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Identification of Port Resilience Variables Against Earthquake in Indonesia

Mufida Nur Aini[1*], Mohammad Arif Rohman[1]
[1]Civil Engineering Departement, Institut Teknologi Sepuluh Nopember

*Corresponding Author's e-mail: mufidana22@gmail.com

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Abstract: *Indonesia is highly exposed to seismic hazards due to its location along the Pacific Ring of Fire, making the resilience of critical infrastructure particularly portsa national priority. Ports play a strategic role in maintaining logistics continuity, supporting economic stability, and facilitating post-disaster response. However, existing studies on port resilience in Indonesia remain limited and predominantly emphasize structural aspects, with insufficient consideration of operational, managerial, and recovery-related dimensions. This study aims to identify and validate key variables influencing port resilience to earthquake hazards in the Indonesian context. The research represents an initial stage of a broader resilience assessment, with a specific focus on variable identification and relevance validation rather than framework formulation or weighting analysis. A mixed-method approach was employed, combining a systematic literature review and expert judgment. A total of 16 resilience variables across physical, operational, managerial, and environmental dimensions were identified and evaluated using a Likert-scale relevance assessment. The results show that all 16 variables were classified as relevant, with mean relevance scores ranging from 3.33 to 5.00 and low to moderate standard deviations, indicating overall agreement among experts. Several operational robustness indicators achieved perfect consensus (mean = 5.00, standard deviation = 0.00), highlighting their critical role in port resilience. These findings confirm that port resilience is inherently multidimensional, arising from the interaction of structural performance, operational continuity, managerial preparedness, and recovery capability. The validated variable set provides a robust, context-specific foundation for subsequent analytical stages and supports the development of resilience assessment models and policy-oriented port planning in earthquake-prone regions of Indonesia.*

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INTRODUCTION

Indonesia, an archipelagic nation located along the Pacific Ring of Fire. It sits at the meeting point of the Indo-Australian, Eurasian, and Pacific tectonic plates. This position makes it very susceptible to earthquakes and volcanic activity [1]. According to data from the Indonesian Disaster Information Agency, over the past decade, there have been 251 recorded earthquakes that led to more than 5,000 deaths and significant damage to infrastructure[2]. This highlights the urgent need to include disaster resilience in national infrastructure development. This aligns with Sustainable Development Goals 9 and 11, which promote resili-ent infrastructure and sustainable communities[3].

Ports, especially multipurpose ports, are vital yet vulnerable parts of Indone-sia's infrastructure system. As central nodes in the national logistics network, ports facilitate inter-island connectivity, trade, and economic stability. Disrup-tions to port operations caused by seismic events can lead to major delays, logistical problems, and economic losses [4]. A notable case in the 2018 Central Sulawesi earthquake (Mw 7.5), which caused a tsunami and liquefaction, severely damaging the Pantoloan, Wani, and Donggala ports. The incident showed how port vulnerability can impede logistics continuity and humanitarian response. It underscored the need for improved port resilience assessment frameworks.

Current studies on resilience mainly focus on urban systems, energy infra-structure, and transportation networks [5]. Research on port resilience, particularly against earthquakes, remains limited and often emphasizes only struc-tural performance. There is a gap in understanding how to connect physical, op-erational, managerial, and environmental factors within a single analytical framework.

Accordingly, this study aims to identify and validate key variables that influence port resilience to earthquake hazards in Indonesia. This paper represents an initial and exploratory stage of research, explicitly limited to variable identification and validation based on literature review and expert judgment. The development of assessment frameworks, weighting schemes, or composite indices is beyond the scope of this study.

LITERATURE REVIEW

According to Government Regulation of the Republic of Indonesia No. 61/2009 on Port Affairs, a port is defined as a terminal and mooring area. This area includes land and or water areas that serve as a place for vessels to berth and for the mobilization of passengers and goods [6]. Ports have both governmental and commercial roles. They support maritime traffic, logistics, and economic activities. In Indonesia, port is generally categorized into three types based on their main functions: (1) public or commercial ports serving cargo and passenger movement, (2) special-purpose ports supporting industrial activities, and (3) fish-ing ports. In the national logistics system, ports are vital point to connecting islands and facilitating international trade. They play a key role in regional and national economic resilience [6]

