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Spatial pattern of global submarine cable network and identification of strategic pivot and strategic channel

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Abstract: As a kind of large-scale connectivity infrastructure, submarine cables play a vital role in international telecommunication, socio-economic development and national defense security. However, the current understanding about the spatial pattern of global submarine cable network is relatively limited. In this article, we analyze the spatial distribution and connectivity pattern of global submarine cables, and identify their strategic pivots and strategic channels. The main conclusions are as follows: (1) The spatial distribution of global submarine cables is significantly unbalanced, which is characterized by the facts that the distribution of submarine cable lines is similar to that of sea lanes, and the agglomerations of landing stations are distributed unevenly along the coastline. (2) The connectivity pattern of global submarine cable network has a significant scale effect. At the micro, meso and macro scales, the connectivity structure presents chain model, cluster model and hub-and-spoke model, respectively. (3) The distribution of strategic pivots and strategic channels shows a pyramidal hierarchical feature. Singapore ranks highest among all the strategic pivots, while the Gulf of Aden and the Strait of Malacca rank highest among the strategic channels. Based on the identification of strategic pivots and channels, six strategic regions have been divided, which face various network security risks and need special attention and vigilance.

Keywords: submarine cable network; spatial pattern; strategic pivot; strategic channel; global scale

1 Introduction

Historically, the global submarine cable network originated in the mid-19th century. In 1851, the French telegraph company Anglo developed a telegraph cable crossing the English Channel, which opened the prelude to global submarine communication. Since Bell invented the telephone in 1876, the submarine cable served the function of voice communication ex-

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cept Morse telegraph code. International communication entered a new era following the advent of optical fiber communication technology in the 1960s and the completion of the first global transoceanic submarine optical cable system (TAT-8) in 1988. Since the 21st century, submarine cables have formed a crisscross global network, carrying over 80% of global communication traffic and 99% of intercontinental communication services (Nakamoto *et al*., 2009). Submarine cables have many advantages, such as large capacity, high communication quality and low cost. In addition to completely replacing the conventional coaxial cable, submarine cables also swiftly replaced the satellite, and occupied an absolute dominant position in the underlying means of correspondence in cyberspace.

Modern society is deeply integrated with cyberspace. In such a background, the strategic position of submarine cable is not only reflected in carrying international communication data, but also infiltrates various fields of national security issues, such as network security, financial security and national defense security. For example, in 2008, two submarine cables near Alexandria, Egypt, were cut off in many places by unidentified persons, affecting 76% of the data exchange business in Europe, the Middle East, North Africa and India. In 2014, Russia repeatedly damaged its submarine cable system facilities to impose sanctions on Ukraine, which resulted in the breakdown of communication services in relevant areas, becoming “information islands”. Thus, it is urgent to make a comprehensive and scientific judgment on the spatial pattern of the global submarine cable network to ensure the global information network security and provide support for the timely optimization of national development strategies.

At present, scholars have conducted a series of studies on the evolution and development (Ye, 2006; Malecki and Wei, 2009), spatial layout (Edwards *et al*., 2009; Kathryn, 2021), impact mechanism (Starosielski, 2015; Saunavaara and Salminen, 2020), network security (Xie and Wang, 2021; Zhang *et al*., 2021), geopolitics (Headrick, 1991; Headrick and Griset, 2001; Liu, 2019), and other aspects of submarine cables. For instance, Kathryn (2021) and Saunavaara & Salminen (2020) discussed the unbalanced structure underlying the global submarine cable network from different perspectives. The former infers that the global submarine cable network structure has “semi-centralized” characteristics, while the latter believes that the current spatial pattern of global submarine cable network is highly centralized, and most submarine cable systems utilize a few fixed offshore connection lines and land in a few areas. Rauscher (2010) highlighted that this inevitable high concentration will bring great risks to the global submarine cable network, that is, the intersection of a large number of submarine cable systems guards global information and ensures communication security.

However, the above studies are limited to simple descriptive analysis or empirical judgment, and lack empirical analysis. Based on the literature related to the backbone network structure of the national Internet (Mitchell and Anthony, 2000; Townsend, 2001), Malecki (2002) first explored the global submarine cable network structure in terms of different indicators, such as landing stations, submarine cable lines and bandwidth. However, Malecki’s research focused on the evolution process of submarine cable network and ignored its spatial pattern in depth. Based on the robustness analysis of the global submarine cable network, Zhang *et al*. (2022) concluded that the international voice of information transmission security is held by a few hub countries. However, Zhang’s research is limited to the national level, and the screening of strategic pivot still needs to rely on highly sophisticated research scales.

