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Enhanced Port Vulnerability Assessment Using Unmanned-Aerial-Vehicle-Based Structural Health Monitoring

Christina N. Tsaimou [1], Stavroula Brouziouti [1], Panagiotis Sartampakos [2] and Vasiliki K. Tsoukala [1,*]

[1] Laboratory of Harbour Works, School of Civil Engineering, National Technical University of Athens, 5 Heroon Polytechniou Str., 15780 Zografou, Greece; ctsaimou@central.ntua.gr (C.N.T.); sbrouziouti@mail.ntua.gr (S.B.)
[2] NIREAS Engineering, 1-3 Skra Str., 17673 Athens, Greece; sartabakos@yahoo.gr
* Correspondence: tsoukala@mail.ntua.gr

Abstract: Port vulnerability assessment is inherently linked to the delivery of sustainable and resilient infrastructure. Identifying the vulnerabilities and weaknesses of a port system allows for the minimization of disaster effects and optimization of maintenance, repair, or mitigation actions. The current port vulnerability assessment practices are built upon the examination of a diversity of indicators (parameters), including technical, physical, environmental, and socioeconomic pressures. From an engineering perspective, and given that ports are tangible infrastructure assets, their vulnerability is highly affected by the structural condition of their facilities. Hence, the present research seeks to enhance port vulnerability assessment by introducing structural condition parameters based on Structural Health Monitoring applications. The four fishing and leisure harbors of the Municipality of Thebes, located in central Greece, were used as a case study. Two approaches were considered for the harbors' vulnerability assessments: (a) enabling and (b) disabling the use of the proposed parameters. In situ inspections were conducted with the employment of an Unmanned Aerial Vehicle (UAV) for condition monitoring. UAV data were analyzed to generate geospatial images that allow for the mapping and detecting of defects and failures in port infrastructure. The overall research assists decision-makers in gaining valuable insight into the system's vulnerabilities and prioritizing their interventions.

Keywords: port vulnerability; fishing and leisure harbors; port vulnerability assessment; port infrastructure; Structural Health Monitoring (SHM); condition monitoring; Unmanned Aerial Vehicles (UAVs)

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1. Introduction

Coastal urban areas are multidimensional, complex systems vulnerable to stressors activated by natural, environmental, and anthropogenic changes [1]. The sustainability concept of such urban areas integrates different aspects of engineering, socioeconomic, and environmental fields [2]. Within the engineering industry, sustainable urban planning and management seek to minimize pressures on infrastructure systems [3]. Hence, decision-makers related to the implementation of sustainable coastal management strategies are tasked with exploring practices to enhance the sustainability of port infrastructure systems.

The sustainability of civil infrastructure tackles the socioeconomic and environmental impacts anticipated to occur during its lifetime [4]. In an attempt to assist decision-making and achieve a comprehensive understanding of the quality of infrastructure, combining sustainability with infrastructure resilience is encouraged. The concept of resilience is linked to the impacts of potential damage and failure or the recovery capability of a structure after it is subject to extreme events. To deliver resilient structures or improve their resilience, management planning policies require the identification of the vulnerabilities of infrastructure systems that act as multifaceted networks, involving different interacting elements (physical, structural, environmental, user-based, and asset-management-based) [5].

Considering this, the vulnerability of a port infrastructure system is highly affected by the interrelationship of physical, human-induced, socioeconomic, and environmental factors.

Ports' vulnerability to diverse threats, including natural disasters (e.g., cyclones, earthquakes, and tsunamis) [6,7], manmade catastrophes (e.g., explosions) [8], and climate change impacts [9–11], has received increasing research interest. Assessing port vulnerability assists in minimizing disaster effects and prioritizing maintenance, repair, or mitigation measures [12]. Given that a direct quantification of vulnerability is a challenging task, indicator-based assessment methods have been proposed as countermeasures to provide measurable and observable quantities of such concepts [9,13,14]. A variety of port vulnerability indicators (also found as parameters or variables in the literature) have been examined related to the different dimensions of vulnerability, including physical, technical, environmental, and socioeconomic aspects [7,9–12,15,16]. This diversity of indicators is due to the scope of the performed vulnerability assessments (e.g., addressing climate or human-induced disasters' vulnerability), the scale of the assessment (i.e., examining a single port or multiple ports at regional, national, or global scales), and the type of ports considered (e.g., fishing shelters and cargo ports) [17]. Despite the numerous indicators and the fact that ports are infrastructure assets involving different types of structures and facilities [18], a limited number of technical indicators have been linked to port infrastructure features such as harbor size, infrastructure age, pier depth, and construction materials [7,11,17]. Besides this weakness in terms of a comprehensive port vulnerability assessment, the inherent relationship between the structural condition and the vulnerability of an infrastructure asset [19] remains unexplored.

The integration of structural condition information into vulnerability assessment methodologies has proven promising for other types of infrastructure systems, such as bridges [20]. Hence, in an attempt to enhance port vulnerability assessment practices with data related to structural integrity, the implementation of in situ inspections and condition monitoring is a prerequisite. The current trends in the condition assessment of civil infrastructure systems involve Structural Health Monitoring (SHM) practices with non-contact-based sensors, such as remote sensing techniques [21]. Unmanned Aerial Vehicles (UAVs) equipped with high-resolution cameras have been employed as a form of remote sensing SHM of port structures [22–24]. UAV-driven SHM facilitates the addressing of the demanding challenges in (i) detecting and quantifying damages and failures and (ii) adapting the structural performance of infrastructure based on the identified system's vulnerabilities [25]. Given that vulnerability is a time-dependent concept [26], short-term and long-term SHM data acquired via periodic UAV flights assist in understanding and monitoring port vulnerabilities related to the structural condition of its infrastructure. Although the contribution of such UAV-assisted SHM applications in assessing port vulnerability can be recognized, their integration into current assessment approaches has not yet been considered.

Based on the above, within the context of strengthening the existing port vulnerability framework, this paper intends to integrate structural condition indicators, herein referred to as parameters, into vulnerability assessment practices by applying remote sensing SHM of port infrastructure. Firstly, a summary of related studies is presented in Section 2. Thereafter, in Section 3, the study area and the proposed UAV-driven SHM methodology for port vulnerability assessment is described. In particular, working on the case study of the port infrastructure of the four (4) fishing and leisure harbors of the Municipality of Thebes, located in central Greece, new technical parameters are considered within a comprehensive framework of port vulnerability assessment that includes four different aspects of vulnerability expressed by technical, physical, environmental, and socioeconomic parameters. Two approaches are applied for this vulnerability assessment: (a) considering the new structural condition parameters related to the presence of defects and damages in port infrastructure through analyzing UAV data, such as surface concrete cracks, chemical attacks on concrete surfaces, concrete scaling, and armor layer displacement, and (b) without integrating the new parameters. The in situ inspections conducted at the four fishing and leisure harbors involved UAV applications for condition monitoring of their infrastructure. In Section 4, the results of the current investigation are included and further discussed, while in Section 5, the major findings are presented. The overall investigation shows that the integration of technical structural condition parameters into port vulnerability assessment practices is valuable to port authorities and operators, helping them gain full awareness of the weaknesses of port systems.

2. Current Port Vulnerability Framework

Vulnerability is a dynamic concept that changes through time and across societies [26]. While coastal vulnerability assessment has evolved into a mature science with numerous publications attempting to modify or update baseline studies (e.g., [27]), depending on the research scope of each authors' team (e.g., geological aspects) [28,29], port vulnerability assessment is still quite a challenging issue, considering the complexity of this infrastructure system. Based on the current literature review, variations were observed in the methodologies applied to quantify vulnerability, the aspects examined to approach vulnerability issues (e.g., ecological, socioeconomic, and physical aspects), and the number and category of parameters integrated into assessment applications, as further explained below. In this section, a summary of the above-mentioned variations is included to conclude with the most suitable quantification approach described in Section 3 and the weaknesses found in existing vulnerability practices that triggered this investigation.

Within the context of assessing port vulnerability, different approaches have been utilized regarding the delivery of a quantified vulnerability outcome, i.e., the estimated values that assist in identifying the weaknesses of a system. For example, Izaguirre et al. examined 2013 ports worldwide and proceeded with vulnerability assessment by considering three aspects: technological capacity, recovery capacity, and resilience [10]. For each of these categories, an indicator was defined via the addition of the relevant attribute (parameter) values. McIntosh and Becker initiated a research study of 22 major seaports in the northeast United States, aiming to correlate the three dimensions of vulnerability (i.e., exposure, sensitivity, and adaptive capacity) with vulnerability indicators (parameters) based on expert evaluation [17]. Thereafter, they used the analytic hierarchy process (AHP) method to assign weights to the parameters of port exposure and sensitivity to climate change [9]. Kontogianni et al. proposed a vulnerability index for the 47 fishing and commercial harbors located on Lesvos Island, Greece [11]. This index consisted of three sub-indices (i.e., physical, social, and economic sub-indices) while, for each sub-index, the corresponding parameters were expressed in terms of a 1–5 scale, a commonly used scale for assessing port vulnerability [30].

