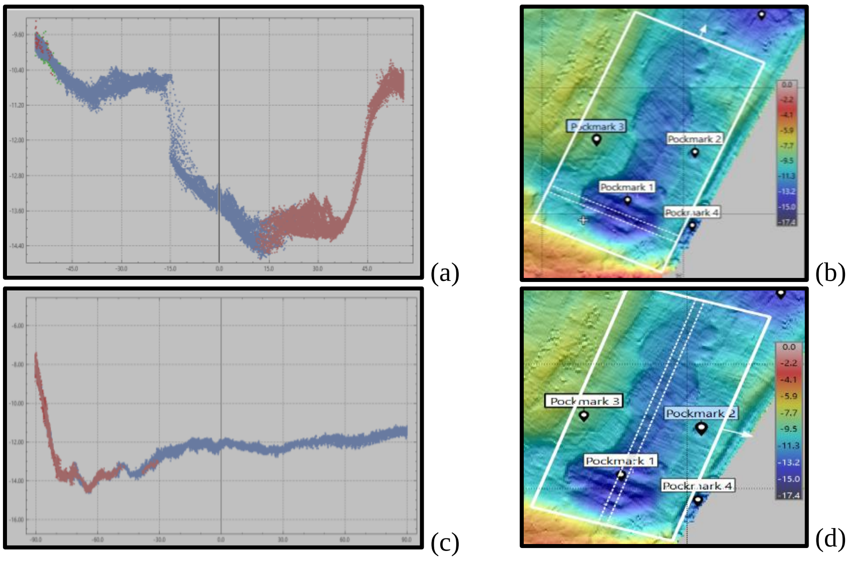


Fig. 9. Bathymetric profile of Pockmark 1 (Elongated Pockmark), the largest surveyed depression. (a) Slice view across the pockmark formation, (b) Illustration of inspection area used for dimension analysis, (c) Slice view along the pockmark formation, (d) Illustration of inspection area used for dimension analysis

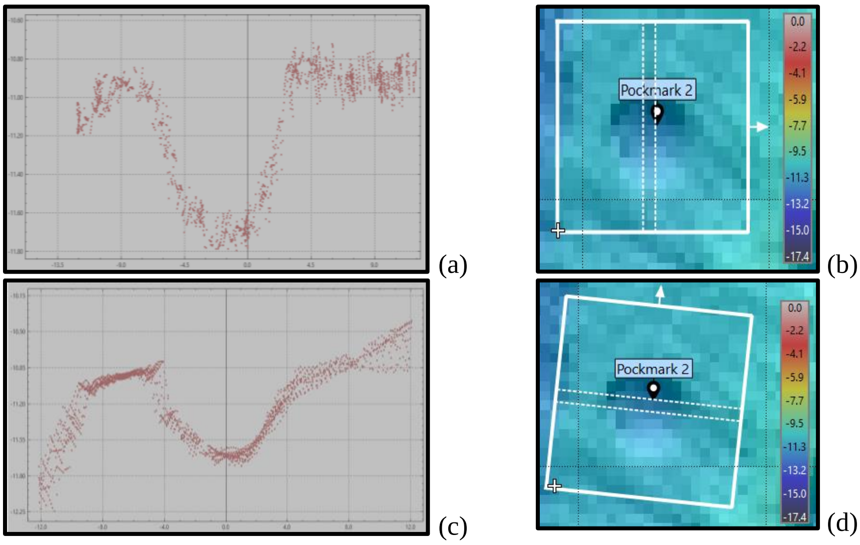


Fig. 10. Morphological profile of Pockmark 2 (Unit Pockmark), a relatively shallow feature. (a) Slice view along the pockmark formation, (b) Illustration of inspection area used for dimension analysis, (c) Slice view across the pockmark formation, (d) Illustration of inspection area used for dimension analysis