An earthquake is a sudden shaking of the Earth's crust caused by the movement of tectonic plates [1]. Earthquakes are divided into two main categories, namely tectonics and volcanic earthquakes. The tectonic earthquake is an earthquake caused by the movement of tectonic plates, while a volcanic earthquake, caused by volcanic activity [1]. Depending on the depth of the focus or hypocen-ter earthquakes are classified as shallow earthquake (less than 70 km), interme-diate earthquake (70–300 km), and deep earthquake (300–450 km). Shallow-focus earthquakes tend to cause more severe ground shaking and damage because they are closer to the surface. Earthquake also assessed using Richter magnitude scale, which classified as: very large (greater 8.0 SR), large (7.0–8.0 SR), destructive (5.0–6.0 SR), moderate (4.0–5.0 SR), and minor (3.0–4.0 SR). These classifications help determine to assess the seismic risk level of infra-structures, including ports located in earthquake-prone coastal regions [1].

Resilience refers to the ability of a system or community to resist, adapt, and recover from disturbances or disasters, whether natural or human-induced without losing its essential functions or identity[7]. The resilience of a system can be assessed by observing changes in the level of function $F(t)$ over time during disturbanceses and until the recovery process is complete as can be seen in Figure 1[8], [9]. According to Hashimoto as cited in the study by Paton and John-son, technical resilience is defined as the speed of recovery after disruption[10]. Meanwhile Holling highlights ecological resilience as the ability to maintain system functionality despite external shocks[10]. In social situations, resilience reflects a community's capacity to adapt to social, political, or environmental pressures. According to Cutter as cited in the study by Parker, it distinguishes resilience from mitigation[7]. Mitigation works to recover, adapt, and change into more sustainable conditions after disturbances. While resilience is dynamic, enabling systems to recover, adapt, and transform into more sustainable conditions after disturbances[11].

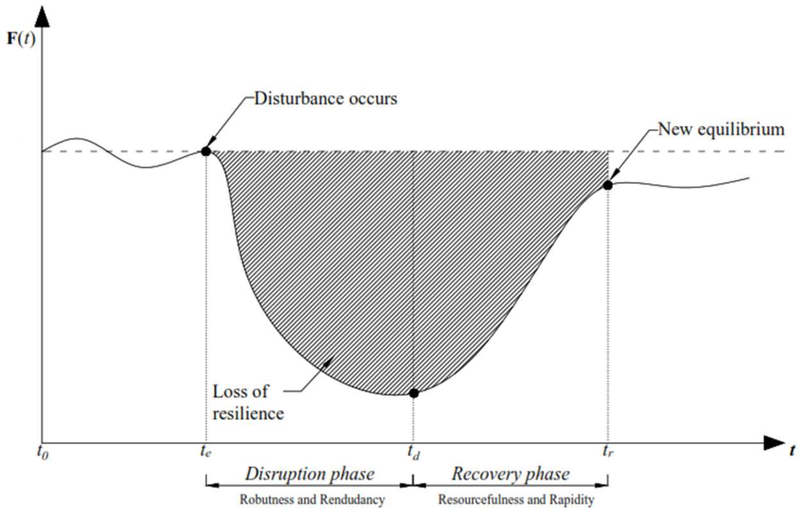

Figure 1. Resilience function (adapted from [8]and [9])

As transport systems become increasingly complex and integrated with smart technologies, the assessment of port resilience requires a multidimensional perspective. To ensure conceptual clarity, resilience variables in this study are explicitly organized around four core resilience principles that are most relevant to earthquake impacts on port systems, namely robustness, redundancy, resourcefulness, and rapidity. Robustness represents the ability of port infrastructure and equipment to withstand seismic forces while maintaining essential functions. Redundancy reflects the availability of backup facilities, alternative access routes, and substitute operational systems that allow continuity when primary components fail. Resourcefulness refers to the capacity of port management and operators to mobilize human, financial, technological, and institutional resources during and after a disruption. Rapidity captures the speed at which port operations can adapt, respond, and recover to an acceptable level of performance following an earthquake.

These four principles provide a focused analytical bridge between the concept of resilience and the identified variables, while remaining consistent with the scope of this study, which is limited to variable identification and validation rather than the development of a comprehensive assessment framework. Strengthening maritime infrastructure resilience has been shown to be more cost-effective than post-disaster rehabilitation and is essential for maintaining continuous port operations [4],[12]. Commonly cited resilience principles in port studies include robustness, redundancy, resourcefulness, rapidity, visibility, flexibility, agility, recovery, collaboration, information sharing, and response capacity [4]. These principles provide a conceptual foundation for identifying measurable variables relevant to port resilience, rather than constituting a finalized assessment framework.