Besides the above-mentioned variations in port vulnerability assessment approaches, discrepancies were also noticed in the selection of the appropriate number and type of vulnerability parameters. As shown in Figure 1, the vulnerability of a port system can be expressed in terms of a variety of parameters, depending on data availability and the type of port. Although several of these parameters are common in the literature (e.g., vessel capacity, extreme events, and population [11,17] or professional usage [11,15] for climate vulnerability), others are unique in each study, based on the vulnerability approach that the authors followed (e.g., wharf productivity and ground access travel time in the context of assessing port vulnerability to a disaster from a socioeconomic operation perspective [12]). Regardless of the vulnerability approach to different hazards (e.g., natural hazards, manmade disasters, and climate change impacts), it is important to comprehensively understand the structural condition of port infrastructure since it represents its adaptive capacity to be less or more vulnerable. However, the inadequacy of such structural parameters was noticed in the existing literature, thus requiring an adjustment of the current port vulnerability assessment practices to integrate information regarding structural issues.

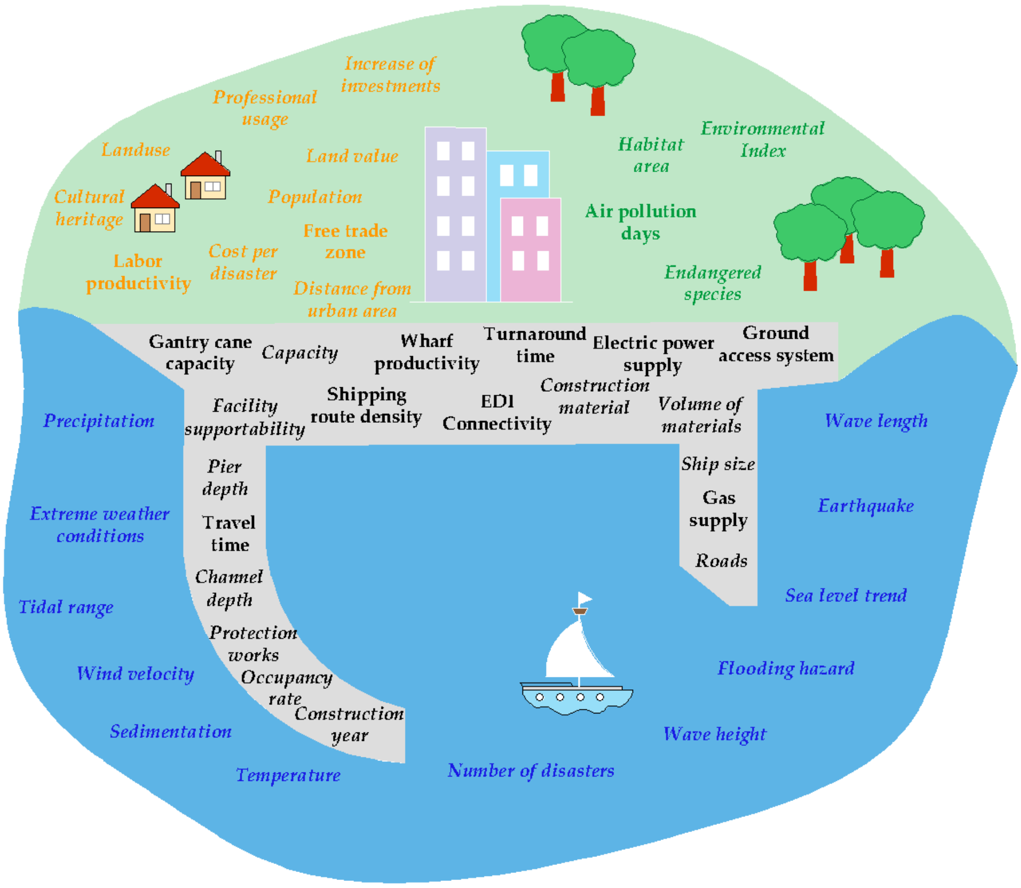

Figure 1. Common port vulnerability parameters (indicators) divided into four categories: technical (black-colored text), physical (blue-colored text), environmental (green-colored text), and socioeconomic (orange-colored text).

It is noted that the information included in Figure 1 was useful in performing the present investigation within the framework of examining the suitability of the different parameters found in the existing literature. Once the sorting of these parameters was complete, the most suitable ones that could reflect the port vulnerability aspects of fishing and leisure harbors (i.e., the present case study) were selected and highlighted in bold text.

3. Materials and Methods

3.1. Case Study

To determine the importance of integrating structural condition parameters into port vulnerability assessment practices, the present research used as a case study the fishing and leisure harbors of the Municipality of Thebes. The Municipality of Thebes is located in the northeastern Corinthian Gulf in central Greece and has a coastline of 62 km in length. Along its coastal zone, four areas indicate the remarkable coastal urbanization associated with the construction and operation of ports that accommodate small crafts, namely Sarantis Beach, Agios Nikolaos, Aliki, and Agios Vasilios (Figure 2). Therefore, to manage its assets and identify their weaknesses, the Municipality of Thebes can benefit from an assessment of the vulnerability of its port infrastructure located in the four above-mentioned areas (Table 1).

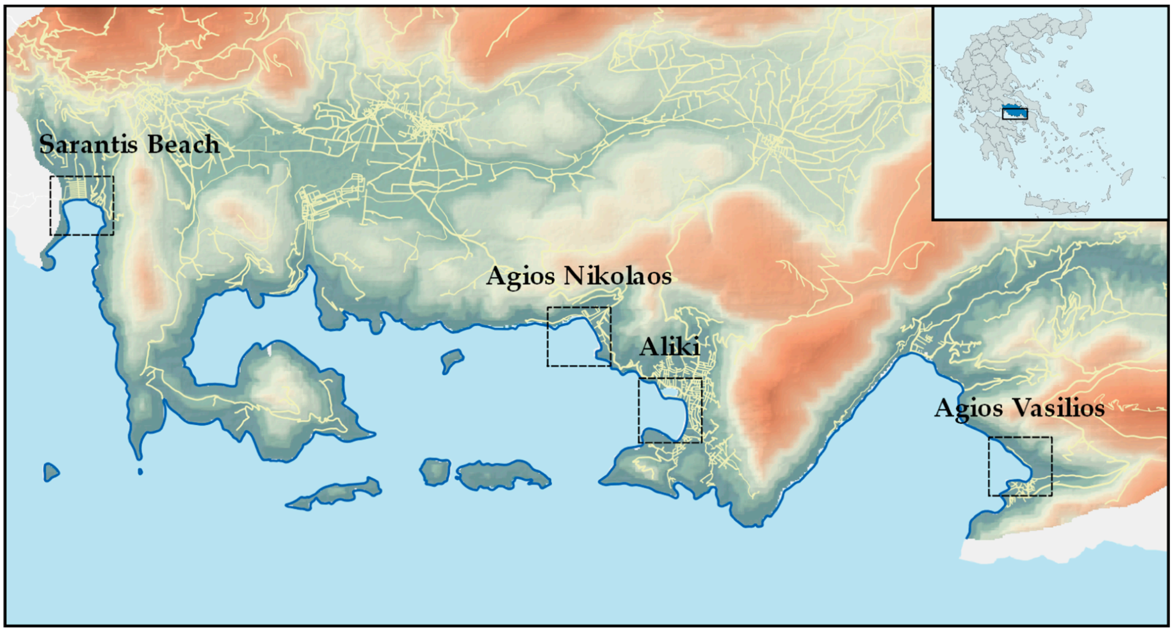

Figure 2. The case study of the four (4) fishing and leisure harbors located in the areas of Sarantis Beach, Agios Nikolaos, Aliki, and Agios Vasilios, in the Municipality of Thebes, Greece. The basemap illustrates the elevation variations within the wider study area of the Municipality with green color denoting lower elevations and brown color denoting higher elevations.

Table 1. The four fishing and leisure harbors of the Municipality of Thebes.

