Assessment of the Resilience of a Complex Network for Crude Oil Transportation on the Maritime Silk Road

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ABSTRACT As one of the most strategically important natural resources, crude oil can be dangerous to transport by sea. The resilience of a maritime transport network denotes the ability of the system to withstand damage and remain operational after disturbances, representing the invulnerability of the network and its ability to recover from harm. In this study, we built a crude oil transportation network titled the Maritime Silk Road using Automatic Identification System (AIS) sensor data, designed a resilience assessment framework based on complex network theory, and assessed the resilience of the maritime crude oil transportation network from both qualitative and quantitative perspectives with the help of complex network metrics and a resilience model. The results show that the topology of the crude oil transportation network has a significant impact on its resilience, in that network density and centrality are negatively related to network resilience, whereas network connectivity and size are positively related to resilience. Subsequently, the resilience of crude oil transportation networks declines at a steady rate under random attacks but declines sharply under intentional attacks. Finally, a comprehensive analysis of invulnerability and recovery in the context of resilience concludes that strengthening small and medium-sized ports in the network is important to enhance network resilience. These results can provide reference and decision support for port planning, route design, optimization, and form a foundation for a more secure and reliable maritime transportation network system.

INDEX TERMS Maritime Silk Road, crude oil transportation network, network resilience, complex network, AIS data.

I. INTRODUCTION

With the increasing trend of globalization, trade relations between countries have become increasingly close, in which maritime transport, the main mode of international trade transportation, is responsible for 90% of the circulation of global trade logistics [1]. Marine transport not only promotes global economic development [2], but also to international political and socio-economic exchanges [3]. At the same time, ports as its transport nodes also play a positive role in the economic development of its hinterland [4].

In international commodity trade, crude oil resources, due to their scarcity, non-renewability, geographical imbalance, and economic importance, make crude oil trade an important way to meet the demand for its consumption in most countries [5]. Marine transportation has become the preferred pathway for international crude oil trade and transportation, due to its low cost and large transport volume advantages [6]. With the continuous development of the shipping industry and the increasing availability of Automatic Identification System (AIS) sensor data [7], there is a critical opportunity to track the activities of tanker vessels and explore the temporal and spatial patterns of tanker vessel transportation. Therefore, the study of crude oil trade and transportation networks based
TABLE 1. Differences between traditional and resilience-based maritime transport safety research.

| Focus                          | Research content                                                                 | Application                                                                 |
|-------------------------------|----------------------------------------------------------------------------------|------------------------------------------------------------------------------|
| Transport node (port)         | Quantifiable analyses of the safety of port infrastructure in the face of risk [12]. | Assessing the safety performance of the port.                                |
| Disruptive incident           | Estimation of economic losses due to port disruptions caused by extreme windstorms [14]. | Evaluating the economic impact of specific disruptive events on the maritime transport system. |
| Policies and regulations      | Analysis of the impact of piracy on the volume of tanker traffic through the Strait of Hormuz [15]. | Analyzing the impact of international economics and politics on the safety of maritime transport. |
| Economic factor               | Implications of ensuring the safety of transport in the Strait of Malacca for the economic development of the littoral States [17]. | Analyzing the weaknesses in the maritime transport system from the perspective of overall interconnectivity and providing recommendations for the relevant operators to plan and respond appropriately. |

The concept of resilience was first applied to the field of ecology [18]. With the continuous development of this idea, its field of application has gradually expanded to other disciplines, such as psychology [19], sociology [20], economics [21], etc. Recent studies have shown that the concept and definition of resilience can also be applied to transmission networks composed of nodes, links, and transmission services connecting them [22]. In the transportation network, resilience is defined as the inherent ability of the network to resist and adapt to adverse conditions, and to recover from the impact of disruptions [23]. In the current literature, except for the work of a few scholars who focus on the resilience characteristics of transport networks, such as air transport [24] and railway transport [25], there is little research on the resilience of maritime transport networks due to data-level limitations. Marine transportation is the most important mode of transportation in international trade, and maintaining its safety and stability is critical to the healthy development of global trade. With the development of high spatial resolution satellite observation technology [26], the Automatic Identification System (AIS) for ships can realize real-time monitoring and recording of tanker navigation status [27]. The speed and accuracy of its data collection compensate for the low spatial and temporal resolution of traditional crude oil trade data. This allows us to study the resilience of complex networks for maritime transportation based on AIS sensor data. In addition, it provides an excellent opportunity to revisit maritime transportation safety (as shown in Table 1). Based on these systems, this study combines tanker AIS trajectory data with complex network theory to study the relationship between the topological characteristics of maritime crude oil transportation networks and network resilience at the microscopic level, creating an opportunity to perform a more detailed on tanker AIS trajectory data has gradually gained considerable interest.

The regions along the Maritime Silk Road are rich in crude oil resources and are among the most active areas in crude oil trade and tanker transportation. Most of the crude oil imports of China come from regions along this path, such as Russia, Saudi Arabia, and Angola, which are rich in crude oil resources [8]. Approximately 70% of global maritime crude oil transportation occurs in this region [9]. Therefore, ensuring the safety of maritime crude oil transportation in the region is significantly important to maintain a stable supply of crude oil in the countries along the route.

