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Structural Persistence and Topological Resilience of Maritime Corridors: A Case Study of the Intermediary Role of the Guangdong–Hong Kong–Macao Greater Bay Area

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Abstract

The Guangdong–Hong Kong–Macao Greater Bay Area (GBA) comprises the two Special Administrative Regions of Hong Kong and Macao, and the nine municipalities of Guangzhou, Shenzhen, Zhuhai, Foshan, Huizhou, Dongguan, Zhongshan, Jiangmen and Zhaoqing in Guangdong Province. The GBA serves as China’s strategic maritime hub and a core engine for marine economic development. However, existing research has underexplored the structural connectivity and topological resilience of its port network from the perspective of a maritime corridor within the GBA. Therefore, using port network data from 2022 to 2023, this study identifies the core topological structure of the GBA maritime corridor and examines how resilience evolves under stochastic connection disruptions. The results show that the GBA maritime corridor exhibits an asymmetric cross-shaped backbone structure that connects domestic coastal ports with international markets (Southeast Asia, Japan, and South Korea). The network density of the GBA port system reaches 0.41258, indicating substantial connectivity that supports efficient regional and global logistics circulation. Regarding resilience level, the probability of connection disruption is the key factor that significantly affects the stability and anti-interference ability of the GBA maritime network. These findings clarify the backbone framework of the maritime corridor for marine economic development, thereby providing theoretical support for strengthening the safety and stability of the GBA maritime transport system.

Keywords: maritime corridor; structural persistence; topological resilience; Guangdong–Hong Kong–Macao Greater Bay Area; algebraic connectivity

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1. Introduction

As the primary mode of transportation in international trade, sea freight accounts for more than 90% of the world’s cargo volume [1,2]. However, global uncertainties, such as the Red Sea Crisis, have shifted the focus of maritime research from efficiency toward resilience. Correspondingly, the traditional single-port model of maritime transport is shifting toward an integrated maritime corridor. As a regional gateway system, the corridor function requires integrated connectivity across “port–waterway–hinterland”, thereby integrating scattered port resources, improving transportation efficiency, and achieving economies of scale [3].

The Guangdong–Hong Kong–Macao Greater Bay Area (GBA), as one of the most developed and dynamic regions in the world economy, is actively advancing marine economic development, establishing itself as a prominent maritime gateway. Within the GBA, port clusters such as Hong Kong, Shenzhen, and Guangzhou not only possess abundant maritime infrastructure and resources but also contribute to national economic security. For instance, Zhong et al. [4] argue that the GBA port group is an important network hub connecting domestic and foreign markets and that it plays a key role in both the local and global economies. Data show that Shenzhen, Guangzhou, Hong Kong, and other GBA core ports are among the world's top container ports, indicating their status as global shipping hubs [5]. Hence, maintaining the backbone of maritime corridors is no longer merely a transport necessity but is critical for ensuring the stability and security of both domestic markets and the global economy.

Additionally, maritime corridors are dynamic systems. Therefore, maintaining a sufficient degree of resilience is imperative for the security of the GBA port network [6]. A review of the existing literature reveals two key gaps. On the one hand, there is a lack of systematic analysis of the specific role in connecting domestic coastal ports to international markets through a maritime corridor framework. On the other hand, from the perspective of the maritime corridor, the existing research rarely discusses the relationship between network connectivity and resilience. Therefore, the quantification of the resilience of the backbone maritime corridor can provide theoretical support for inter-port cooperation. This study addresses two research questions based on GBA port activities to develop an analytical framework for examining the main structure and resilience of the maritime corridor.

1. *What is the topological backbone structure of the GBA maritime corridor, and how does it function as an intermediary hub connecting domestic coastal ports to international markets?*
2. *How does the connectivity of the GBA maritime corridor's backbone framework evolve under varying probabilities of stochastic connection disruptions, and what does this reveal about the corridor's topological resilience?*

This study examines changes in the connectivity and resilience of the GBA maritime corridor's stable backbone through network analysis and algebraic connectivity. The results demonstrate the stability of the backbone framework and the resilience level of the maritime corridor under random perturbations in connection relationships. The value of this study lies in identifying the backbone framework of the GBA maritime corridor, which highlights the importance of unimpeded internal and external circulation for regional economic development. Additionally, coordinated port development within the GBA can not only improve logistics efficiency but also provide critical support for regional economic growth.

This study makes three contributions. First, it characterizes the topological features of the port transportation network in the GBA region. Second, it identifies the backbone structure of the GBA maritime corridor. Third, it quantifies the corridor's resilience using algebraic connectivity, thereby providing theoretical support for strengthening the safety of maritime corridor management. In summary, this study proposes a spectral framework for quantifying corridor-level resilience via the algebraic connectivity of the Laplacian matrix under stochastic edge perturbations. The GBA case study serves to illustrate and validate this framework, converging on a single persistent backbone structure.

The remainder of this paper is organized as follows. Section 2 presents a literature review. Section 3 describes the research questions and analytical methodology. Section 4 presents the results, including the basic features of the port network in the GBA region, the backbone structure of the GBA maritime corridor, and the resilience analysis under random perturbations. Finally, Section 5 concludes the paper.

2. Literature Review

2.1. Construction of Maritime Corridor

The development of maritime corridors enhances two-way connectivity by sea and land, thereby promoting comprehensive coordination between China's coastal and inland regions [7]. Existing studies on maritime corridors fall into three categories: economic impact assessment, risk and safety management, and resilience-oriented analysis. In the first strand of literature, Li et al. (2023) examine the impact of maritime connectivity on regional economic growth using a dynamic difference-in-differences method (DID) with the Panama Canal expansion as a quasi-natural experiment [8]. Liu et al. (2021) evaluate the impact of the Northern Sea Route on the effectiveness of Russia's coastal economic policies using multi-source data [9]. Wu et al. (2024) analyze the economic feasibility of container transportation between the Northeast Passage and the Suez Canal Route using multi-source shipping data from 2021 to 2023 and projections for 2025 to 2065 [10]. In the second stream, Chang et al. (2023) use Bayesian network and fault tree methods to analyze maritime transport risks for LNG liners operating from China to Australia [11]. Zhang and Ju (2023) use an extensible cloud model to evaluate the navigable environment of five sections of the Northeast Passage Corridor [12]. In the third stream, Gu and Liu (2025) highlight the importance of critical corridors for maritime safety from the resilience perspective [3]. In summary, few studies combine corridor-level strategic analysis with port-level network structural evaluation, despite advances in multi-source data analysis and methodological diversity.

2.2. Port Network Connectivity

Port network connectivity is an important indicator of regional economic and trade activity. Existing research mainly focuses on the central role of high-connectivity ports in improving maritime efficiency and regional economic integration. For example, from the perspective of network topology-based methods, Yang et al. (2025) examine hub port location and routing within a single-hub network, considering the connectivity of liner transportation networks [13]. Zhang et al. (2024) analyze the mismatch arising from the limited explanatory power of transportation economics, which is caused by the homogenization of the existing global maritime transportation network [14]. Guo et al. (2024) explore inter-port relationships, cooperation patterns, and regional transport distributions of liner shipping trade from 2006 to 2021 [15]. From the perspective of risk assessment, Jiang et al. (2024) adopt an enhanced cascading fault model based on a non-linear capacity framework to explore the dynamic vulnerability of the 21st Century Maritime Silk Road container shipping network [16]. Wang et al. (2023) examine the impact of port node failure on the overall maritime network security degree [17]. Finally, from the perspective of economic and policy-oriented methods, Yap et al. (2023) analyze the impact of port network connectivity on maritime alliance policy [18]. Nadarajan et al. (2023) examine the impact of seaport network efficiency on global maritime economic growth using data envelopment analysis [19]. In summary, few studies simultaneously identify the backbone structure of the port network and assess its resilience under stochastic disruptions.

2.3. Port Network Resilience

Port network resilience refers to the ability to maintain stable operation of the maritime network when risks are triggered, thereby reducing the negative impact of disruptions. Existing studies mainly focus on port network stability and anti-interference capabilities, with particular attention to the robustness of key port nodes within the overall network, which provides decision support ranging from node optimization to

network-level recovery strategies. For example, Su and Lu (2025) identify an operational strategy for the recovery of global liner shipping networks during the pandemic [20]. Gu et al. (2025) use a superefficient slack-based measure network data envelopment analysis (SBM-NDEA) methodology to evaluate the resilience of nine major Chinese ports from 2011 to 2021 [21]. Chang et al. (2025) examine the dynamic evolution patterns of container port network resilience based on a case study of Tianjin and Hebei Ports using the Markov chain method [22]. Qu et al. (2024) simulate the dynamic impact of maritime network congestion on the global supply chain using an agent-based network model, using the Suez Canal congestion as an example [23]. Gu and Liu (2023) develop a hierarchical holographic modeling (HHM) approach in conjunction with a fuzzy cognitive map (FCM) to analyze the interconnectedness of factors affecting port network resilience [24]. Wang et al. (2023) propose a Bayesian-based network resilience assessment method to enhance resistance to risk and uncertainty [17]. In summary, existing research has established various evaluation methods for network resilience, but investigations of maritime network resilience from the perspective of corridors remain limited. In our study, we adopt algebraic connectivity for assessing corridor-level resilience because it captures how the entire network degrades under edge perturbations, rather than how individual nodes lose prominence.