No.	Areas of the Fishing and Leisure Harbors	Vessel Capacity	Time of Construction	Coordinates (Greek Geodetic Reference System)			
				X_{start}	Y_{start}	X_{end}	Y_{end}
1	Sarantis Beach	37	1980s	402,315.51	4,232,200.73	402,326.71	4,232,300.36
2	Agios Nikolaos	30	2000s	415,054.18	4,229,624.24	414,113.00	4,229,694.50
3	Aliki	45	1980s	416,570.95	4,227,811.84	416,733.74	4,227,767.08
4	Agios Vasilios	35	1980s	424,695.80	4,225,888.08	424,550.75	4,225,907.69

Among the four fishing and leisure harbors, the most recently constructed is Agios Nikolaos, built around the 2000s, while the construction of the remaining three dates back to the 1980s. The port infrastructure of the four fishing and leisure harbors involves the following structures:

- Sarantis Beach fishing and leisure harbor: a rubble-mound windward breakwater of ~50 m in length with a concrete crown wall and quay walls of ~110 m in total length (Figure 3a);
- Agios Nikolaos fishing and leisure harbor: a windward breakwater of ~85 m in length constructed via placing concrete blocks with a concrete crown wall, a small rubble-mound upward breakwater of ~20 m in length, and quay walls of ~145 m in total length (Figure 3b);
- Aliki fishing and leisure harbor: a rubble-mound windward breakwater of ~75 m in length with a concrete crown wall, a small concrete upward breakwater of ~9 m in length, and quay walls of ~125 m in total length (Figure 3c);
- Agios Vasilios fishing and leisure harbor: a rubble-mound windward breakwater of ~25 m with a concrete crown wall and quay walls of ~70 m in length (Figure 3d).

(**a**)

(**b**)

(**c**)

(**d**)

Figure 3. Images captured during the in situ inspections [31] illustrating the berthing facilities of the fishing and leisure harbors of (**a**) Sarantis Beach, (**b**) Agios Nikolaos, (**c**) Aliki, and (**d**) Agios Vasilios.

3.2. SHM-Based Port Vulnerability Assessment

The structural condition of port infrastructure is fundamentally interlinked to port vulnerability since pressures including climate change impacts [32], occurring natural hazards [33], highly corrosive marine environments, and human-induced factors [34] challenge infrastructure resilience. To address such vulnerability issues, condition monitoring can be a useful tool to strengthen and support decision-making in prioritizing interventions for maintenance, recovery, or upgrades [35]. To this end, it is essential to examine the impact of integrating SHM applications into the vulnerability assessment practices of port infrastructure.

The vulnerability assessments of the four fishing and leisure harbors of the Municipality of Thebes were performed via implementing an SHM-based methodology that introduced new technical parameters related to the structural condition of the port infrastructure (Figure 4). As shown in Figure 4, to achieve a comprehensive approach to assessing port vulnerability, it was vitally important to begin with an extensive literature review aiming to identify the vulnerability parameters and optimize their number, based on data availability and parameter suitability for the specific case study. Given the inadequacy of integrating structural condition parameters into current practices, an investigation was performed to introduce new parameters related to port infrastructure performance, thus strengthening vulnerability assessment. All selected vulnerability parameters were estimated via combining in situ inspections, data aggregation (e.g., inventory data and the use of open-source databases), and analysis (e.g., the processing of monitoring data). This information was processed using Geographic Information System (GIS) tools, herein the QGIS, to quantify, map, and visualize spatial data. Finally, a ranking of the fishing and leisure harbors was performed, based on their vulnerability outcomes.

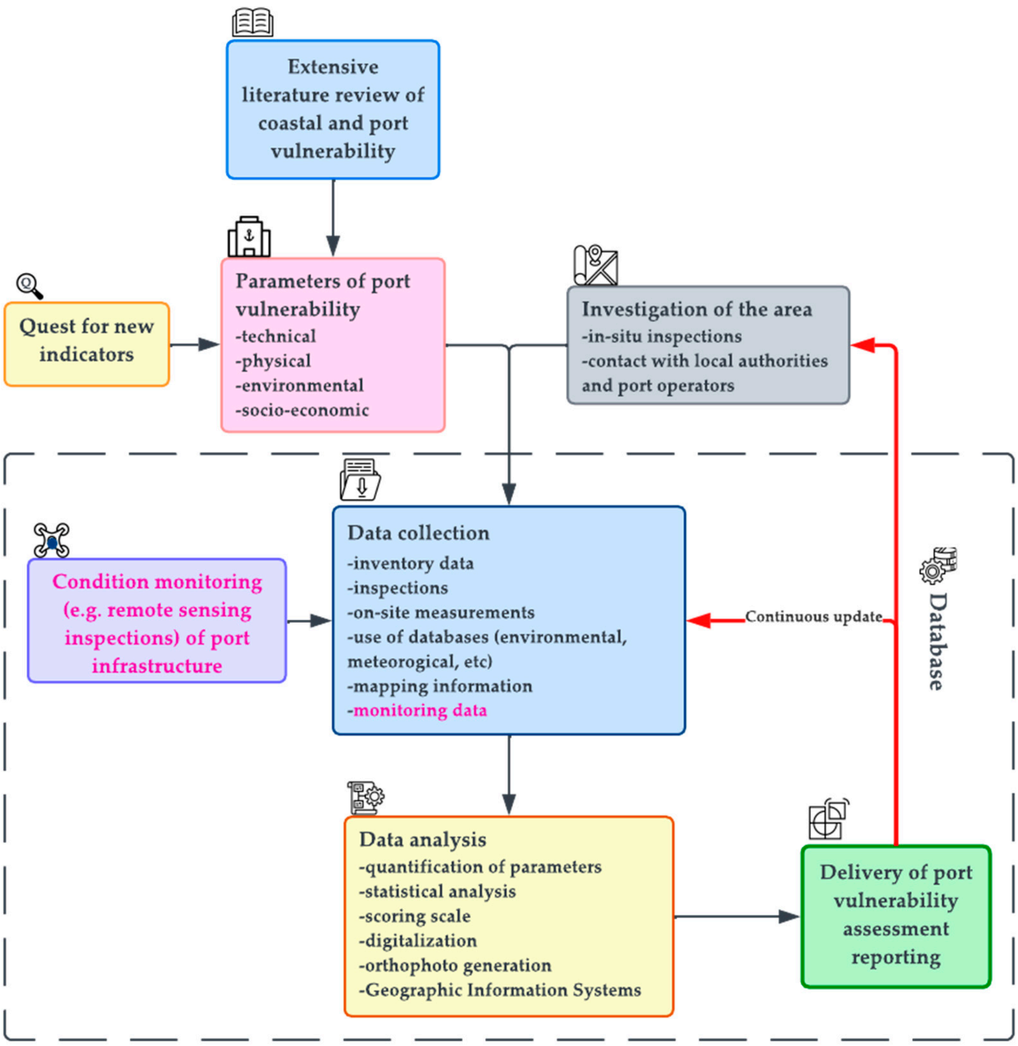

Figure 4. The proposed SHM-based vulnerability assessment methodology.

As indicated in Figure 4, all information acquired during the process of port vulnerability assessment can be used as an input into coherent databases that can be continuously updated with new information. Therefore, deep insight will be gained into the system's weaknesses to optimize management actions. These databases can be also enhanced by using new SHM data based on a periodic or ad hoc inspection plan (e.g., routine inspections or inspections after a disaster or rehabilitation) [36]. In this research, SHM practices were applied only during the first vulnerability assessment of the four fishing and leisure harbors. The achieved outcomes could be used not only to manage potential short-term threats but also to make predictions about future responses to long-term threats, such as climate change impacts, by assuming that no maintenance measures will be applied and that structural condition will be degraded based on prediction models.

3.3. Port Vulnerability Index

The vulnerability assessment was performed in terms of estimating a total Port Vulnerability Index (PVI) expressed by four sub-indices, (a) the technical sub-index (VI_T), (b) the physical sub-index (VI_{Ph}), (c) the environmental sub-index (VI_E), and (d) the socioeconomic sub-index (VI_{SE}), through adjusting the equation of [11] to the needs of the current research (Equation (1)):

$$PVI = VI_T + VI_{Ph} + VI_E + VI_{SE} \tag{1}$$

Since vulnerability parameters are inherently linked to the three dimensions of vulnerability (i.e., exposure (E), sensitivity (S), and adaptive capacity (AD) [17]), the values of each sub-index VI_i were estimated using Equation (2) [37],:

$$VI_i = E \times S \times AD \tag{2}$$

where i is T, Ph, E, or SE.