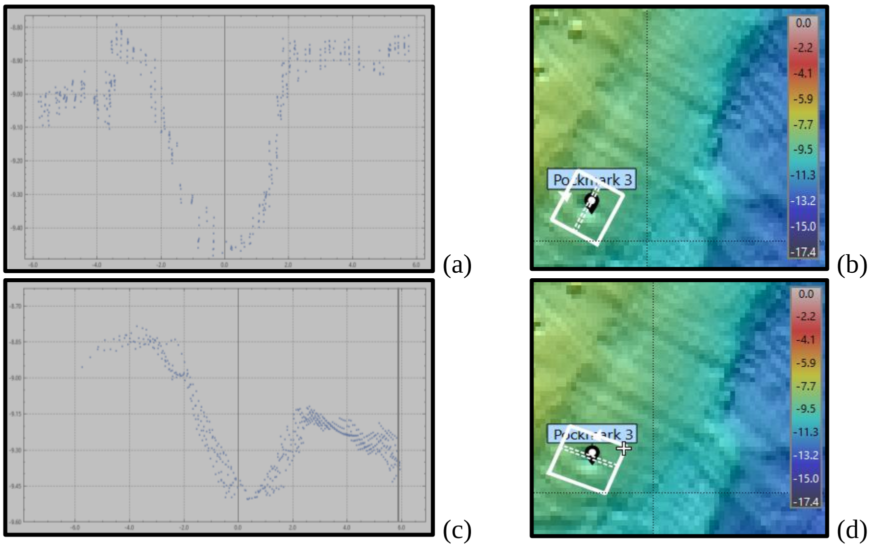


Fig. 11. Bathymetric profile of Pockmark 3 (Unit Pockmark), the largest surveyed depression. (a) Slice view along the pockmark formation, (b) Illustration of inspection area used for dimension analysis, (c) Slice view across the pockmark formation, (d) Illustration of inspection area used for dimension analysis

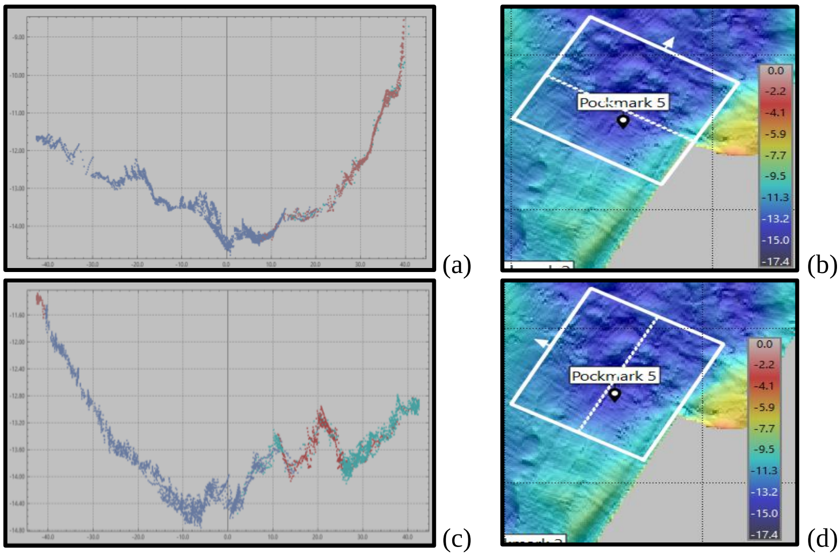


Fig. 12. Bathymetric profile of Pockmark 5, one of the widest formations surveyed. (a) Slice view across the pockmark formation, (b) Illustration of inspection area used for dimension analysis, (c) Slice view along the pockmark formation, (d) Illustration of inspection area used for dimension analysis