However, there are many potential risks in maritime crude oil transportation [2, 10], as this process is easily disturbed by external factors such as natural disasters (typhoons, earthquakes, and tsunamis), terrorist attacks, and port worker strikes. Traditional research on the safety of marine transportation systems has mostly focused on specific destructive events or safety assessment of key transport nodes. Furthermore, most of these studies emphasize the roles of international economics and politics, although these studies involve the safety of ports and sea channels in marine transport, they often cannot accurately and comprehensively reflect the instability of the overall structure of marine transport in the disturbance phase and the recovery phase after the disturbance. Reducing the impact of disturbances impact is difficult in most cases because of the unpredictable and disruptive nature of these events [11]. With invulnerability and recovery as its core components, the resilience analysis framework can evaluate the security of the transportation system from the topological level of the crude oil transportation network. The results of this evaluation not only make up for the lack of overall interconnectivity analysis in traditional maritime transportation safety studies (Table 1), but also play an important role in ensuring the normal operation of the crude oil transportation system along the Maritime Silk Road and reducing uncertainties and potential damage.
and comprehensive safety assessment of maritime crude oil transportation networks.

The rest of this paper is organized as follows: Section II reviews the literature on maritime transport network security and network resilience. Section III introduces a framework for assessing the network resilience of maritime crude oil transport, including the study area and data processing. Section IV explains the results of the assessment, whereas Section V provides a discussion of the assessment results, and Section VI provides concluding remarks on the resilience of the maritime Silk Road crude oil transport network.

II. LITERATURE REVIEW

A. COMPLEX NETWORK-BASED MARITIME TRANSPORT SECURITY

Considering the importance of maritime transport for international trade flows, research on maritime transport security has attracted the attention of scholars. Complex networks can better explain the regularity of maritime transport flows, and with the help of complex network analysis, maritime transport systems can be abstracted into a topology with ports as nodes and maritime navigation links as edges. Scholars have begun to assess the security of maritime transport from the overall perspective of complex networks, such as network robustness [28] and vulnerability [29], [30]. Their study methods mainly focus on analyzing the criticality of maritime network failure due to an attack by comparing changes in complex network metrics such as node degree, clustering coefficient, and average shortest path before and after an attack on ports or critical channels. For example, Peng et al. [28] examined three attack strategies: random attacks, degree-based attacks, and betweenness-based attacks for different structures of the maritime transport network. Their results showed that the bulk transport network is the most robust, while the container transport network is the most vulnerable. Ducruet [29] analyzed network dependence on port and route distributions on the Suez and Panama Canals during container maritime transport, upon removing routes associated with the canal from the transport network, they found that Asia, Europe, and North America are more dependent on the canal than other on other regions. Calatayud et al. [30] constructed multiple complex networks and simulated attacks on seven strategic nodes in the Americas, which show that the vulnerability of international cargo flows to shipping network disruptions depends on the role of the port/state in the liner shipping network.

B. CONCEPTS AND APPLICATIONS OF NETWORK RESILIENCE

In different fields of research, the concept of resilience has different meanings. Hoiling [31] first proposed the concept of resilience in his study of ecosystems, defining it as the ability of a system to maintain its function and keep its state intact while experiencing external disturbances. In engineering, resilience is defined as the ability of a system to resist external oscillations and return to an equilibrium steady state in the event of damage [32]. Several different interpretations of resilience have been discussed in the literature. Nevertheless, there is a general consensus that resilience is characterized by four main features, often referred to as the 4R: robustness, redundancy, resourcefulness, and rapidity [33]. Among them, robustness and redundancy are used to assess and enhance the invulnerability of the network, whereas resourcefulness and rapidity are related to recovery capability.

As the concept of resilience and research methods continue to be refined, an increasing number of scholars are focusing on the application of resilience in transportation networks. For example, Ip and Wang [34] used undirected graphs to represent the transportation network, taking cities as nodes and roads as edges, and built a model to study the resilience of the railway network in mainland China. The results show that the resilience of a network with more dispersed nodes is better than the resilience of a network with more concentrated nodes, but research has mainly focused on calculating the resilience of each node, while ignoring the influence of the overall topology of the network on resilience; Zhang et al. [35] and D’Lima and Medda [36] conducted research on the resilience of Shanghai and London metro networks based on network topology and mean-reverting stochastic models, respectively, which indicated that network resilience not only depends on the importance of interfering nodes, but also on the overall connectivity of the network. Clark et al. [11] and Dunn and Wilkinson [37] focused on the recovery strategy of resilience and conducted a resilience study on airport networks in the United States and Europe based on the attributes and characteristics of the networks, and the results showed that adaptive recovery strategies can significantly improve the resilience of the network.

C. NETWORK RESILIENCE ASSESSMENT TECHNIQUES

Current research on network resilience can be broadly classified into three categories. The first category is an empirical summary of various theoretical perspectives. For example, Reggiani et al. [38] analyzed the role of connectivity in transport resilience; Gu et al. [23] studied the characteristics of reliability, vulnerability and resilience and explained their measurement and application. The second category is the quantitative calculation of resilience, which includes two research methods. One quantifies network resilience through mathematical modeling and simulation. For example, Zhang et al. [39] and Zhang et al. [40] used matrix theory and nonlinear functions to mathematically model network resilience. However, these studies were generally conducted without real-world data, and most of them did not use such data to measure network resilience. The other approach to quantitative research is to use network topology to quantify network resilience using specific data. For example, Dixit et al. [41] evaluated the resilience of a supply chain network based on network structure parameters; Meng et al. [42]
concluded that network topology greatly affects the resilience of the network by studying the topological characteristics of a water supply network. The third category is the qualitative analysis of resilience, which focuses on the conceptual framework and index system of resilience. For example, Vugrin et al. [43] proposed a framework for resilience analysis based on absorptive capacity, adaptive capacity, and recovering capacity; Mattsson and Jenelius [44] divided resilience into dynamic and static resilience.