Given the wide range of parameter values and the need to provide dimensionless indices, each parameter (p) was normalized via the application of Equation (3) [11,12,38]:

$$I_p = \frac{x_p - \min(x_p)}{\max(x_p) - \min(x_p)} \tag{3}$$

where, I_p is the normalized value of each parameter, x_p is the value of the parameter, $\min(x_p)$ is the minimum value of the parameter, and $\max(x_p)$ is the maximum value of the parameter [39].

3.4. SHM Vulnerability Parameters

The proposed methodology was based on existing practices for the vulnerability assessment of ports enhanced with SHM applications to identify the structural condition of their infrastructure and encourage the integration of new parameters. Hence, although an integrated approach to port vulnerability assessment is presented herein, the main focus of the research was the description of the steps required to design structural condition parameters. Given that ports involve different types of structures [40], the structural condition of each structure was expressed in terms of its specific distresses/defects and failures related to its type of material, loading conditions, etc. The port facilities of the four fishing and leisure harbors of the Municipality of Thebes include concrete wharves and rubble-mound protection structures, thus requiring the investigation of defects and failures associated with these types of port structures [24,36].

To identify the structural condition of the examined port infrastructure, in situ inspections were conducted at the four fishing and leisure harbors through employing a UAV, the DJI Mavic 2 pro [31]. This specific UAV has an integrated camera (model L1D-20c) with a 5472 × 3648 resolution, a 10.26mm focal distance, and a 2.41 × 2.41 μm pixel size. The images captured during the UAV flights were analyzed with photogrammetry processes [41] via employing Agisoft software, version 1.4. The geospatial output of the photogrammetry analysis (i.e., the orthophotos of each fishing and leisure harbor illustrated in Figure 5) allowed for the mapping of the structural condition of the superstructure [23,24,42]. Within the context of this paper, the processing of the geospatial metadata (i.e., the orthophotos) was achieved using GIS tools.

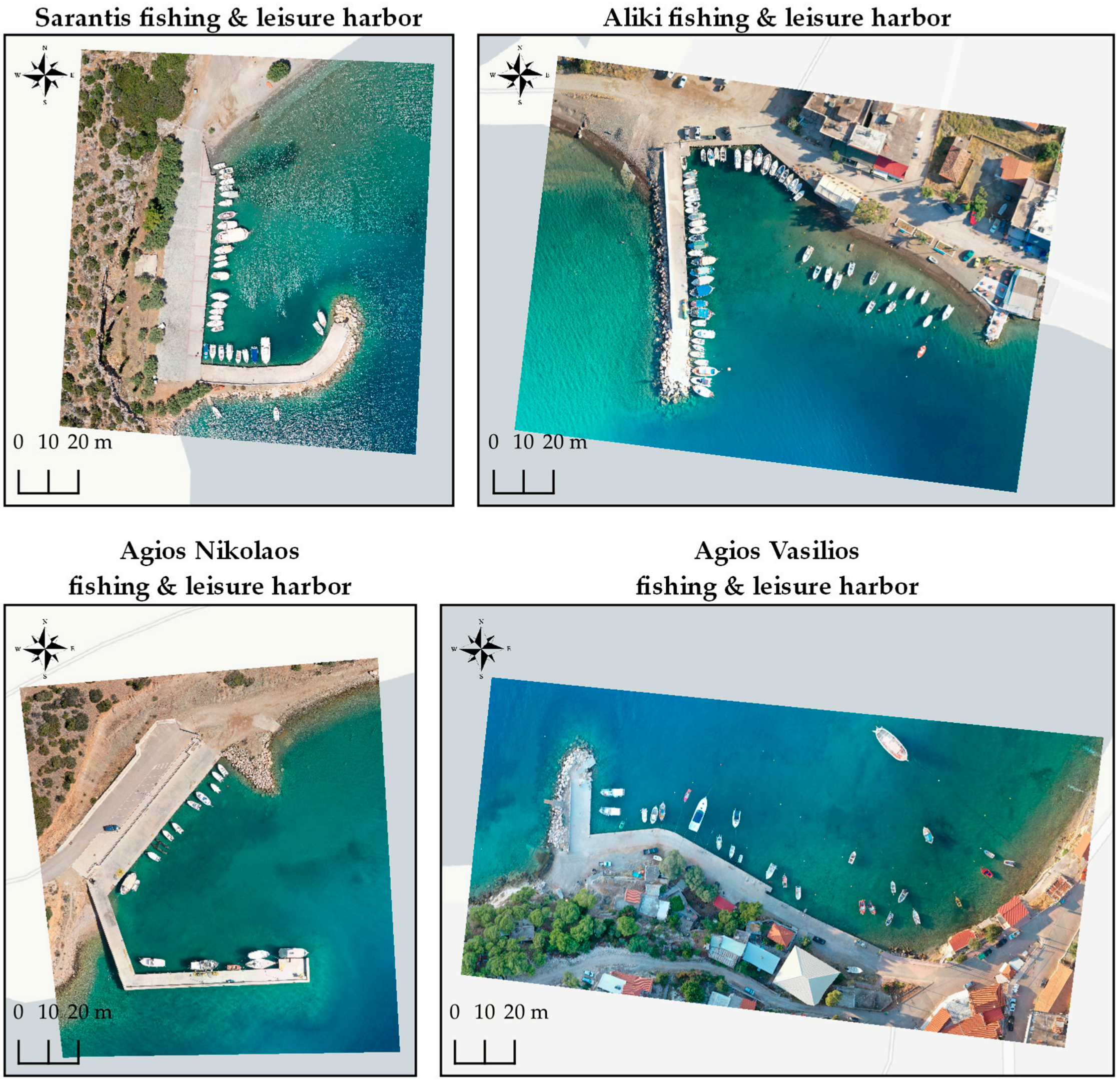

Figure 5. The generated orthophotos of the four fishing and leisure harbors of the Municipality of Thebes.

For this specific case study, and based on the capabilities of a UAV-driven SHM framework to detect the defects and failures of the port infrastructure, the following aspects of the structural condition of the four fishing and leisure harbors were investigated:

- Cracks on the concrete wharf surface, represented by parameter T6 (Table 2);
- Chemical attacks on the concrete wharf surface, represented by parameter T7 (Table 2);
- Concrete scaling, represented by parameter T8 (Table 2);
- Armor layer displacement, represented by parameter T9 (Table 2).

Table 2. Vulnerability parameters of the case study of the four fishing and leisure harbors of the Municipality of Thebes.

ID	Sub-Index	Category	Parameters	Units	Exposure	Sensitivity	Adaptive Capacity
T1	VI_T	Port layout	Port size	m^2	•		
T2		Connectivity	Distance from main roads	m		•	
T3			Distance from other ports	m		•	
T4		Serviceability	Vessel capacity	-	•		
T5			Occupancy rate	%	•		
T6		**Structural condition**	**Surface concrete cracks**	%			•
T7			**Chemical attack on concrete surface**	%			•
T8			**Concrete scaling**	%			•
T9			**Armor layer displacement**	%			•
Ph1	VI_{Ph}	Climatic factors	Annual precipitation	mm	•		
Ph2			Wind velocity	m/s	•		
Ph3			Annual temperature	°C	•		
Ph4		Seismic activity	Distance from the closest major fault	m	•		
Ph5		Wave characteristics	Significant wave height	m	•		
E1	VI_E	NATURA 2000 network	Number of endangered species	-		•	
E2			Number of habitat areas	-		•	
E3		Aquaculture	Distance from aquaculture	m		•	
SE1	VI_{SE}	Culture heritage	Distance from archaeological sites and historical monuments	m		•	
SE2		Urbanization	Distance from urban area	m		•	
SE3		Population characteristics	Population	-		•	
SE4			Percentage of population above 65 years old	%		•	
SE5			Unemployment rate	%		•	
SE6			Average number of household members	-		•	

The symbol "•" indicates that each parameter corresponds to the vulnerability dimension of exposure, sensitivity or adaptive capacity.

While, for the four examined fishing and leisure harbors, the structural condition were linked to these types of defects and failures, the proposed methodology can be adjusted to the features of all port infrastructure by modifying the structural condition parameters, depending on the requirements of each port. Furthermore, it was noted that the presence of defects and failures adversely affected the vulnerability status of the examined harbors since the higher the damage, the more vulnerable the system.