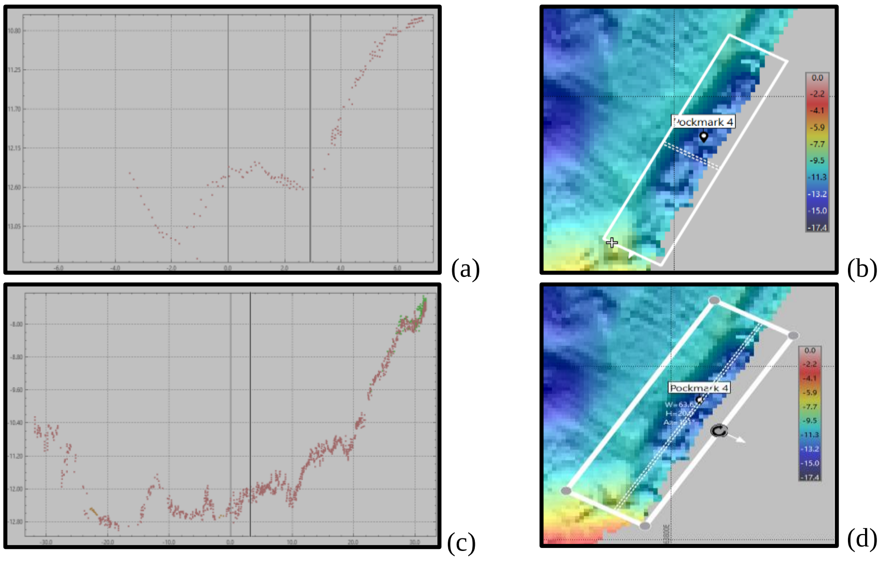


Fig. 13. Bathymetric profile of Pockmark 4. (a) Slice view across the pockmark formation, (b) Illustration of inspection area used for dimension analysis, (c) Slice view along the pockmark formation, (d) Illustration of inspection area used for dimension analysis

Table 2 provides a systematic summary of the key characteristics of the surveyed pockmarks, including only those whose morphology was comprehensively mapped. It presents the depth, width, and length of the selected formations, offering a structured overview of their morphometric properties. Below is the summary table:

Table 2. Summary of fully surveyed pockmarks with depth, seabed depression, width, and length

Pockmark	Average Depth (m)	Depth from Seabed (m)	Width (m)	Length (m)
Pockmark 1	-14.8	5.0	65	180.0
Pockmark 2	-11.8	1.0	8	13.5
Pockmark 3	-9.5	0.6	6	4.0
Pockmark 4	-13.0	2.0	10.0	60.0
Pockmark 5	-14.7	2.5	80	90.0

4.3 Backscatter Data

The backscatter processing of the seabed data revealed a range of acoustic intensities between -16 dB and -35 dB, with a predominant occurrence of high to medium backscatter values [Fig. 14]. Backscatter values ranging from -15 to -35 dB, with predominant values around -22 dB, indicate a seabed composition that is likely moderately coarse, such as coarse sand or a mix of sand and gravel. The higher backscatter values closer to -15 dB suggest harder and rougher substrates, such as rocky areas or gravel, while the lower values near -35 dB correspond to softer, smoother materials like fine sand, silt, or mud. The predominant value of -22 dB suggests a seabed that is generally coarse but not entirely hard, likely with a mix of sediment types. The variability across the range reflects spatial changes in seabed composition, with potential transitions between rough and soft areas, indicating a heterogeneous seabed environment.