In addition, in the fields of transport geography and information geography, scholars have also presented some discussions on submarine cable network. On the one hand, Rodrigue (2020) believes that submarine cable, as an important carrier for information transmission between different regions, is a novel type of transportation content in the post Fordism era. Accordingly, submarine cables should be classified under the research category of transportation geography, and it should also be a new field of the development of transport geography. In fact, research on road (Joe, 2012; 2017), railway (Jiao *et al.*, 2017; Xu *et al.*, 2018; Hu *et al.*, 2019), shipping (Viljoen and Joubert, 2016; Guo *et al.*, 2017), pipeline (Chedida and Kobroslya, 2007; Tavana *et al.*, 2012) and other transportation networks is relatively mature, and the national telecommunications backbone network has also received the attention of transport geographers (Grubesic *et al.*, 2003; Murray *et al.*, 2007; Kim, 2012). Despite existing studies, the quantitative analysis of submarine cable network is still very limited.

On the other hand, research in the field of information geography attaches great significance to Internet infrastructure. When Castells (1996) proposed the concept of "space of flows", he regarded the infrastructure integrating the global electronic communication network as the core of the "space of flows". Since then, Bakis and Lu (2000) put forward the concepts of information port and information advantage area to emphasize the new form of geographical space based on global network services. Sun *et al.* (2009, 2011) explored the spatial pattern of the global Internet information flow and believed that the Internet geography research based on the external level is the fundamental method to reveal the overall picture of information and communication geography. However, these studies have not focused on the spatial pattern of infrastructure itself.

In summary, currently there is limited literature on the spatial pattern of the global submarine cable network, and the existing studies are limited to qualitative description or national scale. Although the achievements in the field of transport geography and information geography can provide horizontal reference, the empirical research on submarine cable network still needs to be supplemented. In view of this, this study considers the global submarine cable as the research object. First, the distribution pattern of landing stations and submarine cables are described. Second, the global submarine cable network is constructed and the multi-scale connectivity pattern is analyzed. Finally, the strategic pivot and strategic channel are identified by using complex network indicators.

Based on the systematic analysis of the global submarine cable network from a geographical perspective, this paper will help to enrich the research content of transport geography, reveal the underlying structure in the research of information and communication geography, and provide a scientific basis for a country to formulate an information network security strategy and optimize the layout of submarine cable network.

2 Data and methodology

2.1 Data processing

2.1.1 Construction of global submarine cable network

Submarine cable network is a type of facility network, which is similar to the traditional transportation facility networks, such as railway, highway and pipeline networks. In the research process, the key facility nodes and channels should be emphasized. Therefore, the construction of a submarine cable network is the core content of this study, as illustrated in Figure 1.