A thorough review of the literature on maritime transportation safety and network resilience shows that although the research is relatively mature, there are still some limitations. First, although the existing studies on maritime transportation safety based on complex networks comprehensively analyze the instability of maritime networks in the event of disturbances and identify ports and channels that have a larger influence on network stability, they neglect the ability of the network to recover from disturbances. Second, current research on transportation network resilience focuses on quantitative analysis methods, but neglects to evaluate the intrinsic characteristics of networks that affect resilience from a qualitative research perspective. Finally, since maritime transport network traffic data are not easily available, there are only a few studies of network resilience that have been conducted in this context.

AIS records the trajectory of ships, and the generated data contain the port of origin and the port of destination of each ship, which can be represented as O (origin) and D (destination) points in a complex network, where a line between OD (origin-destination) is an edge of the complex network [45]. This provides an excellent opportunity for the study of network resilience.

Therefore, this paper uses AIS sensor data and proposes a resilience assessment framework based on complex network theory, which not only analyzes the inherent ability of marine transportation networks to respond to risks through their topology and operational attributes (i.e., invulnerability), but also assesses the potential actions that can be taken by marine transportation networks after a risk occurs (i.e., resilience). In addition, combining quantitative calculation and qualitative analysis, and focusing on the relationships between network structural characteristics and resilience would aid in comprehensively and systematically evaluating the safety of the Maritime Silk Road crude oil transportation network.

III. METHODOLOGY

A. STUDY AREAS

The Maritime Silk Road has two main routes. One is from China’s coastal ports across the South China Sea through the Taiwan Strait, then through the Strait of Malacca to the Indian Ocean, through the Persian Gulf and the Strait of Hormuz to West Asia, and then to Europe and Africa. The other crosses the South China Sea from China’s seaports and extends to the South Pacific Ocean. The coverage of these routes includes Asia, Africa, Oceania, and Europe. Considering that Asia has the largest area and longest coastline, the study area is divided into seven regions: Northeast Asia, Southeast Asia, South Asia, West Asia, Africa, Oceania, and Europe, as shown in Fig. 1.

B. DATA

Since 2002, AIS has been applied to ships and ports, aiming to avoid collisions between ships by collecting real-time position information [46]. AIS is composed of sensors, GPS locators, and other devices, and the real-time data it generates are mainly divided into static and dynamic data. Static data include basic information about a given ship, such as the Maritime Mobile Service Identity (MMSI) number, ship name, and model. Dynamic data include shipping information such as the ship’s latitude, longitude, heading, speed, and time stamp. The network construction process is as follows. First, the tanker’s transport trajectory information is extracted based on the ship’s MMSI number (Fig. 2a). Subsequently, the crude oil transportation process from port to port is modeled using the timetable information in the AIS data, including departure and arrival information (that is, the OD points of the shipping network) as nodes in the complex network, in which the port information is represented by the port index number (Fig. 2b). Finally, the identified O and D points are connected sequentially as edges in a complex network, where the weight of each edge is represented by the navigation frequency (Fig. 2c).

A port’s basic information and vector data are derived from the World Port Index (WPI), issued and provided publicly by the National Geospatial-Intelligence Agency of the United States. The WPI table includes the port index number, port name, country, longitude and latitude, port type, port size, and other information. We use the port index number to match the data from AIS with port geographic information. Taking the 21st Century Maritime Silk Road study area as the boundary, we extracted a total of 303878 AIS data records and 40188 OD data records, involving 1438 ports and 126 countries and regions. The topology of the constructed Maritime Silk Road crude oil transportation network is shown in Fig. 3.
C. NETWORK RESILIENCE ASSESSMENT METHODS

1) QUANTITATIVE CALCULATION OF RESILIENCE

Based on the complex network constructed using the AIS trajectory data, we referred to the resilience formula proposed by Dixit et al. [41]. In addition, we used the network topology index to calculate the resilience of the crude oil transportation network of the Maritime Silk Road, as shown in (1):

$$ R = \frac{NV \times NS}{ND \times NC} $$

where $R$ represents network resilience, $ND$ represents network density, $NC$ represents network centrality, $NV$ represents network connectivity, and $NS$ represents network size.

Network density ($ND$) is the number of nodes contained in the network per unit distance. If any local damage occurs in the marine transportation network, such as an earthquake or tsunami, higher network density means that more ports and routes will be affected, which adversely affects the resilience of the transportation network. The density of the network is therefore inversely proportional to its resilience, and the formula for $ND$ is shown in (2):

$$ ND = \frac{n}{\text{dis}_{\text{avg}}} $$

where $n$ represents the total number of nodes in the network and $\text{dis}_{\text{avg}}$ represents the average distance per edge, the formula for which is shown in (3):

$$ \text{dis}_{\text{avg}} = \frac{\sum_{i=1}^{M} d_i}{M} $$

where $M$ represents the total number of edges in the network and $d_i$ represents the length of the route $i$ in the network.