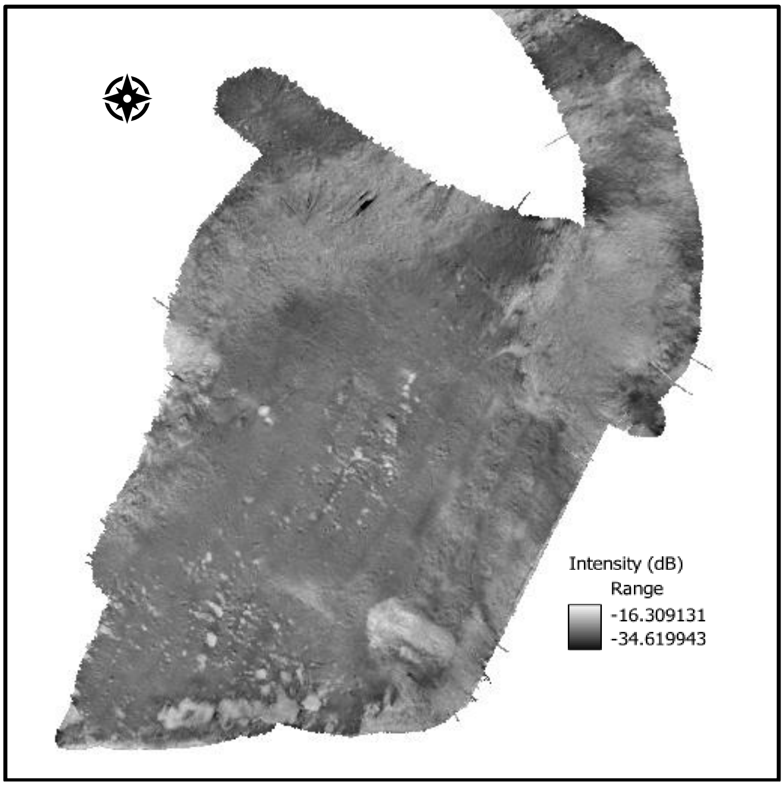


Fig. 14: Backscatter data from hydrographic survey in Katakolo, Greece, illustrating acoustic intensity variations in dB

4.4 Error Margins

The Total Vertical Uncertainty (TVU) for the survey area was computed using the standard equation, as indicated by the 6th edition IHO Standards for hydrographic surveys:

$$\text{TVUmax (d)} = \sqrt{a^2 + (b \times d)^\wedge 2} \tag{1}$$

The parameters for the International Hydrographic Organization (IHO) Exclusive Order are defined as a=0.15 m15 and b=0.0075. For an average survey depth of 20 meters, the maximum allowable TVU was calculated to be 0.212 meters. The accompanying figure [Fig.15.] presents the estimated vertical uncertainty at the 95%

confidence level as a function of cross-track distance. The blue curve represents the observed TVU, while the gray line denotes the IHO threshold. The observed TVU follows a characteristic U-shaped distribution, exhibiting lower uncertainty values at the nadir and increasing towards the outer beams. Notably, the measured TVU remains consistently below the IHO-prescribed limit across the entire swath width, indicating that the survey adheres to the vertical uncertainty requirements established for the Exclusive Order.

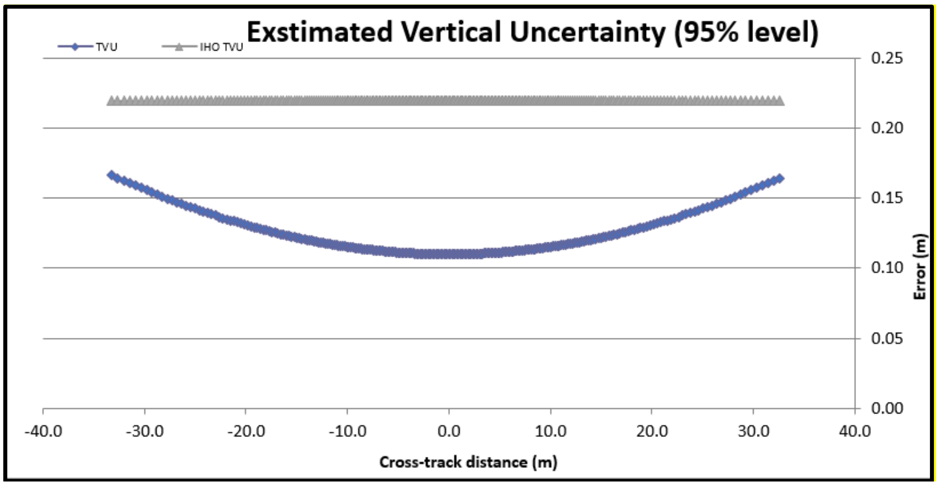


Fig. 15. Estimated Total Vertical Uncertainty (TVU) at the 95% confidence level across track in a hydrographic survey, compared to IHO TVU standards