3.5. Summary of All Vulnerability Parameters

The finalized vulnerability parameters used for the case study of the four fishing and leisure harbors of the Municipality of Thebes are presented in Table 2, where T_i denotes the technical parameters, Ph_i denotes the physical parameters, E_i denotes the environmental parameters, and SE_i denotes the socioeconomic parameters. The methods applied to estimate each vulnerability parameter are included in Table 3. It is noted that, since all the examined fishing and leisure harbors are within the Natura 2000 network, the parameters E1 and E2 did not affect the vulnerability results, and consequently, they were not considered in Equation (2). Therefore, twenty-one parameters were examined to assess the port vulnerability of the fishing and leisure harbors. To apply Equation (2) for the estimation of each sub-index, a mean value of the parameters belonging to the same category was calculated. For example, regarding the structural condition category, the adaptive capacity was expressed through the mean value of parameters T6, T7, T8, and T9.

Table 3. Estimation methods for the vulnerability parameters of the case study of the four fishing and leisure harbors of the Municipality of Thebes.

Parameters	**Method**
T1: Port size	GIS-based processing of the generated orthophotos
T2: Distance from main roads	GIS-based processing of the generated orthophotos and the available platform maps
T3: Distance from other ports	GIS-based processing of the generated orthophotos and the available platform maps
T4: Vessel capacity	Computer-aided design (CAD) processing of the generated orthophotos
T5: Occupancy rate	Computer-aided design (CAD) processing of the generated orthophotos and the aerial imagery provided by Google Earth
T6: Surface concrete cracks	GIS-based processing of the generated orthophotos and verification using images captured during the visual survey
T7: Chemical attack on concrete surface	GIS-based processing of the generated orthophotos and verification using images captured during the visual survey
T8: Concrete scaling	GIS-based processing of the generated orthophotos and verification using images captured during the visual survey
T9: Armor layer displacement	GIS-based processing of the generated orthophotos and verification using images captured during the visual survey
Ph1: Annual precipitation	Use of data acquired via the Hellenic National Meteorological Service (http://www.emy.gr/emy/en/index_html? (accessed on 31 March 2023))
Ph2: Wind velocity	Use of data acquired via the Hellenic National Meteorological Service (http://www.emy.gr/emy/en/index_html? (accessed on 31 March 2023))
Ph3: Annual temperature	Use of data acquired via the Hellenic National Meteorological Service (http://www.emy.gr/emy/en/index_html? (accessed on 31 March 2023))
Ph4: Distance from the closest major fault	GIS-based processing of the generated orthophotos and the available platform maps with data acquired via open-data sources (https://zenodo.org/record/4897894 (accessed on 28 April 2023)) and GIS tools
Ph5: Significant wave height	Use of [43]
E1: Number of endangered species	https://natura2000.eea.europa.eu/ (accessed on 28 April 2023)
E2: Number of habitat areas	https://natura2000.eea.europa.eu/ (accessed on 28 April 2023)
E3: Distance from aquaculture	GIS-based processing of the generated orthophotos and the available platform maps in combination with Google Earth imagery data
SE1: Distance from archaeological sites and historical monuments	GIS-based processing of the generated orthophotos and the available platform maps in combination with Google Earth imagery data
SE2: Distance from urban area	GIS-based processing of the generated orthophotos and the available platform maps in combination with Google Earth imagery data
SE3: Population	Processing of data acquired via the Hellenic Statistical Authority (HAS) (https://www.statistics.gr/en/home/ (accessed on 17 February 2022))
SE4: Percentage of population above 65 years old	Processing of data acquired via the HAS (https://www.statistics.gr/en/home/ (accessed on 17 February 2022))
SE5: Unemployment rate	Processing of data acquired via the HAS (https://www.statistics.gr/en/home/ (accessed on 17 February 2022))
SE6: Average number of household members	Processing of data acquired via the HAS (https://www.statistics.gr/en/home/ (accessed on 17 February 2022))

Moreover, for all parameters except Ph4: Distance from the closest major fault, E3: Distance from aquaculture, SE1: Distance from archaeological sites and historical monuments, and SE2: Distance from urban area, the higher the value, the higher the vulnerability of the fishing and leisure harbor in terms of the specific parameter. On the contrary, an increase in the distance from the major faults, aquaculture, cultural heritage, and urban areas led to decreased vulnerability.

Once all vulnerability parameters were estimated, the following steps were applied to calculate the total vulnerability index (PVI) of each fishing and leisure harbor:

- Normalization of the parameters' values based on Equation (3) to acquire dimensionless values within the same range;
- Estimation of the mean value of each vulnerability component/dimension: exposure (E), sensitivity (S), and adaptive capacity (AC) of each sub-index;
- Estimation of each sub-index based on Equation (2);
- Calculation of the total PVI based on Equation (1).

4. Results and Discussion

The vulnerability assessment of the four fishing and leisure harbors of the Municipality of Thebes was performed by taking into account technical, physical, environmental, and socioeconomic parameters, based on data availability and suitability for the specific case study. Regarding the technical sub-index, two approaches were applied: (a) estimation of the sub-index with the new structural condition parameters ($VI_{T,SC}$) and (b) typical estimation of the sub-index without the new parameters ($VI_{T,typical}$), aiming to explore the importance and influence of the additional parameters on the technical vulnerability output. Thereafter, two total vulnerability indices were estimated: (a) with the new structural condition parameters (PVI_{SC}) and (b) without the new parameters ($PVI_{typical}$).

4.1. Analysis of Estimated Vulnerability Parameters

The values of the estimated vulnerability parameters, as shown in Table 3, are included in Table 4. Regarding the fishing and leisure harbor of Sarantis Beach, five out of the twenty-one parameters denoted the lowest vulnerability compared to the other harbors, while three denoted the highest vulnerability. For the harbors of Agios Nikolaos and Aliki, both the cases of the lowest and the highest vulnerability included eight parameters. Moreover, for the harbor of Agios Vasilios, nine out of the twenty-one parameters denoted the lowest vulnerability compared to the other harbors, while five parameters denoted the highest vulnerability. A closer look at the parameter values included in Table 4 indicated that the harbor of Agios Nikolaos was vulnerable in terms of more technical parameters compared to the other harbors. In particular, this harbor indicated less adaptive capacity expressed by the parameters of structural condition since more defects were detected in its infrastructure. The harbor of Agios Vasilios was vulnerable in terms of more physical parameters, indicating that this specific harbor is more exposed to physical stressors. The harbor of Aliki was more vulnerable in terms of socioeconomic aspects, contrary to the harbor of Agios Nikolaos, which had four out of the six socioeconomic parameters indicating the lowest vulnerability. Considering the above, it was observed that each harbor was more vulnerable in terms of different vulnerability aspects, all equally important to acquire a comprehensive understanding of the weaknesses of port systems. Therefore, it was vital to examine the technical, physical, environmental, and socioeconomic aspects separately before proceeding with the estimation of the total vulnerability of each harbor.

Table 4. Values of the estimated vulnerability parameters of the four fishing and leisure harbors of the Municipality of Thebes.

ID	Parameters	Units	Fishing and Leisure Harbors			
			Sarantis Beach	Agios Nikolaos	Aliki	Agios Vasilios
T1	Port size	m^2	740.65	1029.75	759.99	646.54
T2	Distance from main roads	m	287.71	667.45	204.53	200.17
T3	Distance from other ports	m	19,215.2	3746.14	3681.37	12,688.72
T4	Vessel capacity	-	37	30	45	35
T5	Occupancy rate	%	86	37	100	43
T6	Surface concrete cracks	%	0.00	0.30	0.00	0.00
T7	Chemical attack on concrete surface	%	1.07	2.87	0.00	0.00
T8	Concrete scaling	%	0.00	0.00	59.58	100.00
T9	Armor layer displacement	%	6.85	4.40	14.80	5.17
Ph1	Annual precipitation	mm	463.3	438.84	400.97	382.29
Ph2	Wind velocity	m/s	3.8	4.1	4.2	4.9
Ph3	Annual temperature	°C	17.57	16.7	17.7	17.39
Ph4	Distance from the closest major fault	m	6811	4888	4645	2270
Ph5	Significant wave height	m	1.49	1.19	1.27	1.71
E3	Distance from aquaculture	m	8510	10,972	12,123	17,941
SE1	Distance from archaeological sites and historical monuments	m	7036.32	>>	0	>>
SE2	Distance from urban area	m	287.71	667.45	0	0
SE3	Population	-	160	16	279	100
SE4	Percentage of population above 65 years old	%	31.41	9.62	38.41	31.15
SE5	Unemployment rate	%	17.31	23.08	17.39	14.75
SE6	Average number of household members	-	2	3	2	2

The symbol ">>" indicates that the corresponding value is much greater than the other values.