Network centrality ($NC$) is defined as the average of the degree centralities of all the nodes in a network and reflects the influence of the nodes in the network. The greater the degree centrality of the port in a maritime network, the more connections the port has with other ports in the network. If a port with a high degree centrality is destroyed, more routes will be affected. Therefore, a higher network centrality reduces the resilience of the network, that is, network centrality is inversely proportional to resilience. The formula for $NC$ is shown in (4):

$$ NC = \frac{\sum_{i=1}^{n} C_D(i)}{n} $$

where $C_D(i)$ represents the degree centrality of the node, which is calculated as shown in (5):

$$ C_D(i) = k_i $$

where $k_i$ represents the degree value of a node. In a complex network, the degree is a basic parameter of the network topology, and the degree of a node is defined as the number of neighbors directly connected to that node; assuming that there is a fixed number of nodes in the network, the degree indicator $k_i$ is calculated as shown in (6):

$$ k_i = \sum_{j=1,j\neq i}^{n} L_{ij} $$

where $L_{ij}$ is the number of edges between node $i$ and node $j$.

Network connectivity ($NV$) is defined as the number of paths in a network from the starting node to the demand node. Adenso-Díaz et al. [47] pointed out that the number of potential transport connections between all nodes is an important factor that affects the resilience of the network. The impact of connectivity on resilience mainly affects the network’s recovery strategy. When the network suffers a shock, a well-connected network can quickly provide alternative paths to recover from the disruption. Therefore, network connectivity is proportional to resilience. The formula for calculating $NV$ is shown in (7):

$$ NV = M_{\text{max}} $$

where $M_{\text{max}}$ represents the maximum number of links that may exist in the network, calculated as shown in (8):

$$ M_{\text{max}} = n \times (n - 1) $$

Network size ($NS$) is determined by the total number of nodes and edges in the network. The larger the network size, the more redundant the network is. This is because of additional nodes and edges to buffer the network in case of disturbances [48]. Therefore, network size is proportional to resilience. The formula for $NS$ is shown in (9):

$$ NS = n + M $$

2) QUALITATIVE ASSESSMENT OF RESILIENCE

In accordance with the literature, we define robustness and redundancy in the resilience profile as invulnerability, that is, the network’s ability to maintain its function in the event of an attack or partial disruption. We define resourcefulness and rapidity in the resilience profile as recovery, that is, the ability of the network to recover to its normal state after being disturbed. Fig. 4 represents the relationship among...
invulnerability, recovery, and resilience by the resilience triangle [33]. It can be found that the network’s invulnerability determines the degree of degradation in network performance under disturbance, and its recovery reflects the recovery efficiency of the network after disturbance. The resilience of the network can be improved by strengthening invulnerability and recovery. The qualitative evaluation results based on the framework of invulnerability and recovery can also be used to explain the results of the quantitative calculations.

\( a: \text{EVALUATION OF NETWORK INVULNERABILITY} \)

According to the research of Gao et al. [49], the invulnerability of a network is related to its heterogeneity. Networks with strong heterogeneity show robustness against random attacks and vulnerability against intentional attacks [50]. In this study, the Gini coefficient [51] is used to measure the degree of network heterogeneity, and the Lorenz curve is used to measure the Gini coefficient, as shown in Fig. 5. First, the nodes \( i \) in the network are arranged in increasing order of their degree values \( k_i \), their order of arrangement is marked as 1, 2, ..., \( n \), and the abscissa is defined as the ratio of the cumulative number of nodes to the number of total nodes, that is, \( i/n \). The ordinate is defined as the ratio of the cumulative node degree to the total degree value, that is, \( \sum_{j=1}^{i} k_j / \sum_{j=1}^{n} k_j \), and the diagonal is defined as the complete homogeneity line, representing the case in which all nodes in the network have the same degree. The Gini coefficient \( H \) is calculated as in (10), assuming that \( y_1 \) represents a perfectly homogeneous line, \( y_2 \) represents the fitting formula of the Lorenz curve, \( S_A \) is calculated as in (11), and \( S_B \) is calculated as in (12).

\[
H = \frac{S_A}{S_A + S_B} \quad (10)
\]

\[
S_A = \int_0^1 y_1 - y_2 \quad (11)
\]

\[
S_B = \int_0^1 y_2 \quad (12)
\]

where \( S_A \) is the area between \( y_1 \) and \( y_2 \), and \( S_B \) is the area between \( y_2 \) and the abscissa.