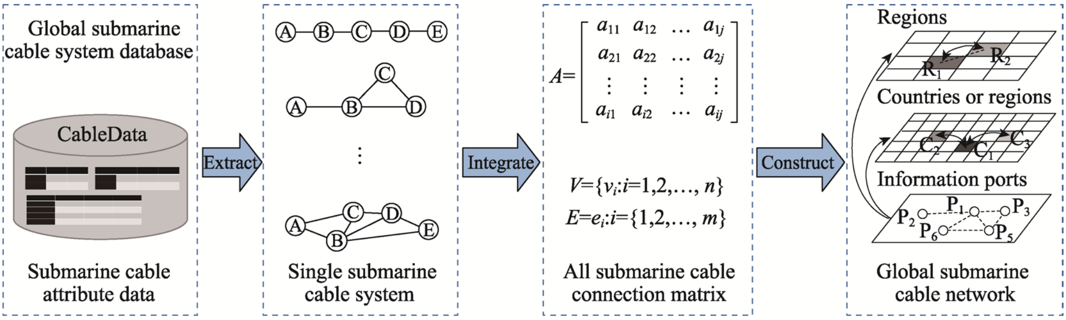


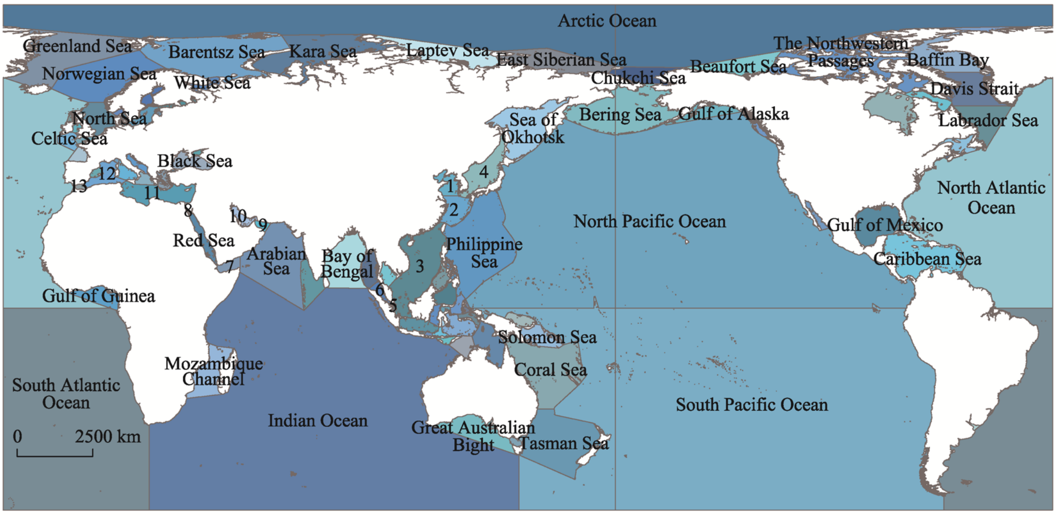
Figure 1 Construction framework of global submarine cable network

The first step is to develop a global submarine cable system database. The data of this study was sourced from TeleGeography company, including name, capacity, length, landing station, completion date and other attributes. All those that were completed before the end of 2020 and currently in service, were considered as the screening criteria. In total, 469 submarine cable systems were finally selected as the research samples of this study. The second step is to extract a single submarine cable system. Since each submarine cable system can be regarded as a network, it is crucial to extract every single submarine cable system (ⒶⒷⒸ indicate the landing station of the submarine cable system), particularly since the connection between submarine cable systems is realized through the same landing node. The third step involves integrating all single submarine cable systems and building all submarine cable connection matrix (A). Finally, the global submarine cable network is constructed based on the needs of different scales. Here, E represents the edge in the network, V represents the node in the network. In the micro, meso and macro scales, the nodes are information ports (P), countries or regions (C) and regions (R), respectively.

It is worth mentioning that the submarine cable network is a type of large connectivity infrastructure network, with the landing station as the portal and the country as the service unit. However, the distribution of landing stations is extremely close and complex, which causes great difficulties in network analysis. For instance, some cities or smaller administrative units may have multiple landing stations. This study draws on the concept of "information port", and integrates some complex landing stations into an information port to facilitate statistics and analysis. All the simplified schemes are implemented in the same sea area and do not affect the results of other analyses. Ultimately, 350 information ports were integrated as the minimum node for network analysis. The naming of these information ports primarily refers to the name of the cities and the name of the national sub-administrative units, and comprehensively considers the country or area names of island units, small area units and complex units.

2.1.2 Division of global marine areas

Submarine cables are laid on the seabed. It is necessary to divide the global sea areas to depict the spatial pattern of cables in the global marine areas and accurately identify the importance and strategic position of specific marine areas in the global submarine cable network. In this study, referring to the International Hydrographic Organisation (IHO) and considering the route and marine geography involved in the laying of submarine cables, we divided several marine areas or marine channels, as illustrated in Figure 2.



1. Yellow Sea 2. East China Sea 3. South China Sea 4. Japan Sea 5. Singapore Strait 6. Strait of Malacca 7. Gulf of Aden 8. Gulf of Suez 9. Gulf of Oman 10. Persian Gulf 11. Mediterranean Sea-Eestern Basin 12. Mediterranean Sea-Western Basin 13. Strait of Gibraltar

Figure 2 Division of global marine areas

2.1.3 Division of global land areas

Although the landing stations of submarine cable are set up on the coastal land, the network serves an entire country or region. The land needs to be divided into larger areas to analyze from a macro scale. Considering the five continents as the regional division framework is too rough, and it is easy to overlook the internal differences of each continent. Therefore, based on the macro geographical regions and geographical sub-regions (United Nations geographical zoning list), considering the integrity of the region, and referring to the division basis of SIS international research, this study divides the countries and regions of the world into 12 regions, namely East Asia, North America, Europe, North Africa, South America, Oceania, Central America, North Asia, Caribbean islands, sub-Saharan Africa, West and Central Asia, South and Southeast Asia.