As far as the estimation of the structural condition parameters is concerned, the quantification conducted with the use of the GIS tools resulted in the estimation of the percentage of the port infrastructure areas with cracking (parameter T6), chemical attacks (parameter T7), scaling (parameter T8), and armor layer displacement (parameter T9). An indicative example of each detected type of defect is presented in Figure 6. Agios Nikolaos Harbor was characterized by the presence of cracking along the concrete berthing facilities (Figure 6a, Table 4), while the other three harbors had no (or almost no) cracked concrete areas. Moreover, at the same harbor, a significant percentage of its concrete berthing facilities were subject to chemical attacks (Figure 6b, Table 4). A typical illustration of concrete scaling is depicted in Figure 6c, where it is obvious that the concrete berthing facilities of Agios Vasilios harbor were subject to a loss of mortar around the aggregates. This result may be associated with the type and the low-strength concrete used for the construction of the specific port facilities back in the 1980s, along with the absence or inadequacy of maintenance treatments. Hence, the total concrete area of Agios Vasilios harbor was characterized by scaling. Regarding the structural condition parameter of armor displacement, an indicative area mapped within the windward breakwater of Sarantis harbor is illustrated in Figure 6d. Besides the inappropriate armor grading, the in situ inspection showed that the armor layer material had been displaced in several areas (e.g., the area in Figure 6d with a light orange color).

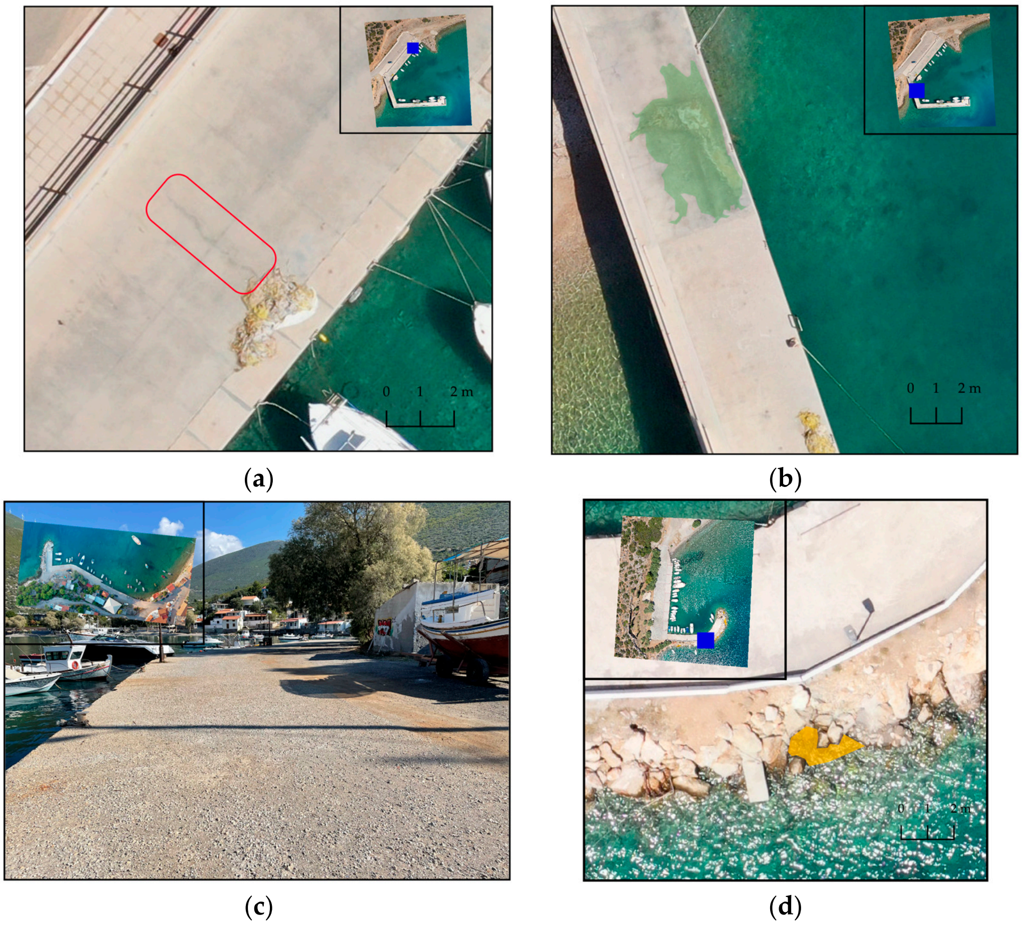

Figure 6. Mapping and quantifying structural condition parameters for the vulnerability assessment of the four fishing and leisure harbors of the Municipality of Thebes: (**a**) cracking at the wharf facilities of the fishing and leisure harbor of Agios Nikolaos as shown within the red frame; (**b**) chemical attacks on the concrete surface, denoted with a light-green-colored polygon, at the windward breakwater of the fishing and leisure harbor of Agios Nikolaos; (**c**) concrete scaling at the wharf facilities of the fishing and leisure harbor of Agios Vasilios; (**d**) armor layer displacement, denoted with a light-orange-colored polygon, at the rubble-mound windward breakwater of the fishing and leisure harbor of Sarantis Beach.

The comparative evaluation of the values of the structural condition parameters included in Table 4 showed that armor layer displacement was identified within all four harbors, with the harbor of Aliki being the most vulnerable. Moreover, concrete scaling was detected in the harbors of Aliki and Agios Vasilios, with the first harbor having approximately half of its berthing facilities distressed, while the second harbor was characterized by a loss of mortar along the total concrete surface. Finally, chemical attacks were more prevalent in the harbor of Agios Nikolaos, while concrete cracking was only detected in the same harbor. In general, the percentages between the detected defects were significantly different, ranging from very low (i.e., 0.00%) to very high (i.e., 100%), indicating that, while some defects are present to a very low extent at the examined port facilities, thus corresponding to very low vulnerability, others occupy larger parts of the facilities, resulting in very vulnerable structures in terms of the specific parameter. Based on the above, it can be stated that, although it is significant to examine the vulnerability changes between the harbors, it is also of paramount importance to investigate the variations between similar concept-based parameters (e.g., parameters belonging to the structural condition category) since their impacts can alter the vulnerability outcome.

The structural condition parameters mentioned above and included in Table 4 are time-dependent features that may be altered during port infrastructure's lifetime not only over the long term but also over the short term. For example, extreme wave forces during a sudden event may result in a higher percentage of armor layer degradation, and consequently, new UAV-based SHM practices would be required to estimate again the value of parameter T9. Considering this, it is obvious that effective SHM planning and implementation assist in examining the dynamic aspect of vulnerability. It is noticed that, in addition to the variability of the structural condition parameters, other parameters may also change within a shorter time-scale such as the distance from main roads if new construction works are foreseen to be undertaken in a short time. However, the majority of the parameters shift on a larger temporal scale, thus making port vulnerability outcomes particularly susceptible to the time dependence of the structural condition parameters.

4.2. Vulnerability Assessment of the Four Fishing and Leisure Harbors

Once the parameters' values were estimated, the sub-indices of technical, physical, environmental, and socioeconomic vulnerability were calculated with the normalized values derived from Equation (3). As shown in Table 4, several values were equal to zero. Hence, to avoid setting Equation (2) to zero, thus neglecting the influence of the non-zero parameters, normalization was performed between the values of one to two. The calculated sub-indices and the total PVI based on Equation (1) are included in Table 5 for each assessment approach: (a) with, denoted by "SC", and (b) without, denoted by "typical," the proposed structural condition parameters. It is clear that only the values of the technical sub-index and the PVI changed through the implementation of these two approaches. Given that the structural condition expresses the adaptive capacity of a port system to be prepared for imminent threats, this vulnerability aspect was only considered for the approach of integrating the new parameters (i.e., parameters T6, T7, T8, and T9).

Table 5. Vulnerability values and ranking of the four fishing and leisure harbors of the Municipality of Thebes. For the cases of the technical sub-index and the total PVI, the values are estimated through two approaches (a) with the proposed structural condition parameters denoted by "SC" and (b) without the proposed structural condition parameters denoted by "typical".