\( b: \text{EVALUATION OF NETWORK RECOVERY} \)

According to the research of Zhang et al. [52], network resilience is related to the assortativity of the network. A disassortative network structure is relatively scattered, core nodes tend to connect with non-core nodes, and there are likely to be more connections in the network, which affects the network’s recovery. In this study, the Pearson correlation coefficient method is used to quantify the assortativity of the network by calculating the joint probability distribution of
the nodes at both ends of any edge in the network [53]. The formula is as in (13):

\[
r = \frac{M^{-1} \sum_i k_{ui}k_{vi} - \left[ M^{-1} \sum_i \frac{1}{2} (k_{ui} + k_{vi}) \right]^2}{M^{-1} \sum_i \frac{1}{2} (k_{ui}^2 + k_{vi}^2) - \left[ M^{-1} \sum_i \frac{1}{2} (k_{ui} + k_{vi}) \right]^2}
\] (13)

where \( r \) is the degree correlation coefficient and \( k_{ui} \) and \( k_{vi} \) are the degrees of the nodes at both ends of either edge in the network. The range of the value of \( r \) is \([-1, 1]\). When \( r > 0 \), node degree is positively correlated and the network is considered assortative, and high (low) degree nodes in the network tend to connect with high (low) degree nodes, indicating that the network is relatively closed. When \( r = 0 \), there is no correlation in the network; when \( r < 0 \), node degree is negatively correlated, indicating a disassortative network, and high (low) degree nodes in the network tend to connect with low (high) degree nodes, indicating that the network is relatively scattered.

IV. RESULTS
A. QUANTITATIVE CALCULATION OF RESILIENCE BASED ON NETWORK TOPOLOGY

The quantitative resilience results obtained based on the network topology index are shown in Table 2. Using the quantitative network resilience evaluation system proposed by Dixit et al. [41], this result has a large value, which shows that the Maritime Silk Road crude oil transportation network is comparatively resilient.

1) COMPLEX NETWORK CHARACTERISTICS

As shown in Table 2, the density of the Maritime Silk Road crude oil transportation network is relatively high. The average length of each route in the network is 2007 km, and the number of ports per unit distance is 0.7. The reason for the higher network density is that there are many routes in the network with similar distances. According to statistics, the number of shorter routes than the average routes accounts for 67.8% of the total routes. The route distribution is shown in Fig. 6 (a). The largest number of routes have lengths within 100 km, totaling 3535 routes. Short-distance routes mostly exist within a single country (that is, are not international), and there may be two reasons for this: one is that crude oil is transshipped domestically, and the other is that tankers call at one port and then sail to a neighboring destination port. The highest density of short-distance routes is found in Northeast Asia and Europe. Long-distance routes mainly appear between Northeast Asia and Europe, Southeast Asia and West Asia, Oceania and Europe, and South Africa and Europe. The route distribution is shown in Fig. 6 (b). When there are a large number of routes between ports in close proximity, small-scale disturbances can affect a larger number of routes and adversely affect the resilience of the network.

Ports with a greater degree of centrality in the marine transportation network have a greater impact on network centrality. Table 3 shows the top 20 ports by the degree of centrality. From the results of the centrality calculation, it can be seen that the Jurong Island Port, Keppel Port, Pulau Bukom Port, Serangoon Port, and Pulau Sebarok Port in Singapore have greater port centrality values, indicating that the ports of Singapore have a comparatively large number of routes in the entire Maritime Silk Road crude oil transportation network and possess many network connection resources. In addition to the ports of Singapore, the ports of the United Arab Emirates (UAE), the Netherlands, Belgium, Spain, China, and Japan are central to the network. These ports are typical of regions with major maritime traffic areas,
TABLE 3. Degree centrality ranking.

| Rank | Degree centrality | Port          | Country       | Rank | Degree centrality | Port          | Country       |
|------|-------------------|---------------|---------------|------|-------------------|---------------|---------------|
| 1    | 592               | Jurong Island | Singapore     | 11   | 378               | Göteborg      | Sweden        |
| 2    | 524               | Keppel        | Singapore     | 12   | 366               | Serangoon     | Singapore     |
| 3    | 489               | Eurooort      | Netherlands   | 13   | 365               | Ulsan         | South Korea   |
| 4    | 469               | Antwerpden    | Belgium       | 14   | 357               | Europa        | Gibraltar     |
| 5    | 452               | Maassluis     | Netherlands   | 15   | 354               | Zaandam       | Netherlands   |
| 6    | 425               | Khawr Fakkan  | United Arab Emirates | 16   | 352               | Pulau Sebarok | Singapore     |
| 7    | 406               | Algeciras     | Spain         | 17   | 337               | Vlaardingen   | Netherlands   |
| 8    | 401               | Pulau Bukom   | Singapore     | 18   | 329               | ZhouShan      | China         |
| 9    | 397               | Chiba         | Japan         | 19   | 325               | Marsaxlokk    | Malta         |
| 10   | 391               | Fujairah      | United Arab Emirates | 20   | 324               | Hoek Van Holland | Netherlands |

Network connectivity and network size are related to the numbers of nodes and edges in the network. From the perspective of port distribution, as shown in Fig. 1, European ports are the most densely distributed, with a total of 662 ports, accounting for 46% of the total number of ports in the region, followed by Northeast Asia, which has a higher number of ports. There are fewer ports in West Asia, the Mediterranean coast, and the Gulf of Guinea, which are rich in crude oil resources. From the perspective of network connectivity, the greater the number of nodes in the network, the greater the number of potential connections. An analysis of the existing route distribution is shown in Fig. 7. In addition to the higher number of routes within the same region, the numbers of routes between Europe and West Asia and between West Asia and Africa are comparatively large, with 1080 and 1093 routes, respectively. Northeast Asia has more routes to Southeast and West Asia, with 801 and 424 routes, respectively. South Asia, which is located at the choke point of the Maritime Silk Road, has the geographical advantage of connecting Northeast Asia, Southeast Asia, and West Asia, as well as Africa and Europe. However, due to the relatively small number of ports in the region and inconsistency in ports’ levels of modernization, there are relatively fewer routes between South Asia and other regions.