5 Discussion and Conclusions

The bathymetric data revealed a diverse range of pockmark formations within the seafloor of the Port of Katakolo, Greece, indicating active geological processes that may pose long-term structural risks to port infrastructure. These formations vary in size and intensity, highlighting the complexity of subsurface gas release and sediment instability in the area. Notably, the proximity of these craters to the port pier and specifically the presence of pockmark No.4 beneath the quay, raises significant concerns regarding the stability and resilience of the port structures. The presence of pockmarks in close vicinity to critical port infrastructure like the Port of Katakolo, highlights the urgent need for on-going monitoring and proactive management risk strategies The structural integrity of the quay is particularly vulnerable to sediment weakening caused by the underlying pockmark, which could accelerate structural deterioration under loading pressures. This poses a direct risk to vessel operations, personnel and visitor safety. A structured monitoring programme should be implemented to ensure the long-term stability of port infrastructure, incorporating regular surveys.

To address these challenges, it is imperative to implement a robust monitoring program that includes regular inspections of both the surface and subsurface conditions of critical structures. Utilizing advanced geophysical techniques, such as high-resolution marine remote sensing, can facilitate the detection of early signs of structural deterioration and sediment displacement. For instance, the Patras Gulf Pockmark field study [23], employed multibeam echosounders and sub-bottom profilers to map fluid escape structures and their pathways, providing valuable insights into subsurface conditions

The integration of advanced survey technologies, including Multibeam Echo Sounders (MBES), photogrammetry and sub-bottom profilers, on an annual basis, is crucial for the continuous monitoring of the Port of Katakolo infrastructure. MBES when used at varying angles, not only captures detailed bathymetric data, but also provides high-resolution imaging of submerged structures such as quay walls and foundations [29,30], allowing for early detection of potential weaknesses or changes in stability. Photogrammetry offers precise inspections, also identifying cracks and deformations [31] both below and above water structures like piers and breakwaters. Sub-bottom profiling is essential for assessing the geological conditions beneath the seabed, identifying possible sediment instability or gas pockets that could impact the port's foundation [8,32]. Coupled with real-time structural health monitoring systems, which track stress and strain on critical components, these technologies enable proactive, data-driven risk assessment. This integrated approach allows for early identification of potential structural failures, facilitating timely maintenance and reinforcing the Port of Katakolo resilience against evolving threats.

Hydrographic surveys are essential for safe navigation, supporting the operational integrity of ports, and facilitating the maintenance of marine infrastructure. This research emphasized the critical role of hydrography in monitoring seafloor features, using the port of Katakolo, Greece, as a case study. There, the presence of pockmarks has previously led to quay failures, under-scoring the hazards these formations pose to port infrastructure. The findings highlight the necessity of annual hydrographic surveys in the port of Katakolo, to monitor pockmark generation rates, asses their potential seabed changes and proactively manage risks to port structures. Routine data collection will enable local authorities to detect early signs of pockmark-related hazards, allowing for timely interventions that safeguard both port facilities and operational safety.