2.4. Summary and Research Gap

While existing studies have constructed a theoretical framework for analyzing corridor connectivity and port network resilience, and have revealed maritime corridors’ critical value in regional economic development using cascading failure models, network analysis with resilience curves, literature-based resilience indices, and Bayesian network, few studies have examined the relationship between backbone structure and changes in network resilience under conditions of stochastic connection perturbations. Therefore, this study aims to reveal the backbone structure of the GBA maritime corridor, especially its practical value as a regional gateway, and to derive relevant management implications. From the perspective of the literature, this study also provides a new approach to resilience analysis in complex network research. Table 1 summarizes the methods used for assessing resilience level in existing research.

Table 1. Comparison of existing studies and our study.

Study	Primary Method	Backbone Structure	Stochastic Connection Changes	Resilience Metric
Jiang et al., 2024 [16]	Enhanced cascading failure model	No	Random node failure	Network performance
Su and Lu, 2025 [20]	Network analysis	No	Specific event	Resilience curve and connectivity rate
Gu and Liu, 2025 [3]	Literature analysis	No	No	Resilience index
Wang et al., 2023 [17]	Bayesian network	No	Node failure	Readiness and response capacities
Our study	Algebraic connectivity and centrality index	Asymmetric cross-shaped backbone structure	Yes	Algebraic connectivity

3. Methodology

3.1. Data and Network Description

To identify the GBA maritime corridor, our data filtering criterion retains only routes that follow the pattern X (Origin) → GBA → Y (Destination), which is identified by filtering the adjacency matrix for paths that transit through GBA ports. This ensures that the network

accurately reflects the GBA's role as an intermediary hub in the global shipping chain, rather than representing a generic global port network. Using this approach, we compiled data from HiFleet shipping schedules, encompassing 315 port nodes and 40,809 routes from May 2022 to May 2023. Specifically, a connection between two port nodes is represented by 1, and the absence of a connection by 0, yielding a binary adjacency matrix for the 315 port nodes without edge weights. The binary matrix allows us to examine whether the backbone topological skeleton of the maritime corridor remains stable under stochastic disruptions, thereby facilitating the analysis of structural connectivity. The network visualization and centrality adopt the NetworkX library in Python 3.9. Centrality measures and algebraic connectivity are basic analytical indices for network structure. Note that the shipping schedules operate on a high-frequency rolling basis, especially liner shipping activities, which feature metastable routes and port calls within a single year in response to market conditions. Moreover, according to Clarkson's report in December 2021, by mid-2021, the global seaborne trade volume has recovered to the pre-pandemic level, and the annual trade volume is expected to reach 12 billion tons, an increase of 3.6% over 2020 [25]. The data of our study captures a post-recovery maritime activity of the GBA maritime corridor. Therefore, a full annual cycle is sufficient to capture the steady-state topology of a maritime corridor.

3.2. Network Feature Measures

We examine five network metrics, namely degree centrality, betweenness centrality, closeness centrality, PageRank, and network density, in order to describe the basic properties of the maritime network. These metrics help characterize the overall properties of the network and identify key nodes, enabling us to extract the corridor structure of the GBA maritime network.

3.2.1. Degree Centrality

Degree centrality measures the number of direct connections a node has in the network and is a fundamental index of network performance [26,27]. A higher degree centrality indicates a more central and influential node.

$$DC(i) = \frac{\sum_{j=1}^n a_{ij}}{n-1} \quad (1)$$

a_{ij} is the direct connections of nodes i and j . The denominator is the maximum degree value of node connection. When there is a connection between nodes, the value is $a_{ij} = 1$, else 0.

3.2.2. Betweenness Centrality

Betweenness centrality represents the proportion of shortest paths between all node pairs that pass through a given node [28]. The measure is calculated through normalization and mainly reflects a node's capacity to act as an intermediary between other nodes. It also captures the extent to which a node controls the flow of information or goods between otherwise disconnected regions of the network.

$$BC(i) = \frac{2}{(n-1)(n-2)} \sum_{j \neq k \neq i} \frac{\sigma_{jk}^i}{\sigma_{jk}} \quad (2)$$

n is the number of nodes. σ_{jk} shows the shortest path from the node j to the node k . σ_{jk}^i represents the number of shortest paths from node j to node k . Nodes with high betweenness centrality act as bridges in the network, linking different nodes.

3.2.3. Closeness Centrality

Closeness centrality is an important metric in network analysis that measures how close a node is to all other nodes in the network, defined as the reciprocal of the average shortest path length from that node to all other nodes [29,30]. A higher closeness centrality value indicates that the node is closer to the center of the network.

$$CC(i) = \frac{n-1}{\sum_{j \neq i} d_{ij}} \quad (3)$$

d_{ij} shows topological distance from node i to node j . n is the number of nodes.

3.2.4. PageRank Value

From the perspective of graph theory, the PageRank value of nodes is derived from the importance scoring algorithm developed by Google [31,32]. The basic idea is that each node in the network starts with an equal initial PageRank value, which is iteratively updated. Therefore, the sum of the PageRank values of all nodes always equals 1 throughout the iterations. The PageRank formula is as follows:

$$PR(u) = \frac{(1-d)}{N} + d \sum_{v \in B(u)} \frac{PR(v)}{N_v} \quad (4)$$

d is a damping factor, which is generally set to 0.85 [33]. This value implies that a random walker has an 85% probability of following an outgoing link and a 15% probability of jumping to any node in the network uniformly at random. $(1-d)$ represents the contribution parameter from the indirectly connected node. $PR(u)$ and $PR(v)$ show the scores of the node u and node v , respectively. N_v is the number of outgoing connections to the node. Hence, the special case of Formula (4) is as follows.

$$PR(u) = \sum_{v \in B(u)} \frac{PR(v)}{N_v} \quad (5)$$

In the maritime network, the damping factor captures a realistic balance between route-following behavior due to scheduled liner services and contractual logistics arrangements. In our analysis, this parameter ensures that ports with connections to other high-importance hubs receive proportionally higher PageRank scores, reflecting their systemic role in the GBA-mediated maritime corridor.

3.2.5. Network Density

Network density is an important indicator of node connection density within the network [34]. It is the ratio of the number of actual edges in the network to the maximum possible number of edges. For directed graphs, density is calculated as follows:

$$d(G) = \frac{L}{N(N-1)} \quad (6)$$

L represents the actual number of edges in the network. N is the total number of nodes in the network.

3.3. Resilience Assessment Based on Algebraic Connectivity

3.3.1. Conceptual Basis for Algebraic Connectivity in Resilience Analysis

Algebraic connectivity is commonly used to evaluate network stability. In this study, we use algebraic connectivity to measure the stability of the backbone topological structure of the maritime network via the second smallest eigenvalue of the Laplacian matrix. A

larger eigenvalue indicates greater network stability. Based on this eigenvalue analysis, we calculate the ratio of the algebraic connectivity under the original network structure to that under randomly perturbed conditions. This ratio quantifies the change in network resilience and provides an approximation of the network resilience value. The motivation about resilience method is that the algebraic connectivity can capture the global cohesion of a network. While centrality metrics are useful for identifying critical individual ports, they do not sufficiently quantify how well the entire network holds together when edges are randomly disrupted.

3.3.2. Computing Algebraic Connectivity

The matrix $A = [a_{ij}]$ represents the network adjacency structure. Let $d_i = \sum_{j=1}^N a_{ij}$, $i = 1, \dots, N$ be established. $\{d_1, d_2, \dots, d_N\}$ is the order of degree, which shows as $D = \text{diag}\{d_1, d_2, \dots, d_N\}$. This matrix is a diagonal matrix, called degree matrix [35,36]. Therefore, the Laplace matrix can be defined as $L = D - A$. In this study, matrix A is the adjacency matrices, connected to 1 and otherwise 0. The eigenvalues are arranged in increasing order as follows.

$$0 = \lambda_1 < \lambda_2 \leq \dots \leq \lambda_N \quad (7)$$

If $\lambda_2 > 0$ holds, it means that the network is connected. The smallest non-zero eigenvalue λ_2 is the second smallest eigenvalue. A larger algebraic connectivity value indicates greater network stability.