2) NETWORK CHANGES UNDER DIFFERENT ATTACK STRATEGIES

To further explore the resilience of the Maritime Silk Road crude oil transportation network, we simulate random and intentional attacks to observe the changes in the network topology and the impact of these attacks on resilience. A random attack randomly removes nodes from the network, which can simulate the impact of random events such as typhoons, tsunamis, and earthquakes on the Maritime Silk Road crude oil transportation network. An intentional attack removes nodes in descending order of degree centrality, simulating a targeted attack on the nodes in the network. This type of attack can simulate the impact of intentional events, such as terrorist attacks or military blockades on the Maritime Silk Road crude oil transportation network. Experiments are carried out for different attack strategies conducting continuous simulated attacks on the network. Each time a node in the network and its edges are deleted (the nodes with the largest degree centrality in the current network need to be recalculated in case of intentional attack). In addition, the ND (network density), NC (network centrality), NV (network connectivity), and NS (network size) of the network are recalculated. The cycle continues until all nodes in the network are deleted or become isolated nodes, that is, the network fails completely.

The X-axis in Fig. 8 and Fig. 9 represents the attack ratio, that is, the ratio of the number of nodes attacked in the network to the number of original network nodes; the Y-axis in
Fig. 8 represents the current network structure characteristic metrics: network density, network centrality, network connectivity, and network size; and the Y-axis in Fig. 9 represents the current network resilience value.

Fig. 8 shows the changes in the topology of the Maritime Silk Road crude oil transportation network under different attack modes. Under the random pattern attack, the network topology index shows a slow and continuous decline as the attack ratio increases. It can be seen that the network topology changes caused by intentional attacks based on node degree are significantly different from those caused by random attacks. During intentional attacks, the network density first increases and then decreases, mainly because ports with higher degrees control most of the routes in the network. After these ports are removed, the total length of routes in the network decreases sharply, corresponding to a sharp decline in the average distance of routes, causing network density to increase. Then, as the number of ports removed increases, the total numbers of nodes and edges decrease sharply. Thus, network density shows a downward trend. The value of
The closer the Gini coefficient is to zero, the more even the classification of intervals: (0,0.2), (0.2,0.3), (0.3,0.4), (0.4,0.5), and (0.5,1). According to the regulations of the United Nations Development Programme (UNDP), the Gini coefficient is divided into five categories. The Gini coefficient of the network is 0.6124. According to (13), the degree correlation coefficient of the Maritime Silk Road crude oil transportation network is -0.074, indicating that it is a disassortative network. It shows that the network is scale-free, that is, nodes with a larger degree value occupy a smaller proportion of the network, and nodes with a smaller degree value occupy a larger proportion.

With the help of Bradford’s law [54], we divide the ports of the Maritime Silk Road crude oil transportation network into a core layer, semi-core layer, and non-core layer. The number of ports with smaller degree values being affected during random attacks, and the failure of these nodes will not have a significant impact on the topology of the network. Therefore, in the face of random attacks, the network has strong invulnerability, and the network resilience value maintains a relatively stable rate of change. The core ports, which account for a very small proportion of the network, play a vital role in maintaining the connectivity of the entire network. Therefore, in the face of intentional attacks, the ability of the network to resist attacks is poor, and the network resilience value decreases sharply.

From the perspective of redundancy of resilience features, the number of edge ports in the network is large and widely distributed; these ports can not only share parts of the routes of the core ports, but also increase random access to the network. This mode of port distribution improves the redundancy of transportation to some extent, and the heterogeneous network has strong fault tolerance in the face of disturbances [55], which improves the stability of network resilience.

The resilience of the Maritime Silk Road crude oil transportation network is analyzed from the point of view of network recovery. According to (13), the degree correlation coefficient of the Maritime Silk Road crude oil transportation network is -0.074, indicating that it is a disassortative network. The connections between the core and non-core ports in the network are relatively close, trade flows can be diffused through many connections between the core and periphery, and maritime transportation is more substitutable, which also explains why most real-world transportation networks are disassortative networks [53]. After a disassortative network is disturbed, it can repair and rebuild efficiently using available resources, showing strong recovery.

**TABLE 4. Port layer classification.**

| Layer            | Port degree value | No. of ports | Percentage |
|------------------|------------------|--------------|------------|
| Core layer       | 187-592          | 100          | 6.95%      |
| Semi-core layer  | 83-186           | 217          | 15.09%     |
| Non-core layer   | 1-82             | 1121         | 77.96%     |

**FIGURE 10. Port degree distribution (source: authors’ elaboration).**

The resilience of the Maritime Silk Road crude oil transportation network is analyzed from the point of view of network invulnerability. As calculated by equations (10)– (12), the Gini coefficient of the network is 0.6124. According to the regulations of the United Nations Development Programme (UNDP), the Gini coefficient is divided into five intervals: (0.0,2), (0.2,0.3), (0.3,0.4), (0.4,0.5), and (0.5,1); the closer the Gini coefficient is to zero, the more even the distribution. In this maritime transportation network, the value of the Gini coefficient is located in the highest interval, which indicates the strong heterogeneity of the Maritime Silk Road crude oil transportation network, showing that the degree distribution of nodes in the network is very unbalanced. The degree distribution of the ports is shown in Fig. 10. It shows that the network is scale-free, that is, nodes with a larger degree value occupy a smaller proportion of the network, and nodes with a smaller degree value occupy a larger proportion.