METHODS

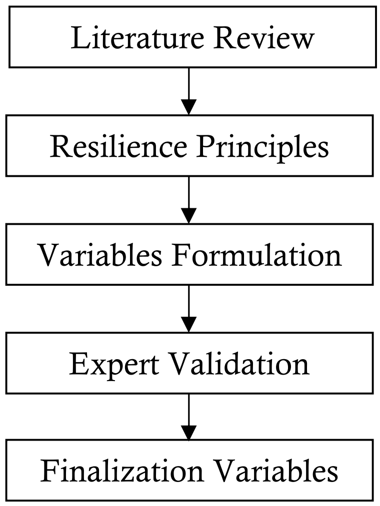

Figure 2. Research Flow Diagram

Figure 2 illustrates the research workflow adopted in this study, highlighting the sequential process used to identify and validate port resilience variables against earthquake hazards. The workflow begins with a systematic literature review, followed by conceptual mapping to core resilience principles, variable formulation, expert validation, and finalization of validated variables.

Research Workflow:

1. Literature Review
   Review of studies on port resilience, earthquake hazards, and infrastructure resilience to extract commonly used resilience principles and indicators.
2. Identification of Core Resilience Principles
   Selection of four fundamental principles (robustness, redundancy, resourcefulness, and rapidity) as the theoretical basis of the study into four dimensions of port POME (physical, operational, managerial, environmental)
3. Variable Formulation
   Translation of abstract resilience principles into measurable port-related variables relevant to Indonesian earthquake-prone contexts shown in Table 1.
4. Expert Validation

Assessment of variable relevance using a five-point Likert scale to evaluate how well each variable represents its associated resilience principle. Variables were assessed using a five-point Likert scale ranging from 1 (strongly disagree) to 5 (strongly agree).

5. Finalization of Variables
Compilation of validated resilience variables as the main output of the study, forming a basis for future framework development.

This study uses a mixed-method approach that combines qualitative and quantitative measures to determine variables for evaluating port resilience against earthquake and tsunami hazards. Resilience indicators were first collected from a detailed review of literature related to port engineering, natural hazard management, and infrastructure resilience frameworks. We then evaluated the initial list of variables by consulting experts to ensure they were relevant and suitable for Indonesian port conditions. We used a purposive sampling method to choose experts with at least five years of experience in port planning, structural engineering, operations management, or disaster preparedness.

Experts were selected using purposive sampling, with eligibility criteria including a minimum of five years of professional experience in port planning, structural engineering, port operations, or disaster risk management. Methodologically, the identified variables were operationalized by explicitly linking each indicator to one of the four core resilience principles robustness, redundancy, resourcefulness, and rapidity derived from literature. This bridging step ensured that each variable was not treated as an isolated metric, but as a measurable representation of a broader resilience principle relevant to earthquake impacts on port systems. Each expert was provided with a structured validation sheet containing proposed resilience dimensions, variables, operational definitions, and supporting literature sources. Variables were assessed using a five-point Likert scale ranging from 1 (strongly disagree) to 5 (strongly agree). Experts were asked to evaluate the relevance of each variable in representing its associated resilience principle within the context of Indonesian ports exposed to earthquake hazards. This validation process served as a methodological bridge between abstract resilience principles and empirically applicable variables, ensuring conceptual consistency across the study.

Table 1. Variables Formulations

Code	Resilience Principles	Variable	Operational Definition	References
RP1	*Robustness*	Percentage of multipurpose wharf remaining functional after an earthquake and tsunami	Measures the proportion of multipurpose wharf facilities that remain operational after a disaster.	[4], [12]
RP2	*Redundancy*	Number of multipurpose warehouses ready for post-disaster	Availability of storage facilities for various cargo types to support emergency logistics.	[12]