3.3.3. Calculating the Resilience Level

Based on the algebraic connectivity value, the resilience level of the backbone topological structure of the maritime network can be determined. Specifically, algebraic connectivity serves as a quantitative indicator of network connectivity [37]. Prior literature supports the relationship between centrality and connectivity [38]. Specifically, when connections between GBA's outbound ports and downstream ports undergo random perturbations, the algebraic connectivity under the perturbed scenario can be calculated. Comparing this value with the original network's algebraic connectivity provides a quantitative measure of resilience, reflecting the degree of network stability. Therefore, following Promsuwan et al. [39], the network resilience is defined using algebraic connectivity as follows:

$$R = \lambda_2^{NEW} / \lambda_2^{OLD} \quad (8)$$

The resilience level of backbone topological structure is R . λ_2^{NEW} and λ_2^{OLD} show the algebraic connectivity value under the new scenario and the original network structure, respectively. A ratio greater than 1 indicates improved network resilience, such as strengthened connectivity in the case of random perturbation. Similarly, the resilience ratio between 0 and 1 indicates degraded connectivity, with the magnitude reflecting the severity of structural damage. By varying R from 0 to 1, we can construct a resilience level that characterizes how the GBA maritime corridor's topological stability degrades as a function of disruption intensity. This curve provides a continuous, interpretable measure of corridor resilience.

4. Case Study

4.1. Basic Features of the Port Network

4.1.1. Degree Centrality

Degree centrality reflects the degree of a node's connectivity in network theory. A higher degree centrality typically indicates a more important node in the network. Table 2 presents the degree centrality of top 10 port nodes in the GBA maritime network.

Table 2. Degree centrality of the top 10 port nodes.

No.	Port	Value	No.	Port	Value
1	Shanghai	0.74204	6	Guangzhou	0.72611
2	Singapore	0.74204	7	Shantou	0.72611
3	Xiamen	0.73885	8	Qinzhou	0.72452
4	Ningbo (including Zhoushan)	0.73726	9	Cai Mep Port (Vietnam)	0.72134
5	Kaohsiung	0.72771	10	Chiwan (Shenzhen)	0.72134

As shown, the top 10 ports in the GBA maritime network in terms of degree centrality, with all showing values indicative of high connectivity within the GBA maritime network. Shanghai and Singapore have the highest connectivity in the network (0.74204). This indicates that these two ports are important transportation hubs with high connectivity in the maritime network. Consistent with their operational status, Shanghai is one of the world's largest ports, and Singapore is one of the world's busiest transshipment hubs. These results confirm the strong connectivity and transport advantages of these ports in global trade.

Xiamen (0.73885), Ningbo (0.73726), Guangzhou (0.72611), Shantou (0.72611), and Qinzhou (0.72452) also rank highly, indicating their strong connectivity with the GBA region. This may be attributed to Guangdong Province's status as one of China's largest manufacturing hubs. Its strategic position in the global industrial chain supports a robust port system, generating substantial maritime trade demand with neighboring coastal provinces and international markets. From the perspective of strategic ports, Kaohsiung (0.72771), Cai Mep (0.72134), and Chiwan Port (0.72134) represent important trade nodes in the Asia-Pacific region that connect key ports in Southeast Asia. Such ports play a vital role in regional trade. Although the values for Shantou (0.72611) and Qinzhou (0.72452) are slightly lower, they remain relatively high and play a key role in supporting the regional logistics network for specific markets or trade routes.

In summary, the top 10 ports serve dual roles in the GBA maritime corridor. On the one hand, they serve as import and export gateways for international cargo. On the other hand, as transshipment hubs and trade distribution centers, they can promote efficient circulation within the overall trade network. Ports with high connectivity typically benefit from strong infrastructure and well-developed logistics services, which create favorable conditions for regional development.

4.1.2. Betweenness Centrality

In network theory, betweenness centrality reflects a node's brokerage capacity, indicating the potential transit capacity of ports in the maritime network. A higher betweenness centrality indicates that a port can serve as a bridge across more shipping routes, reflecting its location advantages in the maritime network. It also reflects the port's distribution function. Table 3 presents the results.

Table 3. The betweenness centrality of the top 10 port nodes.

No.	Port	Value	No.	Port	Value
1	Singapore	0.00447	6	Hong Kong	0.00295
2	Shanghai	0.00382	7	Ningbo (including Zhoushan)	0.00291
3	Xiamen	0.00338	8	Chiwan (Shenzhen)	0.00286
4	Nansha	0.00338	9	Guangzhou	0.00274
5	Fang Chenggang	0.00300	10	Qinzhou	0.00261

Table 3 shows the top 10 ports ranked by betweenness centrality. The results show that Singapore has the highest betweenness centrality (0.00447), indicating its important role as a bridge and transshipment hub for the GBA. Second, Shanghai ranks second, showing a key role as a bridge in the international maritime network. It facilitates trade links between East Asia, Southeast Asia, and other regions, promoting cross-regional trade through its high hub value.

Xiamen (0.00338) and Nansha (0.00338) have similar betweenness centrality, highlighting the importance of these ports' connectivity in regional trade for supporting the global supply chain. Notably, Hong Kong (0.00295) reflects its continued importance as a maritime hub. Although some cargo has been transferred to Shenzhen and other places in recent years, its unique geographical location and port positioning make it an important node connecting China to other countries in global trade circulation. Chiwan Port (0.00286) is an important part of Shenzhen's port system and plays a significant role in supporting Shenzhen's development as a maritime center and connecting Southeast Asia with the rest of the world. In addition, Guangzhou Port (0.00274) and Chiwan Port are both key ports in southern China that play an essential role as bridges for trade between China and Southeast Asia.

4.1.3. Closeness Centrality

Closeness centrality measures a node's proximity to all other nodes in the network, reflecting the average shortest path length from that node to all other nodes. A higher closeness centrality implies shorter distances to other nodes in the network, higher shipping efficiency, more effective logistics flows, and stronger market influence. Table 4 presents the top 10 ports ranked by closeness centrality.

Table 4. The top 10 ports in the closeness centrality.

No.	Port	Value	No.	Port	Value
1	Shanghai	0.78982	6	Qinzhou	0.77131
2	Singapore	0.78667	7	Kaohsiung	0.76831
3	Xiamen	0.78667	8	Qingdao	0.76238
4	Ningbo (including Zhoushan)	0.78046	9	Shantou	0.76238
5	Guangzhou	0.77131	10	Cai Mep Port (Vietnam)	0.75944

Table 4 shows the top 10 ports in the closeness centrality ranking, highlighting their core hub role in the global supply chain. Specifically, Shanghai (0.78982) is the most centrally positioned node in the global port network, linking ports worldwide more efficiently and accelerating trade flows between China and other countries and regions. This has significant implications for the GBA region. Singapore ranks second at 0.78667, closely approaching Shanghai in closeness centrality. Its close connections to other important ports, such as transshipment hubs, confer significant economic value.

Xiamen (0.78667) has nearly the same closeness centrality as Singapore, indicating Xiamen's equally strong connectivity with other ports in regional trade. As an important port on China's southeast coast, it plays a key role in facilitating Southeast Asian trade, reflecting the value of regional trade, cross-border trade, and logistics circulation. Ningbo (0.78046), as one of the world's largest ports by throughput, also has high centrality, reflecting its rapid connectivity within the global supply chain, especially as a hub linking Europe and Southeast Asia.

Guangzhou (0.77131) and Qinzhou (0.77131) have identical closeness centrality. Specifically, Guangzhou is a key maritime network hub in southern China. Its strong connectivity promotes trade growth between the southern region and other parts of the world, especially through connections with Southeast Asia and global trade routes. Moreover, Guangzhou's

position is further reinforced by its integration with the GBA's manufacturing supply chains. This combination of advantages facilitates trade growth by reducing logistics costs and transit times for both domestic and international cargo. As a bridge connecting China to Southeast Asia, Qinzhou's equally high closeness value also reflects the port's important role in promoting regional trade.

Kaohsiung (0.76831), Qingdao (0.76238), and Shantou (0.76238) have similar closeness centrality values. Specifically, Kaohsiung plays an important role in linking Taiwan with Southeast Asian maritime trade, with strong cargo circulation capacity and the ability to rapidly connect with ports and resources worldwide. As a major port on China's eastern coast, Qingdao Port has strong connections with ports worldwide, especially those in Japan, South Korea, Europe, and the United States. Qingdao's logistics infrastructure supports faster supply chain response. Shantou is a well-connected port on China's southeast coast and plays a vital role in regional trade, especially serving the Southeast Asian market.

4.1.4. PageRank

In this study, PageRank is applied to the GBA-mediated port network to identify ports that are not only well-connected themselves but are also linked to other important ports, thereby identifying the network's key nodes. A high PageRank value indicates that a port is reached by many shipping routes originating from other important ports. Table 5 presents the PageRank-based ranking of hub ports and their connection capacity within the maritime network.

Table 5. The top 10 ports in the PageRank value.