With the help of Bradford’s law [54], we divide the ports of the Maritime Silk Road crude oil transportation network into a core layer, semi-core layer, and non-core layer. The number of ports contained in each structure level is the same, and the hierarchical classification of ports is shown in Table 4. Networks with strong heterogeneity have a higher probability of nodes with smaller degree values being affected during random attacks, and the failure of these nodes will not have a significant impact on the topology of the network. Therefore, in the face of random attacks, the network has strong invulnerability, and the network resilience value maintains a relatively stable rate of change. The core ports, which account for a very small proportion of the network, play a vital role in maintaining the connectivity of the entire network. Therefore, in the face of intentional attacks, the ability of the network to resist attacks is poor, and the network resilience value decreases sharply.

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We use the repetition rate of routes between different levels of ports to analyze the network recovery specifically. The route distribution of core ports, semi-core ports, and non-core ports in the region is shown in Fig. 11. The numbers of routes originating from core, semi-core, and non-core ports are 13082, 13364, and 13743, respectively, among which the repetition rates of routes whose departure ports are a) semi-core ports or non-core ports and b) core ports are 87.32% and 83.71%, respectively. The numbers of routes destined for core ports, semi-core ports, and non-core ports are 13,593, 13,512, and 13,083, respectively, among which the repetition rates of routes whose destination ports are a) semi-core ports or non-core ports and b) core ports are 88.13% and 73.78%, respectively. These results show that although core ports control more contact resources in the network, the numbers of semi-core ports and non-core ports in the network are large, with strong agglomeration and a high route repetition rate with the core ports. If any core port in the region fails, the surrounding ports can become alternative ports to resume transportation, that is, the network has strong resourcefulness and rapidity, enhancing the resilience of the Maritime Silk Road crude oil transportation network.

In summary, core ports play an important role in maintaining the stability and connectivity of tanker transportation. Semi-core and non-core ports located along the coastline play also an important role in the resilience of the maritime network and restoration of normal functioning after a disturbance. Much of the previous research has focused on the status of core ports in network robustness and vulnerability, while neglecting the important role of edge ports in enhancing network resilience. Edge ports can not only share the risks of the tanker transportation system, but also take part in route transportation when the core ports are disturbed, allowing the network to recover quickly from the impact of a disruption and maintain the normal functioning of the tanker transport system.

V. DISCUSSION

A. THE SIGNIFICANCE OF THIS STUDY

The resilience of the Maritime Silk Road crude oil transportation network is greatly influenced by the topological characteristics of the network, which are closely related to the transport of crude oil by sea. Maritime crude oil trade is dependent on the structure of supply and demand, and any change in the pattern of global crude oil consumption directly affects the mode of tanker transportation. As port conditions in many importing countries cannot meet the requirements of ultra large crude carriers (ULCC) for docking, crude oil is first transported to transshipment hub ports by large vessels, which is then transported by small vessels to the destination ports [56]. This mode of transportation has led to the existence of more short-distance shipping routes for the major oil-consuming countries in Europe, northeast Asia, and other regions, as well as to the transshipment hub ports located in important corridors or strait regions that have a high degree of centrality. Examples include the port of Jurong Island, located at the southern tip of the Malay Peninsula and the entrance to the Strait of Malacca, and the port of Europa, located in the southernmost part of Spain and near the Strait of Gibraltar.

However, higher network density and higher degree value concentrations can negatively affect network resilience.
A higher network density causes local disturbances to affect more ports and routes, but the regions with this problem tend to be those with more developed hinterland economies and higher demand for crude oil. In view of the problem that there are too many routes between adjacent ports in this area, we can develop multimodal transport modes to share part of the sea transportation pressure, such as crude oil pipeline transportation and railway transportation. For certain European regions, we can also strengthen inland river shipping. According to Eurostat, as of the end of 2017, the total mileage of inland river shipping (including natural rivers and artificial canals) in the Netherlands alone was as high as 6257 km, of which 47% could carry 1000-ton vessels. Therefore, the developed inland river shipping also guarantees the security of crude oil transportation in Europe.

The high network centrality is due to the relatively small number of ports with transshipment hub status, resulting in a small number of ports holding the majority of transportation resources. Singapore’s Jurong Island Port, Keppel Port, Pulau Bukom, Serangoon, and Pulau Sebarok ports alone hold 112823 routes, accounting for 37.12% of the total. The failure of these ports would not only cause great damage to network resilience, but also accelerate the collapse of the network. Therefore, crude oil transshipment hub ports remain the key to enhancing the resilience of the maritime crude oil transportation network. For ports located in strategic areas, such as the Colombo port in Sri Lanka and Gwadar Port in Pakistan [57], port infrastructure and deep-water terminals should be strengthened to increase the number of specialized berths for tankers. This approach would not only improve the efficiency of port operation and services, but also weaken the resource concentration of some ports and expand the number of affiliated routes of small and medium-sized ports, which would help optimize the resilience of the Maritime Silk Road crude oil transportation network.