Code	Resilience Principles	Variable	Operational Definition	References
		operation		
RP3	*Redundancy*	Number of alternative transportation accesses (roads, railways, shipping routes) to the port	Degree of multimodal connectivity when main access is disrupted.	[13]
RO1	*Resourcefulness*	Percentage of multipurpose cargo-handling equipment (crane, forklift, conveyor, etc.) with digital monitoring	Real-time monitoring coverage of multipurpose cargo-handling equipment.	[14]
RO2	*Rapidity*	Average adjustment time of berth schedule after disruption	Speed of port service adaptation to post-disaster cargo handling schedules.	[12], [15]
RO3	*Rapidity*	Time to recover up to 80% of normal operational capacity	Speed of resuming multipurpose operations for various cargo types to near-normal conditions.	[12]
RO4	*Rapidity*	Average implementation time of worker evacuation and emergency SOPs	Emergency operation response speed at multipurpose facilities.	[12], [16]
RO5	*Redundancy*	Number of alternative transport modes for logistics diversion	Availability of emergency transport modes to maintain logistics flow during disruptions.	[4], [12], [17]
RO6	*Redundancy*	Number of backup operational facilities (electricity, communication, etc.)	Capacity of backup facilities available during major operational disturbances.	[4], [12], [17]

Code	Resilience Principles	Variable	Operational Definition	References
RM1	*Resourcefulness*	Collaboration and communication with logistics stakeholders	Level of coordination with external parties (e.g., shipping lines, logistics operators) during recovery.	[16]
RM2	*Resourcefulness*	Human and financial resources mobilized for emergency operations	Capacity of management to allocate workforce and financial resources during disaster response.	[17]
RM3	*Rapidity*	Percentage of available and updated disaster contingency SOPs for multipurpose cargo	Level of preparedness and availability of emergency operation procedures.	[16]
RM4	*Resourcefulness*	Percentage of retrofitted multipurpose facilities and equipment	Degree of financial risk mitigation through structural strengthening and insurance protection.	[16]
RM5	*Redundancy*	Number of formal emergency cooperation agreements with neighboring ports	Number of formal agreements for emergency cargo redirection and mutual assistance.	[12], [16]
RL1	*Redundancy*	Availability of renewable energy facilities (solar panels, gensets, biofuel) supporting post-disaster operations	Utilization capacity of alternative energy for multipurpose port operations after disasters.	[16]
RL2	*Redundancy*	The number of waste and clean water management systems that remain operational after	Degree of external coordination in regional emergency logistics and recovery operations.	[16]

Code	Resilience Principles	Variable	Operational Definition	References
		a disaster		

RESULT AND DISCUSSION

A. Descrriptive Analysis Respondent Profile

This chapter presents the results of the expert validation from this study. First, it outlines the characteristics of the experts involved to assess relevance of the variables shown in Table 2. It then shares the finalized set of validated indicators used for the resilience assessment. The next section describes the respondents in this study. All results are summarized in the following tables.

Table 2. Respondent Identity

Respondent	Education Level	Expertise	Age	Years of Experience
R1	Master	Port Engineering	>50	15-20
R1	Doctoral	Port Structure	40-50	15-20
R3	Doctoral	Disaster Risk Management	31-40	10-15
R4	Doctoral	Costal Hydro-informatics	31-40	10-15