No.	Port	Value	No.	Port	Value
1	Xiamen	0.00578	6	Guangzhou	0.00543
2	Shanghai	0.00575	7	Qinzhou	0.00543
3	Singapore	0.00562	8	Ningbo (including Zhoushan)	0.00536
4	Nansha	0.00553	9	Hong Kong	0.00526
5	Fang Chenggang	0.00550	10	Kaohsiung	0.00526

Table 5 presents the PageRank ranking of the top 10 ports. Specifically, Xiamen (0.00578) ranks first, indicating its strong influence on the port network. In addition to its direct connections, Xiamen's indirect connections to other important ports contribute to its high PageRank, reflecting that Xiamen is not only an important port node but also plays an active role in maintaining GBA's stability by connecting with other major ports. Shanghai (0.00575) and Singapore (0.00562) also rank near the top, forming strong interactions with other important ports, enhancing their critical influence and prominence in the global port system, and playing an essential role in both information and logistics flows.

Nansha (0.00553) and Fang Chenggang (0.00550) play an important role in linking other southern Chinese ports and in smoothing external circulation for regional logistics activities. Guangzhou (0.00543) and Qinzhou (0.00543) demonstrate strong influence on the regional logistics network as transit points connecting China to Southeast Asia. Ningbo (0.00536), Hong Kong (0.00526), and Kaohsiung (0.00526) are hub ports for regional trade, showing both key connectivity in global trade and their role as important nodes connecting China's international trade routes with foreign markets.

4.1.5. Network Density

Network density is a proportional measure that reflects the degree of actual connectivity relative to potential connectivity among ports, indicating the efficiency of goods and information flows between ports. For example, the network density of the Northeast Asia

region in 2022 was 0.568 [40]. In 2021, the network density of the marine network among 21 major coastal ports in China was 0.2500 [41]. In our study, the calculated network density of the GBA is 0.41258, which suggests sufficient connectivity to support regional and global logistics circulation. Compared with existing studies' network density values, this value falls within a reasonable range. This value also shows the potential for collaboration and competition among ports.

In practice, GBA-wide port cooperation can be facilitated through blockchain and other digital technologies, which can reduce operational inefficiencies caused by geographical fragmentation and improve overall supply chain efficiency [42]. Additionally, the moderate network density also indicates a certain degree of regional port competition. For example, Shenzhen and Hong Kong ports operate under two different regulatory systems. Furthermore, internal competition exists between ports on the east and west sides of Shenzhen. Furthermore, the port density value implies that the port network has several alternative routes and strong redundancy. Last but not least, this translates to substantial redundancy in the shipping network. If one port connection fails, there are on average multiple alternative routes available for cargo rerouting.

In summary, a port network density of 0.41258 indicates substantial connectivity within the GBA port network, sufficient to support the efficient operation of regional logistics and supply chains, realizing the GBA's role as an intermediary hub.

4.2. Maritime Corridor Structure Analysis

To identify the maritime corridor framework, we focus on each port's structural contribution to the GBA. We use input and source nodes to identify the core backbone of the maritime corridor, which represents the minimum support set for the GBA's external circulation. This yields two categories of ports, namely source nodes and sink nodes.

For source nodes representing cargo inflow to the GBA, the top 8 ports are Singapore, Ningbo (including Zhoushan), Shanghai, Chiwan (Shenzhen), Haiphong (Vietnam), Shantou, Tianjin, and Xiamen. These ports have a high degree of upstream connectivity to the GBA, which is an important prerequisite for supporting the GBA's economic development. For sink nodes representing cargo outflow from the GBA, the top 8 ports are Shanghai, Singapore, Xiamen, Ningbo (including Zhoushan), Guangzhou, Qinzhou, Kaohsiung, and Qingdao. Based on the port ranking, we can identify the main structure of the maritime corridor, which reflects the "source nodes → GBA transit hub → sink nodes" flow pattern. These ports have a high degree of downstream connectivity to GBA ports, providing important support for the role of port hubs that is necessary to maintain the GBA's external circulation. Figure 1 shows the backbone framework of the maritime corridor.

Figure 1 shows the main structure of the maritime corridor and internal circulation in the GBA region. First, the main structure is an asymmetric cross-shaped backbone corridor with a hub-and-spoke pattern, which ensures frequent connections with domestic and international markets. This maritime corridor centers on the GBA as a hub, connecting Southeast Asia, Japan, and South Korea. The deep teal lines represent sea route directions, covering major ports along China's coast, including Shanghai, Ningbo, Shenzhen, and Qingdao. The red arrows show the directions of the main corridor lines, which extend northward to Tianjin, southward to Singapore, westward to Vietnam, and eastward to Kaohsiung. The maritime corridor structure connects Southeast Asia, Japan, and South Korea, facilitating container transportation and international trade. Meanwhile, through the South China Sea and the East China Sea, it carries significant trade flows, serving as an important transportation route connecting China to other countries and supporting the global supply chain.

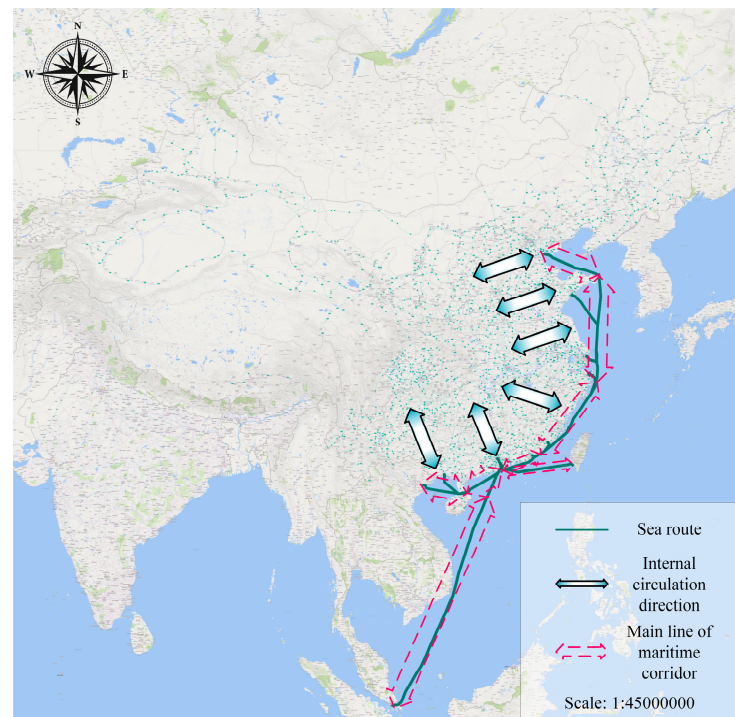


Figure 1. Schematic of the maritime corridor structure in the GBA.

The blue arrows in Figure 1 show the directions of internal circulation around the GBA region, linking coastal ports with major cargo transshipment hubs in China. These ports' maritime routes connect Shanghai, Ningbo, Xiamen, Guangzhou, and other locations, promoting the smooth flow of logistics and trade within the region, strengthening connections between inland and coastal cities, improving the efficiency of domestic goods circulation, facilitating the integration of domestic market demand with the supply chain, and enhancing inter-port linkages.

In terms of core value, the GBA maritime corridor plays a key role in supporting “internal linkage and external connection”, which enhances the GBA's competitiveness within the global supply chain and improves the efficiency of domestic trade. Internal linkage represents strengthened connections between other Chinese provinces and the southeast coastal region, which ensures smooth coordination of production and consumption activities in GBA markets, effectively reducing logistics costs and improving logistics efficiency. External connection reflects the value of accessing global market resources through maritime routes, which strengthens the GBA's economic ties with Southeast Asia, Europe, and the Americas. This trend enhances the GBA's economic development advantages.

Therefore, the GBA can access more market resources and expand its supply chain structure, thereby accelerating trade response times. In particular, within the current complex geopolitical environment, the GBA's regional integration enhances market competitiveness.

4.3. Main Structure Under Random Perturbations

To examine the structural stability of the core maritime corridor under random perturbations, we generate an independent random variable u_{ij} for each port-to-port connection, with threshold probability denoted as p . The threshold logic is $u_{ij} < p$ ($p = 0.3, 0.5, 0.8$). If $u_{ij} < p$ ($p = 0.3, 0.5, 0.8$), the edge value is flipped (0 to 1 or 1 to 0); otherwise, it is preserved. This edge-flipping process reconstructs a new perturbed network for each trial; we adopt such random link modification to generate disturbed network samples, so as to observe how the pre-identified backbone corridor evolves under interference. Note that these random fluctuations primarily affect upstream connections, while the downstream

flow patterns remain relatively stable. Using the same method as the basic network, a complete shipping network through GBA under disturbance conditions can be obtained. We then compare the topological characteristics of maritime corridors reconstructed from networks under three distinct perturbation thresholds. By randomly altering inter-port links to weaken node connections at different probabilities, this method quantifies the structural robustness of the original core maritime corridor. Three independent simulation cases (Case 1, Case 2, and Case 3) are conducted for robustness analysis, each corresponding to a distinct perturbation probability to generate different random network states. Table 6 presents the port importance rankings derived from the reconstructed perturbed networks under the three threshold settings, which reflect the persistence of the original backbone corridor framework when inter-node connections are randomly disrupted.

Table 6. The main framework changes in three kinds of occurrence probability.