References

1. Šiljeg, A., Cavri, B., Mari, I., Barada, M.: GIS modelling of bathymetric data in the construction of port terminals – An example of Vlaška channel in the Port of Ploče, Croatia. International Journal for Engineering Modelling (32), 17-37, (2019). https://doi.org/10.31534/engmod.2019.1.ri.01m
2. Mateo-Pérez, V., Corral-Bobadilla, M., Ortega-Fernández, F., Vergara-González, E. P.: Port Bathymetry Mapping Using Support Vector Machine Technique and Sentinel-2 Satellite Imagery. Remote Sensing (12), (2020). https://doi.org/10.3390/rs12132069
3. Oumeraci, H.: Review and analysis of vertical breakwater failures — lessons learned. Coastal Engineering (22), 3-29, (1994)
4. Sumer, B. M., Whiteouse, J. S., Tørum, A.: Scour around coastal structures: A summary of recent research. Coastal Engineering (44), 153-190, (2001).https://doi.org/10.1016/S0378-3839(01)00024-2
5. Judd, A.G., Hovland, M.: Seabed Fluid Flow: the impact on geology, Biology and the Marine Environment, vol.441 Cambridge University Press, New York (2007)

6. Xu, Z., Li, Y., Yan, W., Lv, Y., Zhang, G., Lu, D., & Zhu, Z.: Identifying Submarine Engineering Geologic Hazards in a Potential Gas Hydrate Target Area on the Southern Continental Margin of the South China Sea. Journal of Marine Science and Engineering, 10(12), (2022). https://doi.org/10.3390/jmse10122008
7. Kiousi, D., Oikonomou, E., Sartampakou, A., Sartampakos, P.: The contribution of Hydrography to pockmark detection, and port construction and maintenance, with the use of modern sonar systems. 2nd International Conference on Design and Management of Port, Coastal and Offshore Works (DMPCO) (2), 236-240 (2023)
8. Prior B.D., Hooper R.J.: Seafloor engineering geomorphology: recent achievements and future directions, Geomorphology (31), 411-439 (1999)
9. Cathles, L.M., Su Z., Chen, D.: The physics of gas chimney and pockmark formation, with implications for assessment seafloor hazards and gas sequestration. Marine and Petroleum Geology (27), 82-91, (2010). https://doi.org/10.1016/j.marpetgeo.2009.09.010.
10. Hovland, M., Judd, A.: Pockmarks and Seepages. Seabed Pockmarks and Seepages: Impact on Geology, Biology and the Marine Environment. (1988) https://doi.org/10.13140/RG.2.1.1414.1286.
11. Andresen, K.J., Dahlin, A., Kjeldsen, K.U., Røy, H., Bennike, O., Nørgaard-Pedersen, N., Seidenkrantz, M.S.: The longevity of pockmarks – A case study from a shallow water body in northern Denmark, Marine Geology (434), (2021)
12. Hovland, M., Gardner, J.V., Judd, A.G.: The significance of pockmarks to understanding fluid flow processes and geohazards. Geofluids (2), 127-136, (2002)
13. Hovland, M.: Modern analogues to middle Ordovician sedimentary mounds and washout depressions. Journal of Sedimentary Petrology (59), 585–589, (1989)
14. Wiguna, T., Rahadian, O.M., Irfan, M.: Single Channel Seismic Application for Gas Charges Sediment Reconnaissance in Geohazard Study of Port Construction at Wetland Area. Jurnal Neutrino: Jurnal Fisika dan Aplikasinya (9), 20-25, (2016)
15. Kordella, S., Ciotoli, G., Dimas, X., Papatheodorou, G., Giuseppe, E.: Methane Emission from Natural Gas Seepage at Katakolo Harbour (Western Greece). Applied Geochemistry (2020)
16. Dierssen, H.M., Theberge, A.E.: Bathymetry: Assessing Methods. Encyclopedia of Natural Resources (2), (2014). doi:10.1081/E-ENRW-120048588
17. Ferreira, I.O., Andrade, L.C., Teixeira, V.G., Santos, F.C.M.: State of art of bathymetric surveys. Boletim de Ciências Geodésicas (28), (2022). doi: 10.1590/s1982-21702022000100002
18. Kang, M.: Analysis of the ME70 Multibeam Echosounder data in echo view -current capability and future directions. Journal of Marine Science and Technology (19), (2011). doi: 10.51400/2709-6998.2197
19. Etiope, G., Christodoulou, D., Kordella, S., Marinaro, G., Papatheodorou, G.: Offshore and onshore seepage of thermogenic gas at Katakolo Bay (Western Greece). Chemical Geology (339), 115-126, (2013) https://doi.org/10.1016/j.chemgeo.2012.08.011
20. Dandapath, D., Chakraborty, B., Karisiddaiah, S.M., Menezes, A., Ranade, G., Fernandes, W., Naik, D.K., Raju, K.N.P.: Morphology of pockmarks along the western continental margin of India: Employing multibeam bathymetry and backscatter data. Marine and Petroleum Geology (27), (2010). https://doi.org/10.1016/j.marpetgeo.2010.09.005
21. Hillman, J. I. T., Watson, S. J., Maier, K. L., Hoffmann, J. J. L., Bland, K. J., Warnke, F., Pecher, I. A., Gorman, A. R., Davy, B., Bull, S., & Woelz, S.: The diverse