From the results of the study, we find that the number of hub ports is low in some major crude oil-exporting countries, such as Saudi Arabia and Iran in West Asia and Libya and Nigeria in Africa. The number of shipping routes directly connected to other regions in these areas is also small. The ports and shipping routes in the study area are mainly concentrated in Europe, Northeast Asia, and Southeast Asia, where surplus ports and connections can play a buffer role when ports are disturbed. For example, the 2011 earthquake in Japan led to the closure of ports such as Sendai and Ofunato in northeastern Japan. These small and medium-sized ports did not cause widespread paralysis in Japan’s shipping industry because Tokyo, Yokohama, Chiba, and other large ports were still in normal operation. Therefore, the ports of crude oil-exporting countries are a bottleneck for increasing the resilience of the maritime crude oil transportation network. Promoting the construction of ports in crude oil-exporting countries and expanding regional route connections could improve network connectivity and expand network scale, thereby continuously enhancing regional resilience and the flexibility of the Maritime Silk Road crude oil transportation network.

The introduction of the Maritime Silk Road policy injected new vitality into the development of regional maritime transportation. First, the number of ports in the region is increasing each year; for example, China has built five major ports in the Indian Ocean to help stabilize crude oil transportation on the Maritime Silk Road. Second, the Chinese government is continuously increasing its investment in small and medium-sized ports. For example, the port of Piraeus in Greece, located on the Mediterranean coast, has gone from decline to revival after joining the One Belt and One Road, and has gradually developed into an important hub port in the Mediterranean. Third, the number of new routes in the region is increasing. For example, in 2018, Qingdao Port opened a direct route to the Piraeus Port, promoting trade communication between Northeast Asia and Europe. It can be seen that the proposal of the 21st Century Maritime Silk Road policy has promoted the development of ports along the route. In addition, it enhanced the resilience of the marine transportation network and ensured the safety and stability of maritime crude oil transportation in the region.

B. THE LIMITATIONS OF THIS STUDY

Although we have analyzed the resilience characteristics from multiple network perspectives, there are still some limitations:

(1) In terms of feasibility, we only analyzed the role of non-core ports in network recovery in terms of route repetition rate, without considering the limitations of non-core ports themselves, such as water conditions, throughput, and the number of specialized berths, which will affect the number of routes that can be shared by non-core ports specifically.

(2) In terms of data, all studies in this paper are based on ship AIS data, which reflects the trade situation of crude oil transportation network through the number of shipping between ports. Its limitations cannot accurately determine the transshipment, distribution, or refilling of crude oil.

(3) In this paper, we only consider the static maritime transport network resilience, but in reality, maritime crude oil transportation faces complex and variable security challenges, which are not only constrained by the network structure, but also greatly influenced by the traffic flow, transportation cost, time consuming, climate and other factors in the port [2].

VI. CONCLUSION

This study built a Maritime Silk Road crude oil transportation network based on complex network theory and combined with tanker AIS trajectory data. Network resilience was evaluated quantitatively and qualitatively with the help of network topological features, the Gini coefficient, and the Pearson correlation coefficient to comprehensively analyze the safety of crude oil transportation networks. Our conclusions are as follows.
First, the resilience of the Maritime Silk Road crude oil transportation network is affected by the combinations of density, centrality, connectivity, and network size. Among them, density and centrality are negatively correlated with resilience, whereas connectivity and size are positively correlated with resilience. The resilience of the crude oil transportation network can be enhanced by decreasing the network density, reducing the concentration of network degree values, improving network connectivity, and increasing network size.

Second, the Maritime Silk Road crude oil transportation network can maintain relatively stable resilience in the face of random attacks, whereas intentional attacks have a greater impact on the resilience of the network. To further enhance the stability of the transportation network in the face of intentional attacks, the construction of port clusters in key regions (oil-producing areas and major maritime transportation routes) with hub ports as the core should be strengthened to gradually form a multi-hub port system, improve the competitiveness of regional ports, and weaken the resource concentration of some ports.

Finally, the heterogeneous characteristics of the Maritime Silk Road crude oil transportation network indicate that the network has good fault tolerance and redundancy. The dis-assortative characteristics of the network indicate that the network can effectively restore transportation functions after disturbances by rearranging and establishing new connections. Ports along the Maritime Silk Road can take advantage of policies that further broaden inter-port shipping links, improve network recovery, and enhance network resilience to ensure the safety and stability of crude oil transportation.

This study has a number of limitations that could be further investigated as part of future research, including the following: (1) a comprehensive consideration of the transport capacity of non-core ports and a quantitative analysis of the specific route share of non-core ports when they are disturbed; (2) further assessment of the resilience of the maritime crude oil transport network in relation to data such as ship load, port throughput, and crude oil trade volume; (3) discuss the resilience of the maritime crude oil transport network further in terms of the time dimension, such as the time required for the network to recover from a disturbed state to a stable equilibrium state; (4) an analysis of the impact of geopolitical policies on maritime transport dynamics and network resilience in relation to international treaties or initiatives (e.g. “the Polar Silk Road”).

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