Case	Probability	The Main Structure of the Maritime Corridor in the Top 8 Ports
Case 1	0.3	Shanghai Port–Singapore Port–Xiamen Port–Ningbo Port (including Zhoushan Port)–Guangzhou Port–Qinzhou Port–Kaohsiung Port–Qingdao Port
	0.5	
	0.8	
Case 2	0.3	Shanghai Port–Singapore Port–Xiamen Port–Ningbo Port (including Zhoushan Port)–Guangzhou Port–Qinzhou Port–Kaohsiung Port–Qingdao Port
	0.5	
	0.8	
Case 3	0.3	Shanghai Port–Singapore Port–Xiamen Port–Ningbo Port (including Zhoushan Port)–Guangzhou Port–Qinzhou Port–Kaohsiung Port–Qingdao Port
	0.5	
	0.8	

Table 6 shows the top ports describing the main structure of the maritime corridor under changes in node connections. A key observation is that the top 8 ports remain identical across all nine simulation scenarios (3 cases $\times$ 3 perturbation levels), demonstrating the structural persistence of the GBA maritime corridor backbone. Specifically, when the node perturbation probability is 0.3, some port connections are affected, but the impact is relatively small, meaning that most port connections still maintain their original structure. This suggests that the maritime corridor structure is highly stable. For example, Shanghai, Singapore, Xiamen, and Ningbo (including Zhoushan) maintain high connectivity and remain key nodes in the network. Although some port connections have changed, network redundancy allows ports such as Guangzhou and Kaohsiung to compensate for the negative effects of random perturbations.

When the perturbation probability is 0.5, most node connections in the network change significantly. Under this threshold, the network undergoes significant topological reorganization, yet the top 8 port ranking remains unchanged. Network stability and redundancy face moderate stress. Ports with low to medium connectivity increase in importance as the network structure is reorganized, assuming a new pivotal role. Some previously minor ports gain connectivity through network reconfiguration, showing a pattern of multi-level reorganization in port substitution and redundancy propagation. For example, Qingdao and Kaohsiung have become stable nodes in the main shipping corridor. Network redundancy provides some resilience against large network disturbances.

When the perturbation probability reaches 0.8, most connections in the network are severely damaged, resulting in substantially reduced overall stability. Some ports that were previously connected to many other ports, such as Tianjin, become disconnected, leading to partial network breakdown. In this case, network vulnerability is amplified, resulting in a marked loss of overall network stability.

In summary, the main structure of the maritime corridor remains unchanged under all conditions. This is because high-traffic ports such as Shanghai, Singapore, and Xiamen

maintain their core connections, which preserve the asymmetric cross-shaped backbone corridor. Therefore, the main structure remains stable even when connection relationships are perturbed under random conditions. These results show that the maritime corridor structure possesses sufficient stability and redundancy to serve the GBA region. In other words, as long as these core backbones remain intact, the topological characteristics of the overall shipping network will not substantially change.

4.4. Resilience Level Changes in the Maritime Corridor

To measure the stability of the maritime corridor under changing connection relationships, we use algebraic connectivity to analyze the resilience of the GBA maritime corridor. This index reflects network or system stability. Generally, a higher algebraic connectivity value indicates a more stable system. The resilience level describes a system's ability to withstand interference. Higher resilience indicates greater system stability. Following Kong et al. [43], we adopt a 5-point Likert Scale to classify resilience into five levels, each corresponding to a specific range. The classification criteria are as follows. The very vulnerable level is 1 and the range is $[0, 0.2)$. The weaker resilience is 2 and the range is $[0.2, 0.4)$. The medium resilience is 3 and the range is $[0.4, 0.6)$. The stronger resilience is 4 and the range is $[0.6, 0.8)$. The very high resilience is 5 and the range is $[0.8, 1.0]$. Table 7 presents the analysis results.

Table 7. Resilience of maritime corridor with random changes.

Case	Probability of Occurrence	Algebraic Connectivity	Resilience Level	Degree of Resilience
Case 1	0.3	2.99914	53.524%	Medium
	0.5	1.99914	35.677%	Weak
	0.8	0.99404	17.740%	Very weak
Case 2	0.3	3.44515	61.484%	Stronger
	0.5	3.46019	61.752%	Stronger
	0.8	0.99979	17.843%	Very weak
Case 3	0.3	4.27751	76.338%	Stronger
	0.5	3.46019	61.752%	Stronger
	0.8	0.99979	17.843%	Very weak

Note: The original result is 5.60337.

Table 7 shows the algebraic connectivity values across different cases and the corresponding resilience levels under random perturbation scenarios. Overall, as the perturbation probability increases, algebraic connectivity decreases, resulting in a significant decline in system resilience. This decrease in algebraic connectivity means that the stability of the GBA maritime network declines, indicating a high degree of vulnerability. Specifically, at a low perturbation probability (0.3), the maritime system's algebraic connectivity and resilience level remain high, indicating strong to moderate resilience. Furthermore, as the perturbation probability increases, the algebraic connectivity value declines toward 1, indicating a very weak resilience level. These results indicate that the stability of the maritime corridor is severely affected by higher perturbation probabilities, with increasing vulnerability. The results are relatively consistent across the three scenarios, showing a significant impact of perturbation probability on system stability.

In Case 1, increasing perturbation probability leads to decreasing stability of the maritime corridor. At a perturbation probability of 0.3, the algebraic connectivity is 2.99914 and the resilience is 53.524%, indicating a certain degree of anti-interference ability. At 0.5, the algebraic connectivity drops to 1.99914 and the resilience falls to 35.677%, indicating that the system enters a weak resilience state, manifested by a reduced ability to withstand external disturbances. At 0.8, the algebraic connectivity drops further to 0.99404, the resilience falls to 17.740%, and the system becomes very weak, rendering the maritime

network highly fragile. Under high perturbation, the system's stability declines significantly, potentially leading to increased uncertainty and the risk of instability events.

Cases 2 and 3 show a similar trend, but the system exhibits strong resilience at a low perturbation probability (0.3). In Case 2, at a perturbation probability of 0.3, the algebraic connectivity is 3.44515 and the resilience is 61.484%, demonstrating strong resistance to the negative impact of system vulnerability. At 0.5, the algebraic connectivity is 3.46019 and the resilience is 61.752%, indicating that system resilience remains at a satisfactory level. At 0.8, the algebraic connectivity drops to 0.99979, the resilience falls to 17.843%, and the system becomes very fragile. The simulation results show that although the system remains relatively stable under low to medium perturbation, it becomes fragile at high perturbation levels.

The results of Case 3 are similar to those of Case 2, showing that the resilience value remains high under medium and low perturbation probabilities. However, under high perturbation, the algebraic connectivity drops to 0.99979 and the resilience level becomes very weak; the system becomes fragile. These results are consistent with those of the previous two scenarios.

In summary, the results in Table 7 show the impact of perturbation probability on the maritime corridor's resilience. First, the perturbation probability is the dominant factor determining network stability in all three simulation cases. An increase in perturbation probability consistently leads to decreased algebraic connectivity and resilience across all cases. Second, while the quantitative resilience values vary across the three cases due to stochastic variation, the qualitative degradation pattern is invariant, confirming that the degree of perturbation in system connectivity is the key factor significantly affecting the stability and anti-interference ability of the GBA maritime network. This phenomenon reflects the principle that macroscopic spectral properties become largely deterministic despite microscopic randomness. From a practical perspective, these results suggest that the GBA maritime corridor can withstand moderate disruptions (e.g., regional trade tensions or seasonal congestion) while maintaining functional stability, but is vulnerable to extreme events that disrupt more than 50% of existing connections. Therefore, in developing the GBA maritime corridor, it is necessary to pay attention to inter-port relationships and emphasize risk management, particularly by building redundant connections and diversifying shipping routes to ensure that the maritime network maintains high resilience and can withstand the impact of disruptions.

4.5. Robustness Analysis

4.5.1. Further Analysis of Backbone Structure for Maritime Corridor in GBA

To further validate the backbone structure of maritime corridor in the GBA, we further use three mathematical methods to demonstrate the validity of the analytical results, including Minimum Spanning Tree (MST), k-core decomposition, and Edge betweenness filtering. Furthermore, we discuss the consistency between the baseline findings and those from these three methods.

The MST represents the minimal connected subgraph of the original graph, which contains all the nodes in the original graph and least edges to keep the graph connected. In our study, we adopt the basic Kruskal's algorithm [44,45] on the unweighted graph to obtain a uniquely connected acyclic subgraph. MST only keeps the minimum necessary routes to maintain the connectivity of the whole network, filters massive short-distance redundant feeder lines, and extracts the natural circulation skeleton of shipping activity for the GBA; priority is given to high-intermediate transit corridors and trans-ocean trunk lines.