Vulnerability		Approach	Fishing and Leisure Harbors			
			Sarantis Beach	Agios Nikolaos	Aliki	Agios Vasilios
(Sub-)Indices	$VI_{T,SC}$	a	2.63	3.38	2.32	1.81
	$VI_{T,typical}$	b	2.29	2.25	1.66	1.43
	VI_{Ph}	N/A	1.40	1.17	1.31	1.85
	VI_E	N/A	2.00	1.57	1.43	1.00
	VI_{SE}	N/A	1.14	1.17	1.86	1.42
	PVI_{SC}	a	7.17	7.29	6.92	6.09
	$PVI_{typical}$	b	6.82	6.17	6.25	5.70
Ranking	$Ranking_{T,SC}$	a	3	4	2	1
	$Ranking_{T,typical}$	b	4	3	2	1
	$Ranking_{Ph}$	N/A	3	1	2	4
	$Ranking_E$	N/A	4	3	2	1
	$Ranking_{SE}$	N/A	1	2	4	3
	$Ranking_{PVI,SC}$	a	3	4	2	1
	$Ranking_{PVI,typical}$	b	4	2	3	1

The incorporation of the structural condition parameters changed the vulnerability ranking between the four fishing and leisure harbors, with the harbor of Agios Nikolaos being the most vulnerable one, whereas in the case of excluding the additional technical parameters, the harbor of Sarantis Beach was the most vulnerable (Figure 7). By comparing the percentage of the variation between the VI_{TSC} and the $VI_{Ttypical}$, it was observed that the technical sub-indices of the harbors of Agios Nikolaos, Aliki, Agios Vasilios, and Sarantis Beach were increased by approximately 50%, 40%, 27%, and 15%, respectively, ranked in order from the highest to the lowest variation. This result indicated that, although the harbor of Agios Nikolaos is the most recently constructed, its adaptive capacity is reduced. It seems that its concrete berthing facilities tend to be more prone to cracking and chemical attacks compared to the other harbors. It was noticed that, given the absence of armor layers in the windward breakwater, the parameter of armor layer displacement (i.e., T9) was limited to the evaluation of the structural condition of only the upward breakwater and thus assigned a smaller value.

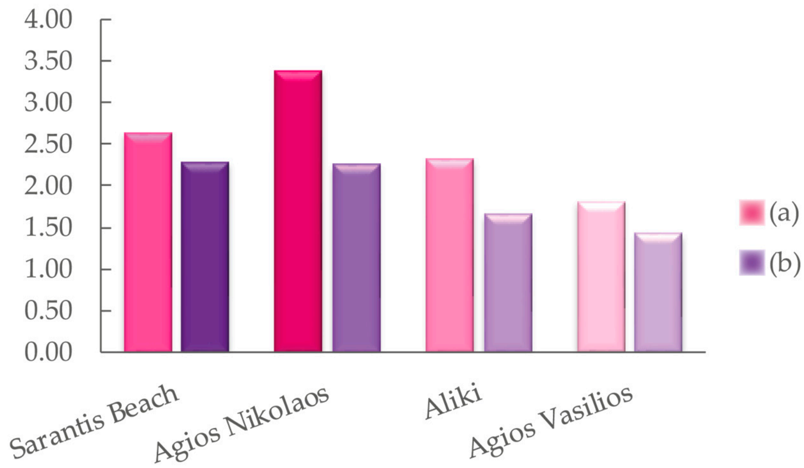

Figure 7. Technical-based vulnerability assessment of the four (4) fishing and leisure harbors of the Municipality of Thebes, Greece: (**a**) by incorporating the structural condition parameters, ranging from a light pink color for the lowest vulnerability to a dark pink color for the highest vulnerability, and (**b**) without the structural condition parameters, ranging from a light purple color for the lowest vulnerability to a dark purple color for the highest vulnerability via the approach.

For both approaches of the technical-based vulnerability assessment, Agios Vasilios was the least vulnerable harbor, followed by the harbor of Aliki. Although the harbor of Agios Nikolaos is the one with the highest number of detected defects (i.e., three out of the four examined defects), and consequently, it ranked higher in the structural condition vulnerability assessment, the berthing facilities of the harbor of Agios Vasilios were totally characterized by concrete scaling, thus decreasing its adaptive capacity. This could not be depicted in the calculation of the technical sub-index since, after the normalization of the parameters' values, such differences were neglected. To eliminate this issue, additional analysis via assigning weights to explore the significance of the parameters could be performed. However, this is beyond the scope of the present research, which focuses on encouraging the integration of structural condition parameters into a comprehensive and time-dependent port vulnerability assessment.

As far as the physical sub-index was concerned, the most vulnerable harbor was the one of Agios Vasilios, which is exposed to high wind velocities (parameter Ph2) and wave heights (parameter Ph5), while it is more prone to earthquake impacts, given its proximity to major faults (Figure 8). The harbor of Sarantis Beach was the most environmentally vulnerable one regarding the distance from aquaculture (Figure 9). The harbor of Aliki indicated the highest socioeconomic vulnerability (Figure 10) since it is close to a more developed urban area, in contrast with the other harbors, and the debris from the ancient town named Sipha is located within the settlement of Aliki.

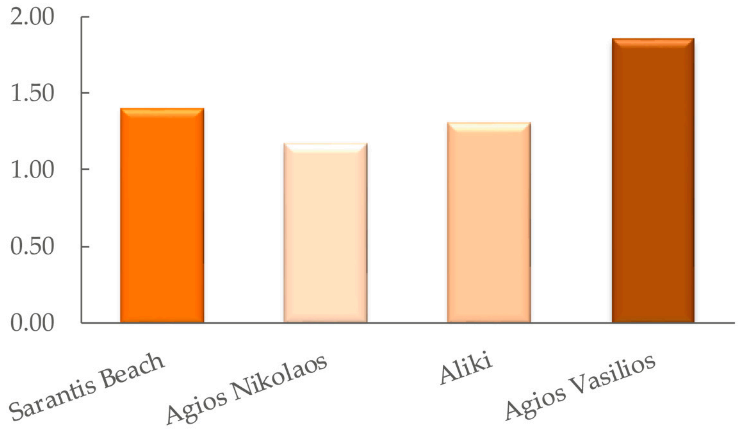

Figure 8. Physical-based vulnerability assessment of the four (4) fishing and leisure harbors of the Municipality of Thebes, Greece, ranging from a light brown color for the lowest vulnerability to a dark brown color for the highest vulnerability.

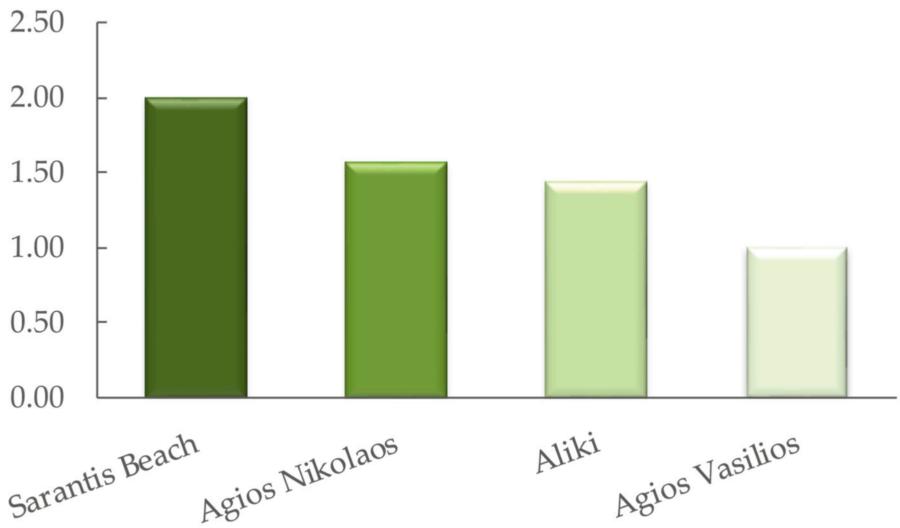

Figure 9. Environmental-based vulnerability assessment of the four (4) fishing and leisure harbors of the Municipality of Thebes, Greece, ranging from a light green color for the lowest vulnerability to a dark green color for the highest vulnerability.

The total vulnerability ranking expressed by the PVI for the two approaches: (a) enabling and (b) disabling the use of the proposed structural condition parameters is shown in Figure 11. For both approaches, the least vulnerable harbor was the one of Agios Vasilios. However, the ranking order changed for the remaining three fishing and leisure harbors after the integration of the structural condition parameters. When using the new parameters, although the most vulnerable harbor was the one of Agios Nikolaos, the PVI values had relatively minor differences, especially between the harbors of Agios Nikolaos and Sarantis Beach. Taking the new parameters out of consideration, the harbor of Agios Nikolaos would be downscaled to the second least vulnerable one since the adaptive capacity weaknesses of this harbor would be neglected. Moreover, the harbor of Sarantis Beach would be the most vulnerable one, followed by the harbor of Aliki. The differences noticed between the PVI values of the first and second most vulnerable harbors were substantially higher than the ones of the approach using the structural condition parameters.