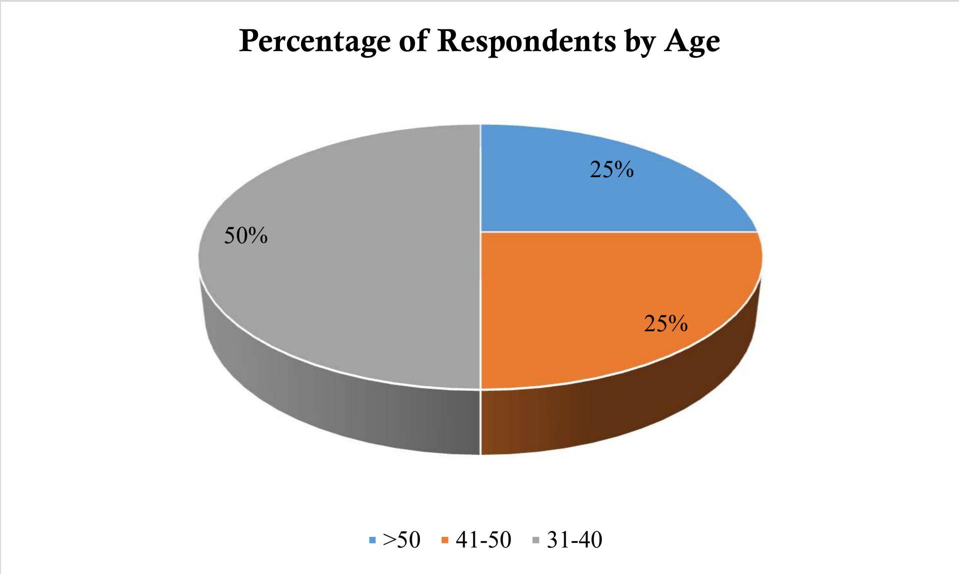

Figure 3. Respondent Profile by Age

Based on the age characteristics shown in Figure 3, the respondents involved in variable validation were predominantly in the 31–40 age group (50%), followed by the 41–50 age group and those above 50 years old, each accounting for 25%. This age composition indicates that the respondents are at a mature professional stage, possessing adequate analytical capacity and experience to evaluate the variables constituting the port resilience.

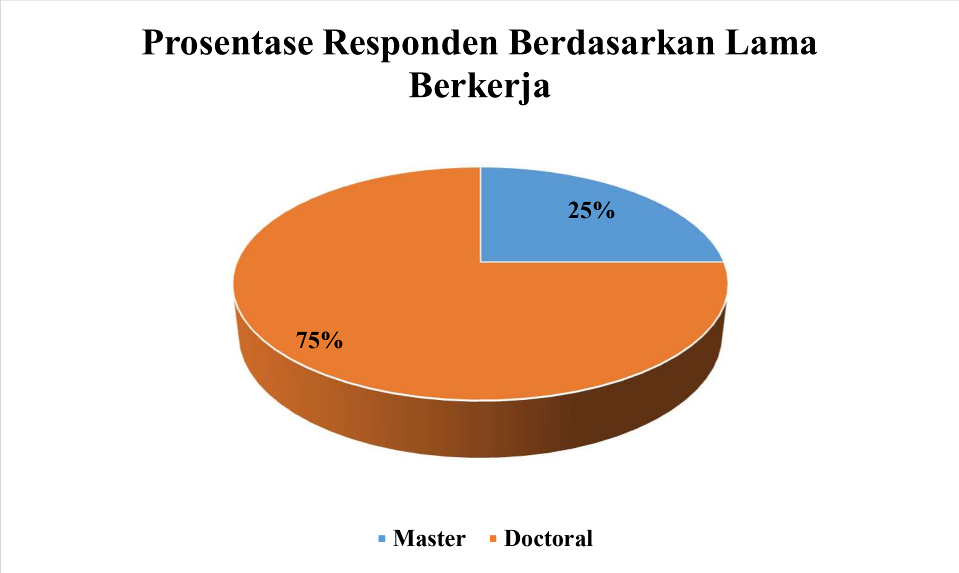

Figure 4. Respondent Profile by Educational Background

As illustrated in Figure 4, most respondents hold doctoral degrees (S3) (75%), while the remaining 25% have master's degrees (S2). The high educational background of the respondents strengthens the quality of variable validation in this study, as the assessments provided are grounded in strong conceptual understanding related to the variables in this study.