The result shows that the network with $N = 315$ and main trunk routes comprise 308 edges (representing the top 1% of trunk-level edges). According to output results with

port pair, the average betweenness of trunk edge is 6.5×10^{-5} and global edge average betweenness is 4.3×10^{-5} . The route connecting the ports at the top of both the inbound and outbound lists represents the highest transit traffic channel in the entire network. For example, Singapore and Shanghai rank top 2 in both the inbound and outbound port lists with asymmetric cross-shaped MST framework. Major East Asian coastal trunk ports including Ningbo, Xiamen, Chiwan and Guangzhou are all included in the top 8 of inbound and outbound rankings, matching the northward extended coastal corridor of the MST backbone. Furthermore, regional branch ports covering Southeast Asia, Bohai Rim, Beibu Gulf and Taiwan Strait appear in differentiated rankings, consistent with the north-south auxiliary vertical branches of the MST topology and the directional characteristics of cargo transportation.

The k-core is a classical algorithm in graph theory, which is used to identify subgraphs with the closest structure and the highest correlation in the network. In our study, we adopt the BZ algorithm to obtain the subgraph, which is the trunk port cluster for GBA [46,47]. Note that the value of $k_{\max}$ represents the most densely connected subgraph of shipping flows, quantitatively confirming that the GBA port cluster occupies a top-tier position in the global shipping network. The results show that the maximum core index reaches $k_{\max} = 183$. The analytical ports from source nodes and sink nodes are embedded in core layer, which locates dense hub cluster, identifying the core port circle layer with the most intensive network traffic interaction.

Edge Betweenness Filter (EBF) refers to the number of shortest paths between all node pairs in a network that pass through a specific edge. If an edge has a high betweenness value, it indicates that it plays a crucial role as a hub connecting two different parts of the network. In our study, we adopt EBF to find the inter-regional transit routes that undertake most global cargo flows, Edge Betweenness Filtering [48,49]. The results show that retaining the top 1% of routes by edge betweenness yields 305 main routes. The mentioned ports in the GBA appear in the list of high-medium trunk ports, which confirms the GBA ports' role as transit nodes in the shortest paths of the network, reflecting intermediary corridor attributes. In brief, we can sort the analytical results as Table 8.

Table 8. Comparing the three methods from the view of core discussion.

Method	The Core Discussion	The Core Result
MST	Description of the maritime corridor by the minimal connection framework	315 ports and asymmetric cross-shaped MST framework
K-core	Hierarchical identification of local high-density hub clusters	$k_{\max} = 183$ for analytical ports with source nodes and sink nodes
EBF	Screen the key routes with the highest transit load in the network	Quantify GBA's status as a trans-ocean transit artery

4.5.2. Further Analysis of Resilience Level in the GBA

To further examine the resilience of the GBA port network, Table 9 summarizes three shock scenarios. First of all, we further analyze the shock scenario from three aspects, including high-degree attack, high-betweenness attack, and full GBA core ports removal. Here, we provide descriptions for each index in Table 9.

The largest connected component ratio (LCC) identifies the largest subset of nodes in an undirected graph such that any two nodes within it are connected by paths [50]. The purpose in our study is to simulate the integrity of the shipping subject system after the impact. Largest Connected Component Ratio (LCC) shows whether the network subject remains intact. The closer the LCC value is to 1, the stronger the resilience, where $LCC = \text{Max components}/N$ with N as a number of ports. Number of Disconnected

Fragments (F) is the total number of disconnected independent subgraphs split by the disturbed network. The greater the F, the more serious the fragmentation and the worse the resilience level [50]. Average shortest path length in maximum connected subgraph (L_{avg}) is to calculate the average value of the shortest path of all port pairs only in the giant connected component, and measure the transit efficiency of goods flow [51]. Backbone Retention Ratio ($R_{backbone}$) represents the proportion of the original MST trunk routes that remain after disturbance to all the original trunk routes. This index mainly measures the damage degree of asymmetric cross core skeleton, as $R_{backbone} = \text{Max components} / \text{Total MST}$. Algebraic connectivity in our study measures the network resilience. The greater the decline of λ_2 , the more severe the destruction of the connected structure at the bottom of the topology. Resilience level (RL) calculates the value for the shock scenario in the case of algebraic connectivity. Global network efficiency (GNE) measures the information transmission capacity and connectivity efficiency of the whole network [52]. The shorter the shortest path of the network and the smoother the information transmission, the higher the global efficiency. Average clustering coefficient (ACC) is the ratio of the actual number of neighbor connections to the maximum number of neighbor connections that may be owned by a specific node in the network [53,54]. Comprehensive resilience level (R_{NET}) analyzes the changes based on the average from the value of LCC, normalized network efficiency, normalized algebraic connectivity, and $R_{backbone}$. Among them, the normalized network efficiency is a ratio of shock scenario to original full network. Similarly, the normalized algebraic connectivity uses the same calculation method. A higher R_{NET} indicates stronger comprehensive structural resilience against port shutdown shocks.

Table 9. Shock scenario analysis.

Shock Scenario	Removed Scale	Max Components	LCC	F	L_{avg}	$R_{backbone}$	Algebraic Connectivity	RL	GNE	ACC	R_{NET}
Original full network	0	315	1.000	1	1.36	1.000	5.60337	100%	0.789	0.844	100%
High-degree attack	5%	294	0.980	7	1.39	0.951	3.59909	64.231%	0.803	0.847	89.76%
High-degree attack	10%	278	0.979	7	1.44	0.893	1.27132	22.688%	0.782	0.825	77.25%
High-degree attack	15%	262	0.978	7	1.48	0.802	1.27124	22.687%	0.762	0.797	74.30%
High-degree attack	20%	246	0.976	7	1.52	0.750	1.27108	22.684%	0.741	0.757	72.26%
High-betweenness attack	5%	294	0.980	7	1.41	0.945	0.44128	7.875%	0.802	0.844	75.47%
High-betweenness attack	10%	278	0.979	7	1.45	0.893	0.44139	7.877%	0.781	0.826	73.50%
High-betweenness attack	15%	262	0.978	7	1.50	0.802	0.44150	7.879%	0.761	0.797	70.54%
High-betweenness attack	20%	246	0.976	7	1.55	0.737	0.26965	4.812%	0.739	0.764	67.42%
Full GBA core ports removal	11 ports	298	0.980	7	1.38	0.964	3.59561	64.169%	0.810	0.854	90.30%

Note: LCC: Largest Connected Component Ratio. F: Number of Disconnected Fragments. L_{avg} : Average shortest path length in maximum connected subgraph. $R_{backbone}$: Backbone Retention Ratio, 308 ports (1%-level). Resilience level: RL. GNE: Global network efficiency. ACC: Average clustering coefficient. R_{NET} : Comprehensive resilience level.

Table 9 yields three key findings. First, the GBA port cluster enables efficient transshipment gains. For example, the global efficiency of the original complete network is 0.789 and the average clustering coefficient is 0.844. When all the ports in GBA are reserved, the circulation path of the giant connected component is shorter, and the global network naturally has the potential of higher transfer efficiency. When the GBA is removed, global efficiency and the clustering coefficient rise slightly. This counterintuitive result indicates that, during normal operation, the GBA absorbs substantial regional transit demand, thereby sharing cargo flow pressure among main ports and optimizing the overall transportation structure. The average shortest path of the original network is only 1.36, and the extremely low average transshipment distance is realized by relying on the dense routes in the Bay Area. Therefore, the GBA can continue to strengthen the multi-port coordinated intermodal transport system, improve the multi-modal transport facilities of inland rivers, railways and seas, give full play to the advantages of regional dense feeder networks, undertake

scattered cargo flows in East Asia, divert the transportation pressure of trunk hubs, and continuously reduce the average transshipment distance of global shipping.

Second, as a large-scale regional port cluster, GBA's ports enrich the redundancy of nodes and routes in the global shipping network, and improve the comprehensive impact resistance of the network. The comprehensive resilience value of the network is 100%, and algebraic connectivity reaches its maximum at 5.60337. The ports in the GBA carry a large number of connecting routes in East Asia, share the trans-ocean transit pressure, reduce the risk of cargo flow concentration in a single hub, and provide sufficient route redundancy buffer for the maritime network. Under the impact of the same scale, the comprehensive resilience of a complete network with GBA as a buffer node is much higher than that without the cluster. Therefore, relevant authorities should further strengthen the backbone positioning of the GBA port cluster, expanding specialized container and bulk cargo berths, expanding ocean trunk routes, enriching redundant links in global shipping networks, and enhancing the overall stability of global supply chains.

Finally, the risk buffer value of GBA's port cluster is outstanding, so it is necessary to build a multi-level transshipment pattern in East Asia. For example, the complete network relies on the multi-cluster cooperation of GBA, Yangtze River Delta and Southeast Asia, and the Bay Area supports a number of East Asian connecting routes among the 308 MST trunk lines, forming complementary corridors with other regional ports. Table 9 shows that the comprehensive index of the network directly drops to 90.30% (3.59561) under the disturbance of the same scale without Greater Bay Area, which directly reflects the supporting value of the Bay Area to the regional multi-level transshipment system. Therefore, relevant departments can further consider promoting the coordinated division of labor between GBA and Shanghai, Ningbo, Singapore and other ports to create a differentiated and complementary multi-polar transshipment network in East Asia.