2.2 Methods

2.2.1 Connectivity analysis

Connectivity is a critical indicator for transportation network evaluation. The connectivity evaluation of submarine cable network effectively reflects the connectivity pattern of information network. The number and capacity of submarine cable connections between nodes form the main basis to reflect the connectivity. Accordingly, the connectivity calculation model of submarine cable network is constructed.

$$c_{ij} = \sum \alpha \ln Capacity_{ij} \tag{1}$$

$$C_i = \sum_{i=1}^{n-1} c_{ij} \tag{2}$$

where c_{ij} denotes the connectivity between any two nodes, C_i indicates the connectivity index of node i and $Capacity_{ij}$ represents the capacity of the submarine cable system between node i and j, α denotes the growth coefficient, which is set as α=6.2.

2.2.2 Identification of strategic pivot

The centrality index of complex network can effectively reflect the significance of nodes in the network. Degree Centrality, Closeness Centrality and Betweeness Centrality can respectively reflect the direct accessibility, relative accessibility, transit and routing functions of nodes in the global submarine cable network. However, these three centralities only reflect the significance of nodes from a singular perspective and are not comprehensive. Therefore, this paper synthesizes three types of centrality characteristics, and uses the System Centrality method to identify the strategic pivot of the global submarine cable network. The formula is as follows:

$$SC = (0.5 \times DC + 0.5 \times CC) \times (1 + BC) \tag{3}$$

$$DC_i = k_i / (n-1) \tag{4}$$

$$CC_i = \left[\sum_{j=1, j \neq i}^{n} l_{ij} / (n-1) \right]^{-1} \tag{5}$$

$$BC_i = \frac{2}{n^2 - 3n + 2} \sum\nolimits_{p=1, q \neq i}^{n} \sum\nolimits_{q \neq i}^{n} \frac{\delta_{qp}^{i}}{\delta_{pq}} \tag{6}$$

where SC denotes System Centrality; DC, CC and BC represent Degree Centrality, Closeness Centrality and Betweeness Centrality, respectively; k_i indicates the degree value of node i; n signifies the number of all nodes in the network; l_{ij} represents the number of edges of the shortest path of node i and node j; δ_{pq} indicates the total number of shortest paths from node p to node q (l_{pq}) and δ_{pq}^{i} denotes the number of paths through node i.

2.2.3 Identification of strategic channel

The importance of each sea area can be effectively tested by simulating the changes of the submarine cable network when the seas are blocked. Specifically, in the simulation process, each sea area is attacked separately. During the attack, the submarine cable lines passing through the sea area are broken and the isolated nodes are removed to form a new global submarine cable network under attack. Based on this, the eigenvalues of the network are calculated and compared with the eigenvalues of the network under normal conditions to identify the importance of each sea area and select the strategic channel.

In this study, four mainstream complex network indicators selected to quantify the changes in eigenvalues of the global submarine cable network before and after simulation, namely the average path length L, network efficiency E, average degree D and the proportion of isolated nodes ΔN. The calculation formulae are as follows:

$$L = \frac{2}{n(n-1)} \sum_{i>j} l_{ij} \tag{7}$$

$$E = \frac{1}{N(N-1)} \sum\nolimits_{i=1}^{N} \sum\nolimits_{j=1}^{N} 1/d_{ij}\,,\ i \neq j \tag{8}$$

$$D = \frac{1}{N} \sum\nolimits_{i=1}^{N} D_i \tag{9}$$

$$\Delta N = \left(1 - \frac{N'}{N}\right) \times 100\% \tag{10}$$

where N and N' represent the total number of nodes before and after network fracture.

3 Results

3.1 Distribution pattern of global submarine cable network

3.1.1 Spatial distribution of landing stations

The PointDensity tool was utilized to explore the spatial distribution characteristics of global submarine cable landing stations, as shown in Figure 3. Overall, the distribution of global landing stations is significantly unbalanced, which is reflected not only in the dual relationship between coastal and inland areas, but also in coastal areas with different geographical conditions. Specifically, northwest Europe, the Persian Gulf, the Malay islands, the North-Eastern United States and the Caribbean islands are the most densely distributed areas of submarine cable landing stations, forming several cluster areas in space. The southeast coast of China, the Mediterranean coast, the west coast of North America, the coast of the African continent and the coast of the South American continent are sub-dense areas, and the submarine cable landing stations are distributed in strips along these areas. The density along the coasts of Africa, Oceania and South America are low, and the distribution of landing stations in the southern hemisphere is significantly less than that in the northern hemi-