morphology of pockmarks around Aotearoa New Zealand. Frontiers in Marine Science (10), (2023). https://doi.org/10.3389/fmars.2023.1235928

22. Wang, Y., Tu, G., Yu, J., Yu J., Yan, P., Jin, Y., Chen, C., Liu, L.: Discovery of pockmarks in the Zengmu Basin, southern South China Sea and the implication. J. Oceanology and Limnology (41), 757–768, (2023)
23. Christodoulou, D., Papatheodorou, G., Geraga, M., Etiope, G., Giannopoulos, N., Kokkalas, S., Dimas, X., Fakiris, E., Sergiou, S., Georgiou, N., Sokos, E., Ferentinos, G.: Geophysical and Geochemical Exploration of the Pockmark Field in the Gulf of Patras: New Insights on Formation, Growth and Activity. Applied Sciences (13), (2023). https://doi.org/10.3390/app131810449
24. Etiope, G., D. Christodoulou, D., Kordella, S., Marinaro, G., Papatheodorou, G.: Offshore and onshore seepage of thermogenic gas at Katakolo Bay (Western Greece), Chemical Geology (339), 115-126, (2013) https://doi.org/10.1016/j.chemgeo.2012.08.011
25. Etiope, G., Papatheodorou, G., Christodoulou, D., Ferentinos, G., Sokos, E., Favali, P.: Methane and hydrogen sulfide seepage in the northwest Peloponnesus petroliferous basin (Greece): Origin and geohazard. AAPG Bulletin, 90 (5), 701 – 713, (2006)
26. Katakolo, https://katakolo.info/limani/, last accessed 2024/11/12
27. Choset, H.: Coverage of Known Spaces: The Boustrophedon Cellular Decomposition. Autonomous Robots (9), 247–253, (2000). https://doi.org/10.1023/A:1008958800904
28. IHO: International Hydrographic Organisation – Standards for Hydrographic Surveys S-44. 6th edn. International Hydrographic Organisation, Principauté de Monaco (2022)
29. Zhanh, S., Zhu, Y., Xiong, W, Cai, C.S., Zhang, J.: Bridge substructure damage morphology identification based on the underwater sonar point cloud data. Advanced Engineering Informatics (62), (2024)
30. Hake, F., Lippman, P., Alkhatib, H., Oettel, V., Neumann, I.: Automated damage detection for port structures using machine learning algorithms in height fields. Applied Geomatics (15), 349-357, (2023)
31. Yu, Z., Shen, Y., Zhang, Y., Xiang, Y.: Automatic crack detection and 3D reconstruction of structural appearance using underwater wall-climbing robot. Automation in Construction (160), (2024)
32. Riera, R., Paumard, V., Gail, d.M., Saqab M.M., Lebrec, U., Lang, S.C., Lane, A.: Origin of Seafloor pockmarks overlying submarine landslides: Insights form semi-automated mapping of 3D seismic horizons (North West Shelf, Austalia), Marine Petroleum Geology (136), (2022)