4.5.3. Further Analysis of the Main Framework for Maritime Corridor

To examine the robustness of the main backbone structure of the GBA maritime corridor, we design two types of Monte Carlo simulations to evaluate the stability of the benchmark top-8 core ports under random upstream disturbances. Consistent with the baseline analysis, we set four upstream perturbation thresholds, such as 0.2, 0.4, 0.6 and 0.8. Each scenario is simulated 10,000 times to reduce random sampling bias with fixed random factor as 42. The first scheme adopts independent-group simulation: four thresholds generate completely non-overlapping random shock samples (40,000 replications in total) to verify the universality of our core findings. The second scheme is paired unified-random-sample simulation, which only requires 10,000 total rounds. In each iteration, we generate a single set of upstream random change values and synchronously compute port rankings under all four thresholds. This design eliminates confounding bias induced by inconsistent random samples across groups and enables rigorous single-variable controlled comparison. Meanwhile, we employ two independent proportion Z-tests to quantify the statistical disparities in the full backbone retention probability across different disturbance intensities.

The specific results can be obtained in the Supplementary Material. In brief, the simulations under both schemes yield similar results about core indications, probability distribution, and analytical laws. Firstly, the probability of completely retaining all eight benchmark core ports drops monotonously with the increase in upstream change intensity, which shows the values from 0.3391 (0.2, *C.I.* : [0.3298, 0.3484, 95%]) to 0.0048 (0.8, *C.I.* : [0.0034, 0.0062, 95%]) under independent simulation and 0.3391 (0.2, *C.I.* : [0.3298, 0.3484, 95%]) to 0.0055 (0.8, *C.I.* : [0.0041, 0.0069, 95%]) under pairing simulation, respectively. The average number of retained core ports keeps decreasing synchronously. The stronger the disturbance, the higher the proportion of samples with

extremely low overlap ($k \leq 4$). Secondly, under mild and moderate disturbances (0.2 and 0.4), at least five benchmark core ports will remain in all simulations, and core port clusters will not be lost more than half. When the disturbance rises to 0.8 severe extreme change, about 15% of the simulations lose more than half of the original core ports, and the backbone frame is at risk of structural reconstruction. Thirdly, all the thresholds of the two groups are less than 0.01. There is a significant difference at the level of 1% significance, which proves that the weakening effect of disturbance intensity on the persistence of the backbone structure is an endogenous feature of the network, not an accidental result caused by random simulation sampling fluctuation.

Robustness test further improves the stability of the benchmark backbone framework, which is complementary to the result in Table 6. Under the scenario of random interruption of small and medium-sized upstream transport capacity, the hierarchical maritime transit network has strong structural resilience, which can stably maintain the head position for core port cluster. In the face of the shock of 80% large-scale simultaneous closure of upstream ports, the network robustness is greatly attenuated with a significant risk of reconstruction of the original maritime backbone pattern. Two independent random sampling simulations yield consistent attenuation patterns and statistically significant results, demonstrating the robustness of our core findings regarding the resilience of the GBA maritime corridor's backbone structure.

5. Conclusions

In this study, we analyze the port network and its main framework from the perspective of a maritime corridor in the GBA using data spanning May 2022 to May 2023. We discuss the roles of internal linkages and external linkages from the maritime corridor perspective using algebraic connectivity, highlighting the importance of maritime corridor development for regional economic development. The main findings are as follows.

First, the main structure of the maritime corridor is an asymmetric cross-shaped backbone corridor that ensures frequent connections with domestic and international markets, including Southeast Asia, Japan, and South Korea, with the GBA as an economic hub and intermediary. Second, the study shows that the degree of perturbation in system connectivity is the key factor affecting resilience, which significantly affects the stability and anti-interference ability of the GBA maritime network.

The management implications are as follows. First, investment in backbone port infrastructure should be increased. Policymakers can prioritize infrastructure investments in these gateway ports and their connecting routes, ensuring that the asymmetric cross-shaped structure remains robust against disruptions. Second, authorities or maritime firms can develop backup shipping routes and alternative port partnerships, particularly between secondary GBA ports (e.g., Zhuhai, Jiangmen) and international destinations. Finally, the non-linear degradation pattern of resilience suggests that small accumulated disruptions can trigger sudden connectivity collapse. A real-time network monitoring system for connectivity metrics could serve as an early-warning tool, alerting authorities when network connectivity approaches critical thresholds.

This study also has some limitations. First, our analysis relies on a single year of data. While this window captures a complete schedule of liner shipping operations, it does not reflect long-term structural evolution and weight changes, such as temporal shifts in trade patterns or changes in route capacity. Future research could extend the analysis to multi-year panel data to examine how the GBA maritime corridor's backbone structure adapts to secular changes in global trade patterns. Second, although the algebraic connectivity method effectively reflects connectivity strength, it does not incorporate multi-dimensional resilience indicators such as functional recovery, node redundancy, or path

substitution. Therefore, future research could combine dynamic simulation with multi-index comprehensive evaluation methods to improve the comprehensiveness of the results.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/math14142529/s1>, Supplementary Material S1: Report the results for robustness analysis in the attachment.

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References

1. Lau, Y.Y.; Chen, Q.; Poo, M.C.P.; Ng, A.K.; Ying, C.C. Maritime transport resilience: A systematic literature review on the current state of the art, research agenda and future research directions. *Ocean Coast. Manag.* **2024**, *251*, 107086. [\[CrossRef\]](#)
2. Rahayu, L.; Busscher, T.; Tillema, T.; Woltjer, J. Maritime transport governance challenges in the Global South. *Mar. Policy* **2024**, *163*, 106147. [\[CrossRef\]](#)
3. Gu, B.; Liu, J. A systematic review of resilience in the maritime transport. *Int. J. Logist. Res. Appl.* **2025**, *28*, 257–278.
4. Zhong, H.; Chen, W.; Gu, Y. A system dynamics model of port hinterland intermodal transport: A case study of Guangdong-Hong Kong-Macao Greater Bay Area under different carbon taxation policies. *Res. Transp. Bus. Manag.* **2023**, *49*, 100987. [\[CrossRef\]](#)
5. World Shipping. The Top 50 Container Ports. 2025. Available online: <https://www.worldshipping.org/top-50-container-ports> (accessed on 27 May 2025).
6. Zhang, Q.; Hu, X.; Xie, Y.; Li, Z. Reconstructing and assessing global maritime transport network: Based on the Port Cargo Composite Transport index. *Marit. Policy Manag.* **2025**, *52*, 723–744.
7. Gao, T.; Tian, J.; Huang, C.; Wu, H.; Xu, X.; Liu, C. The impact of new western land and sea corridor development on port deep hinterland transport service and route selection. *Ocean Coast. Manag.* **2024**, *247*, 106910. [\[CrossRef\]](#)
8. Li, W.; Bai, X.; Yang, D.; Hou, Y. Maritime connectivity, transport infrastructure expansion and economic growth: A global perspective. *Transp. Res. Part A Policy Pract.* **2023**, *170*, 103609. [\[CrossRef\]](#)
9. Liu, C.Y.; Fan, H.M.; Dang, X.J.; Zhang, X. The Arctic policy and port development along the Northern Sea Route: Evidence from Russia's Arctic strategy. *Ocean Coast. Manag.* **2021**, *201*, 105422. [\[CrossRef\]](#)
10. Wu, A.; Che, T.; Xu, Q.; Wang, J.; Chen, J.; Zhu, X. Assessing the economic viability of the Arctic Northeast Passage from 2021 to 2065. *Int. J. Digit. Earth* **2024**, *17*, 2323182. [\[CrossRef\]](#)
11. Chang, Z.; He, X.; Fan, H.; Guan, W.; He, L. Leverage Bayesian network and fault tree method on risk assessment of LNG maritime transport shipping routes: Application to the China–Australia route. *J. Mar. Sci. Eng.* **2023**, *11*, 1722. [\[CrossRef\]](#)
12. Zhang, Z.; Ju, Y. Evaluation of navigation environment of northeast waterway based on extension cloud model. In Proceedings of the Eighth International Conference on Electromechanical Control Technology and Transportation (ICECTT 2023), Hangzhou, China, 19–21 May 2023; Volume 12790, pp. 1620–1624.
13. Yang, L.; Zheng, J.; Wang, J. Hub port location and routing for a single-hub feeder network: Effect of liner shipping network connectivity. *Transp. Policy* **2025**, *160*, 212–227. [\[CrossRef\]](#)
14. Zhang, D.; Tao, J.; Wan, C.; Huang, L.; Yang, M. Resilience analysis of maritime transportation networks: A systematic review. *Transp. Saf. Environ.* **2024**, *6*, tdae009. [\[CrossRef\]](#)
15. Guo, S.; Lu, J.; Qin, Y. Analysis of the coupled spatial and temporal development characteristics of global liner shipping connectivity driven by trade. *Ocean Coast. Manag.* **2024**, *251*, 107071. [\[CrossRef\]](#)