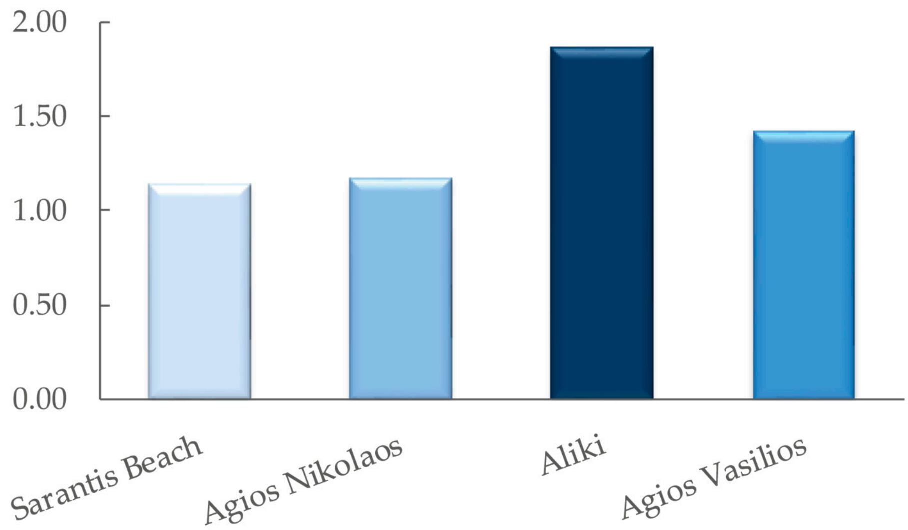

Figure 10. Socioeconomic-based vulnerability assessment of the four (4) fishing and leisure harbors of the Municipality of Thebes, Greece, ranging from a light blue color for the lowest vulnerability to a dark blue color for the highest vulnerability.

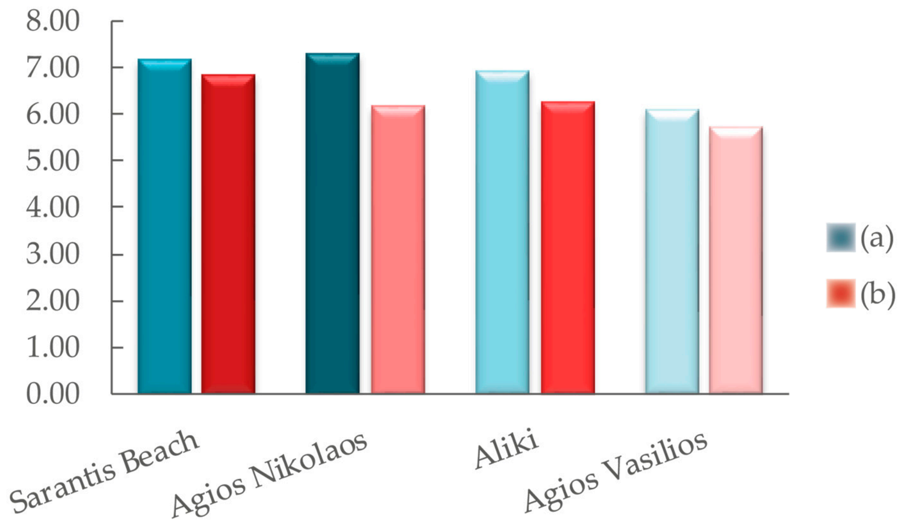

Figure 11. Port Vulnerability Index of the four (4) fishing and leisure harbors of the Municipality of Thebes, Greece: (**a**) by incorporating the structural condition parameters, ranging from a light petrol color for the lowest vulnerability to a dark petrol color for the highest vulnerability and (**b**) without the structural condition parameters, ranging from a light red color for the lowest vulnerability to a dark red color for the highest vulnerability for the approach.

As expected, both the VI_T and total PVI values were different for the two vulnerability assessment approaches. In general, the integration of new vulnerability parameters can alter assessment and ranking outcomes, thus modifying the considerations about prioritizing actions for addressing vulnerability issues and increasing port resilience. Therefore, it is crucial to investigate the importance of the additional parameters and the perspective within which port vulnerability is assessed (e.g., port engineering or environmental perspectives). However, given that ports are infrastructure systems, it is highly recommended that the structural condition parameters are not neglected during vulnerability assessments considering all different types of hazards.

4.3. Research Implications

This research was intended to broaden port authorities' insights into their asset vulnerabilities by integrating UAV-driven SHM applications into vulnerability assessment practices. Currently, SHM has not been considered in similar studies that address port vulnerability issues. The concept of the structural integrity of port infrastructure was introduced into building a port vulnerability index [11] in an attempt to examine the linkage between economic vulnerability and construction materials. However, the structural condition was not associated with the system's adaptive capacity in the contexts of potential disturbances or the post-disaster ability to recover. Moreover, while recent research on the vulnerability issues of fishing harbors has adopted the approach of combining the three dimensions of vulnerability, i.e., exposure, sensitivity, and adaptive capacity, as fostered herein, the current methodologies focus on different aspects of vulnerability, such as eco-socioeconomic aspects [44]. Depending on the requirements of each managing authority, existing practices can be combined with the proposed SHM methodology to achieve a holistic approach to port vulnerability assessment.

Furthermore, although the present work refers to the case study of the four fishing and leisure harbors of the Municipality of Thebes, the applied UAV-driven SHM methodology can be expanded to larger ports with a higher number and different types and sizes of facilities that have already been used as case studies in related work (e.g., [8,10]). UAV inspections favor both the ex ante and ex post reconnaissance of the structural condition of port infrastructure since both extensive logistics and inspection time can be reduced [25], thus achieving rapid and safe condition monitoring. The latter is extremely important, especially in busier ports than the small-craft harbors examined herein, as all management processes such as port vulnerability assessment require quick actions to optimize reaction time. Hence, despite the fact that the results of the present research cannot be compared with the outcomes of similar studies, the applicability of the proposed UAV-assisted SHM methodology to port vulnerability assessment approaches is promising.

5. Conclusions

Assessing port vulnerability is a challenging issue, considering the variety of stressors related to the exposure, sensitivity, and adaptive capacity of a port system to potential threats. Given that ports are strategic infrastructure assets, the interrelationship between the vulnerability concept and the structural condition of their facilities cannot be questioned. Within the framework of port vulnerability assessment, the identified weaknesses regarding the technical parameters of structural condition and the absence of scientific approaches to condition monitoring triggered this specific work. Its major contribution entails the novel aspect of integrating the SHM of port infrastructure into vulnerability assessment practices. Therefore, the present research sought to investigate the applicability of a UAV-based SHM to port vulnerability assessment practices by considering two approaches: (a) assessment with the new structural condition parameters and (b) assessment without the new parameters.

For the examined case study of the four fishing and leisure harbors of the Municipality of Thebes, namely Sarantis Beach, Agios Nikolaos, Aliki, and Agios Vasilios, it was concluded that the integration of the new structural condition parameters significantly affected the vulnerability ranking order except for the harbor of Agios Vasilios, which continued to rank as the least vulnerable harbor. The weaknesses of this specific harbor are mainly reflected in its exposure to physical pressures. Furthermore, the reduced adaptive capacity of the infrastructure of the harbor of Agios Nikolaos was illustrated by the high increase in its technical sub-index, thus making it the most vulnerable harbor after the incorporation of the new parameters. If the structural condition parameters were not considered, the harbor of Agios Nikolaos would rank as the second least vulnerable one, thus neglecting its structural vulnerability. Moreover, the integration of the new parameters resulted in a decrease in the ranking order of both the harbors of Sarantis Beach and Aliki, thus implying that the other parameters were more significant to the vulnerability assessment. Therefore, within the context of managing the four port infrastructure systems, port and local authorities can benefit from gaining valuable insight into the weaknesses of their assets and proceeding with the most suitable countermeasures. In the cases in which the examined ports refer to a wider spatial scale (e.g., a national or international level), the proposed SHM-based methodology can favor port vulnerability assessment practices since it is built upon the employment of UAVs, a widely used practice applied not only for monitoring but also for other purposes within the port industry, such as safety and security. Considering this, the vulnerability outcome of each port can be comparable since the structural condition parameters can be defined in the same manner.

This work was limited to one inspection set for the four harbors through applying SHM of port infrastructure. It is encouraged to establish a periodic SHM program aiming to identify changes in structural condition and update vulnerability information. Moreover, further research is required to employ additional equipment, such as remotely operated underwater vehicles for the condition monitoring of other types and elements of port structures (e.g., the submerged part of a rubble-mound structure or quay walls) to develop an integrated framework for assessing port vulnerability.

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