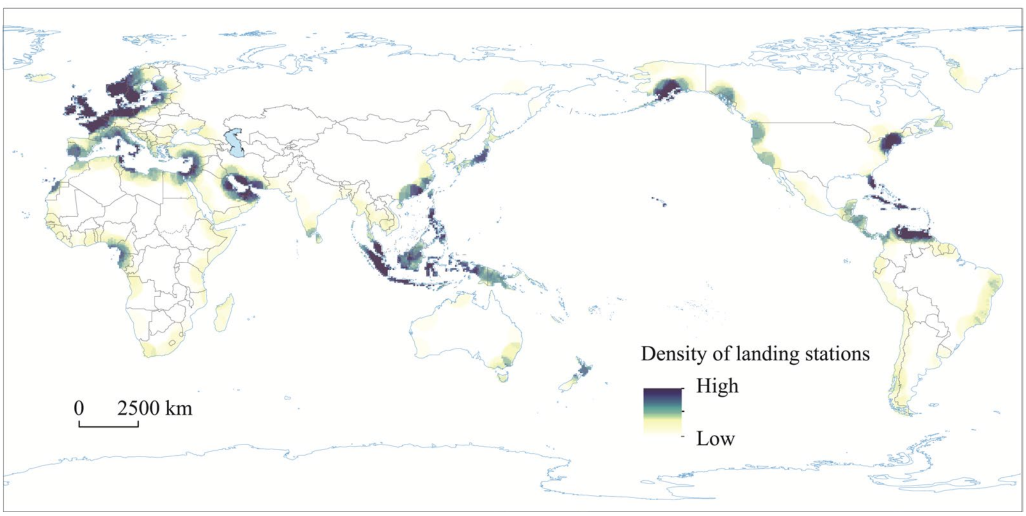


Figure 3 Density distribution of landing stations in 2020

sphere. The density along the coast of the Arctic Circle is very low, and it is the only coastal area with relatively few landing stations.

Based on the distribution of countries or regions, the United States (72) and the United Kingdom (40) are the two countries with the largest number of landing stations, far more than other countries or regions, followed by the Philippines, Indonesia, Japan and Spain, with more than 20. Moreover, there are more than 15 in Sweden and Denmark. The number of landing stations in most countries or regions is small, of which 56.82% are within 3, and 85.8% are within 10. Evidently, the distribution difference of submarine cable landing stations at the national level is extremely significant.

Based on the distribution of each region, Europe (245) has the largest number of landing stations, exceeding the sum of the second and third regions, accounting for approximately 1/4 of the global landing stations. The numbers of landing stations in South Asia, Southeast Asia and North America are also large, with more than 100. However, the standard deviation of these regions with high total amount are also high, exceeding the global average, indicating that the spatial distribution of landing stations has significant inter regional and intra-regional differences on the regional scale.

Based on the above analysis results, the spatial distribution of global submarine cable landing stations is significantly unbalanced. Primarily, there are two reasons for the difference in spatial distribution: (1) The distribution characteristics of islands have an effect, and there will be many landing stations in areas with complex and dense islands, such as the Malay islands and the Caribbean. (2) The coastline of the service subject has an effect, that is, countries with long coastlines generally have sparse distribution of landing stations, such as Australia and India, whereas in areas where many countries with short coastlines gather, landing stations will be densely distributed, such as Europe. The reasons behind the differences in the number of countries or regions are also closely related to social and economic development, particularly the level of digital economy, such as the United States and the United Kingdom, as well as Sweden and Denmark (Pashkevich *et al.*, 2021), which are leading in the digital economy and dominated by the information sector. They all have many submarine cable landing stations.

3.1.2 Spatial distribution of submarine cables

The LineDensity tool was used to explore the tightness of the global submarine cables distribution, as shown in Figure 4. Overall, the distribution of submarine cables in the global sea areas has significant differences. The densely distributed sea areas are connected in series and form several corridors. There are two most dense corridors, one is composed of the Strait of Malacca, the Singapore Strait, the South China Sea, the East China Sea, the northern part of the Philippine Sea, and the other is composed of the Arabian Sea, the Gulf of Aden, the Red Sea, the Gulf of Suez, and the Mediterranean Sea. Trans-North Pacific, trans-North Atlantic and trans-Indian Ocean are three sub-intensive East-West corridors. These five main corridors are connected end-to-end, forming a closed loop around the world. Other submarine cable lines are primarily distributed around Africa, South America and Oceania; however, the degree of tightness is generally low. Furthermore, it is worth mentioning that the waters near the Hawaiian Islands and Guam are two areas with dense routes in the Pacific Ocean.