16. Jiang, L.; Wang, G.; Feng, X.; Yu, T.; Lei, Z. Study on cascading failure vulnerability of the 21st-century Maritime Silk Road container shipping network. *J. Transp. Geogr.* **2024**, *117*, 103891. [\[CrossRef\]](#)
17. Wang, N.; Wu, M.; Yuen, K.F. Assessment of port resilience using Bayesian network: A study of strategies to enhance readiness and response capacities. *Reliab. Eng. Syst. Saf.* **2023**, *237*, 109394. [\[CrossRef\]](#)
18. Yap, W.Y.; Hsieh, C.H.; Lee, P.T.W. Shipping connectivity data analytics: Implications for maritime policy. *Transp. Policy* **2023**, *132*, 112–127. [\[CrossRef\]](#)
19. Nadarajan, D.; Ahmed, S.A.M.; Noor, N.F.M. Seaport network efficiency measurement using triangular and trapezoidal fuzzy data envelopment analyses with liner shipping connectivity index output. *Mathematics* **2023**, *11*, 1454. [\[CrossRef\]](#)
20. Su, W.; Lu, J. Short-term resilience assessment of the global liner shipping network: A case study of COVID-19. *Ocean Coast. Manag.* **2025**, *262*, 107560. [\[CrossRef\]](#)
21. Gu, B.; Chen, J.; Haralambides, H.; Liu, J. A novel method of assessing port resilience and its positive ramifications. *Marit. Policy Manag.* **2025**, *52*, 642–665. [\[CrossRef\]](#)
22. Chang, W.; Li, N.; Zhao, Y. Resilience of regional container port network: Based on projection correlation and dynamic spatial Markov Chain. *Marit. Policy Manag.* **2025**, *52*, 764–780.
23. Qu, S.; She, Y.; Zhou, Q.; Verschuur, J.; Zhao, L.T.; Liu, H.; Xu, M.; Wei, Y.M. Modeling the dynamic impacts of maritime network blockage on global supply chains. *Innovation* **2024**, *5*, 100653. [\[CrossRef\]](#) [\[PubMed\]](#)
24. Gu, B.; Liu, J. Port resilience analysis based on the HHM-FCM approach under COVID-19. *Ocean Coast. Manag.* **2023**, *243*, 106741. [\[CrossRef\]](#)
25. Cnss. Clarkson Research: Year-end Review and Data Glance of Shipping Market in 2021. 2022. Available online: <https://www.cnss.com.cn/html/hygc/20220114/344808.html> (accessed on 1 July 2026).
26. Bonacich, P. Factoring and weighting approaches to status scores and clique identification. *J. Math. Sociol.* **1972**, *2*, 113–120. [\[CrossRef\]](#)
27. Zhang, Q.; Shuai, B.; Lü, M. A novel method to identify influential nodes in complex networks based on gravity centrality. *Inf. Sci.* **2022**, *618*, 98–117. [\[CrossRef\]](#)
28. Freeman, L.C. A Set of Measures of Centrality Based on Betweenness. *Sociometry* **1977**, *40*, 35–41. [\[CrossRef\]](#)
29. Sabidussi, G. The centrality index of a graph. *Psychometrika* **1966**, *31*, 581–603. [\[CrossRef\]](#) [\[PubMed\]](#)
30. Elmezain, M.; Othman, E.A.; Ibrahim, H.M. Temporal degree-degree and closeness-closeness: A new centrality metrics for social network analysis. *Mathematics* **2021**, *9*, 2850. [\[CrossRef\]](#)
31. Xing, W.; Ghorbani, A. Weighted Pagerank algorithm. In Proceedings of the Second Annual Conference on Communication Networks and Services Research, Fredericton, NB, Canada, 19–21 May 2004; pp. 305–314.
32. Wang, P.; Guo, Y.; Xu, Z.; Wang, W.; Chen, D. A novel approach of full state tendency measurement for complex systems based on information causality and PageRank: A case study of a hydropower generation system. *Mech. Syst. Signal Process.* **2023**, *187*, 109956. [\[CrossRef\]](#)
33. Brin, S.; Page, L. The anatomy of a large-scale hypertextual web search engine. *Comput. Netw. ISDN Syst.* **1998**, *30*, 107–117. [\[CrossRef\]](#)
34. Leskovec, J.; Kleinberg, J.; Faloutsos, C. Graphs Over Time: Densification Laws, Shrinking Diameters and Possible Explanations. In Proceedings of the Eleventh ACM SIGKDD International Conference on Knowledge Discovery in Data Mining, Chicago, IL, USA, 21–24 August 2005; pp. 177–187.
35. Shi, D.; Chen, G.; Thong, W.W.K.; Yan, X. Searching for optimal network topology with best possible synchronizability. *IEEE Circuits Syst. Mag.* **2013**, *13*, 66–75. [\[CrossRef\]](#)
36. Aksoy, S.G.; Bruillard, P.; Young, S.J.; Raugas, M. Ramanujan graphs and the spectral gap of supercomputing topologies. *J. Supercomput.* **2021**, *77*, 1177–1213.
37. Fiedler, M. Algebraic connectivity of graphs. *Czechoslov. Math. J.* **1973**, *23*, 298–305. [\[CrossRef\]](#)
38. Reily, B.; Coniff, C.; Rogers, J.G.; Reardon, C. Disruption of Connectivity Graphs in Uncertain Multi-Agent Systems. In Proceedings of the 2022 IEEE International Conference on Omni-Layer Intelligent Systems (COINS), Barcelona, Spain, 1–3 August 2022; pp. 1–6.
39. Promsuwan, P.; Nakayama, S.; Yamaguchi, H.; Kobayashi, S.I. Comparison between algebraic connectivity-based and global efficiency-based vulnerability for railway topology analysis: A case study of Kyushu, Japan. *Asian Transp. Stud.* **2022**, *8*, 100074. [\[CrossRef\]](#)
40. Guo, S.; Lyu, J. Evolution and stability of liner shipping networks in Northeast Asia from 2018 to 2022. *Transp. Policy* **2024**, *158*, 159–174. [\[CrossRef\]](#)
41. He, Y.; Xu, X. Spatial correlation network structure of port performance and its drivers: A case study of Chinese coastal ports. *Ocean Coast. Manag.* **2023**, *244*, 106780. [\[CrossRef\]](#)
42. Digital Customs Affairs. Interpretation of “Several Measures for Customs to Support the Construction of Guangdong-Hong Kong-Macao Greater Bay Area”. 2026. Available online: <https://mp.weixin.qq.com/s/ykrzY5MfuolX6wk22VoEVA> (accessed on 4 June 2026).

43. Kong, L.; Koh, S.L.; Robinson, D.; Sena, V.; Wood, M. A model for assessing maturity of hydrogen supply chain resilience: A complexity-inspired approach. *Int. J. Prod. Res.* **2026**, 1–21. [[CrossRef](#)]
44. Kruskal, J.B. On the shortest spanning subtree of a graph and the traveling salesman problem. *Proc. Am. Math. Soc.* **1956**, 7, 48–50. [[CrossRef](#)]
45. Tewarie, P.; van Dellen, E.; Hillebrand, A.; Stam, C.J. The minimum spanning tree: An unbiased method for brain network analysis. *Neuroimage* **2015**, 104, 177–188. [[CrossRef](#)] [[PubMed](#)]
46. Batagelj, V.; Zaversnik, M. An $o(m)$ algorithm for cores decomposition of networks. *arXiv* **2003**, arXiv:cs/0310049.
47. Seidman, S.B. Network structure and minimum degree. *Soc. Netw.* **1983**, 5, 269–287. [[CrossRef](#)]
48. Brandes, U. A faster algorithm for betweenness centrality. *J. Math. Sociol.* **2001**, 25, 163–177. [[CrossRef](#)]
49. Newman, M.E.; Girvan, M. Finding and evaluating community structure in networks. *Phys. Rev. E* **2004**, 69, 026113. [[CrossRef](#)]
50. Pearce, D.J. *An Improved Algorithm for Finding the Strongly Connected Components of a Directed Graph*; Victoria University: Wellington, New Zealand, 2005.
51. Newman, M.E. The structure and function of complex networks. *SIAM Rev.* **2003**, 45, 167–256. [[CrossRef](#)]
52. Latora, V.; Marchiori, M. Efficient behavior of small-world networks. *Phys. Rev. Lett.* **2001**, 87, 198701. [[CrossRef](#)] [[PubMed](#)]
53. Saramäki, J.; Kivelä, M.; Onnela, J.P.; Kaski, K.; Kertesz, J. Generalizations of the clustering coefficient to weighted complex networks. *Phys. Rev. E Stat. Nonlinear Soft Matter Phys.* **2007**, 75, 027105. [[CrossRef](#)]
54. Kaiser, M. Mean clustering coefficients: The role of isolated nodes and leafs on clustering measures for small-world networks. *New J. Phys.* **2008**, 10, 083042. [[CrossRef](#)]

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