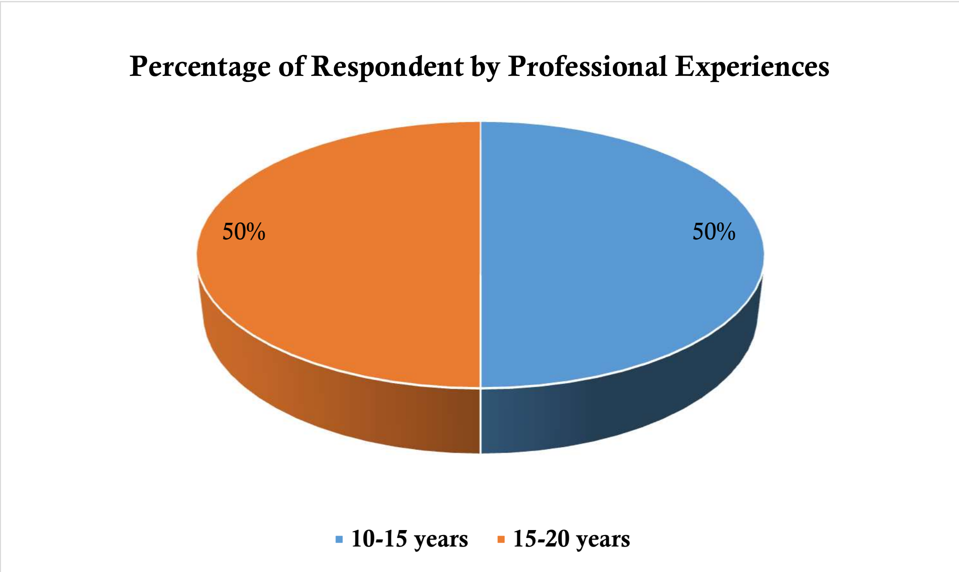

Figure 5. Respondent Profile by Professional Experiences

In terms of professional experience in port-related fields and disaster risk management, as shown in Figure 5, all respondents have more than 10 years of experience. An equal proportion of respondents have 10–15 years and 15–20 years of experience (50% each). This indicates that the variable validation process was conducted by experts with in-depth understanding of port operational conditions and the implications of disaster risks on infrastructure sustainability.

B. Validation of Variable

Based on the table shown above, the background of the respondents in this study. Each respondent has a graduate-level education and expertise in areas like port engineering, port structure, disaster risk management, and coastal hydro-informatics. Their ages and years of experience suggest that all respondents are senior professionals with significant practical knowledge in their fields. The result of the relevance variables shown in Table 3.

Table 3. Relevance of Variables

Variable	R1	R2	R3	R4	Mean	Std. Deviation	Status
RP1	5	5	4	4	4,67	0,58	Relevant
RP2	5	5	4	5	4,67	0,58	Relevant
RP3	3	5	4	5	4,00	1,00	Relevant
RO1	5	5	5	3	5.00	0.00	Relevant
RO2	5	5	4	4	4.67	0.58	Relevant
RO3	5	5	4	5	4.67	0.58	Relevant
RO4	5	5	5	5	5.00	0.00	Relevant
RO5	3	3	5	4	3.67	1.15	Relevant
RO6	5	5	5	4	5.00	0.00	Relevant
RM1	4	3	4	3	3.67	0.58	Relevant
RM2	5	3	5	3	4.33	1.15	Relevant
RM3	5	3	4	4	4.00	1.00	Relevant
RM4	5	2	5	4	4.00	1.73	Relevant
RM5	4	2	4	4	3.33	1.15	Relevant
RL1	4	3	5	3	4.00	1.00	Relevant
RL2	4	3	4	3	3.67	0.58	Relevant

The results of the variable relevance assessment are presented in Table 3. The mean scores of the evaluated variables range from 3.33 to 5.00, with standard deviations indicating low to moderate variability among expert judgments. All variables are classified as "Relevant", confirming that each indicator is considered important for assessing port resilience to earthquake hazards.

Variables related to robustness and operational performance generally achieved higher mean values, with several indicators (RO1, RO4, and RO6) showing perfect agreement among respondents (mean = 5.00; standard deviation = 0.00). This indicates a strong consensus regarding the importance of structural integrity and operational reliability in enhancing port resilience. Meanwhile, variables associated with managerial aspects and recovery capacity also met the relevance threshold, although some exhibited higher standard deviations, reflecting variations in expert perspectives.

Overall, the results demonstrate that none of the proposed variables were excluded during the relevance validation stage, suggesting that the selected indicators comprehensively represent key dimensions of port resilience under seismic risk conditions.

Variables related to resourcefulness and rapidity (RM and RL) also achieved relevance status, although some exhibited higher variability, reflecting differences in expert perspectives regarding managerial capacity and recovery-related aspects.

Overall, the results indicate that no variable was deemed irrelevant, confirming that the proposed indicators comprehensively capture key dimensions required to represent port resilience under seismic risk conditions.

CONCLUSION

The relevance validation confirms that all proposed variables are essential for evaluating port resilience to earthquake hazards. This finding highlights that port resilience is inherently multidimensional and cannot be explained by a single attribute alone. Instead, resilience emerges from the interaction of multiple principles, including robustness, redundancy, resourcefulness, and rapidity. Each validated variable captures a distinct aspect of port resilience, encompassing structural performance, operational continuity, managerial preparedness, and recovery capability. The universal relevance of these indicators supports the robustness of the proposed assessment framework and provides a strong basis for subsequent analytical stages, such as weighting and aggregation, in the development of a comprehensive port resilience evaluation model.

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