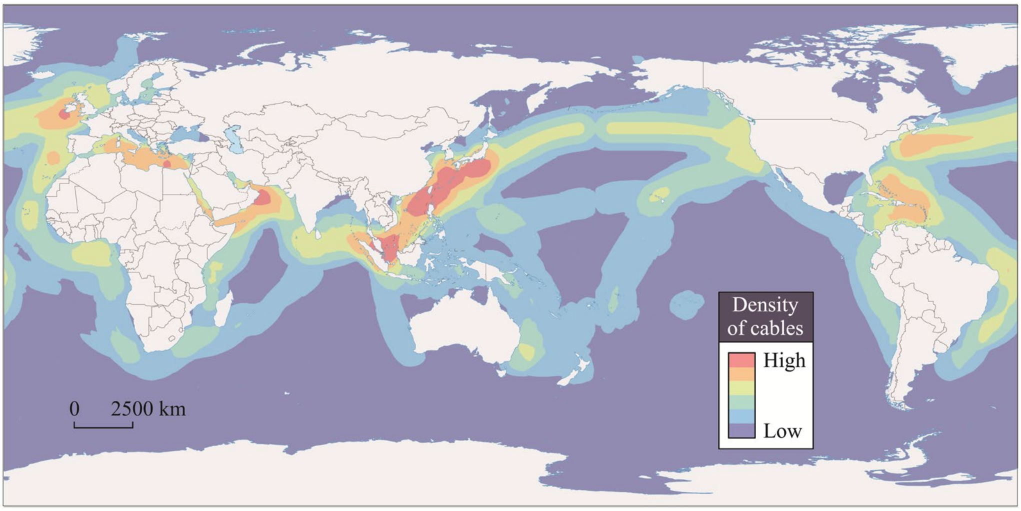


Figure 4 Density distribution of global submarine cables in 2020

As mentioned above, it is evident that the spatial distribution of submarine cable lines is very similar to that of global maritime shipping lines. This phenomenon is caused by many reasons. On the one hand, the constant marine geographical pattern makes the spatial choice of the route extremely limited, regardless of whether it is the submarine cable of the facility network or the shipping of the organization network, and a few key channels become the places that must be passed. For instance, for more than 2000 years, the Strait of Malacca has always been the main channel connecting the Pacific and Indian Oceans. On the other hand, the increase of submarine cable length will not only increase the construction cost, but also affects the transmission efficiency, which determines that the first choice of submarine cable route should be the shortest route at sea. Thus, it is similar to the choice of shipping route. For instance, the submarine cable connecting Europe and Asia does not surround the entire African continent through the Cape of Good Hope, but directly crosses the Gulf of Aden, the Suez Canal and the Strait of Gibraltar. Besides, the opening of the Arctic channel can also confirm this conclusion. In addition to providing a new choice for shipping companies, it also provides a new idea for the construction of submarine cables (Saunavaara and Salminen, 2020).

Indeed, during the construction of submarine cables, the layout of landing stations and submarine cable lines is limited by various factors, such as landform, meteorology and hydrology, geological disasters, engineering development and military use. (Ye *et al*., 2015). However, these objective factors primarily affect the construction scheme and specific station selection, and it is difficult to control the distribution pattern of the submarine cable network from a global perspective.

3.2 Connectivity pattern of global submarine cable network

3.2.1 Microscale: information ports

As shown in Figure 5, the connectivity between any two information ports is obtained according to the connectivity calculation formula. Overall, the connectivity pattern between information ports presents a “chain” structure that is particularly remarkable among highly connected information ports. In the Northeast-Southwest direction along the southern coastal zone of the Eurasian continent, high connectivity port pairs include Singapore-Hong Kong, Singapore-Chiba, Hong Kong-Chiba and Songkhla-Hong Kong; in the Northwest-Southeast direction, there are Singapore-Tamil Nadu, Satun-Mumbai, Mumbai-Fujairah and Karachi-Zaafarana. Along the eastern coast of the African continent, there are Zafarana-Djibouti, Djibouti-Mombasa, Mogadishu-Djibouti and KwaZulu Natal-Mombasa. Across the North Pacific, the high connectivity ports include Hong Kong-California and Chiba-Oregon. These highly connected information ports are connected in an "M" chain structure, which is profoundly consistent with the main laying paths of submarine cable lines in space.

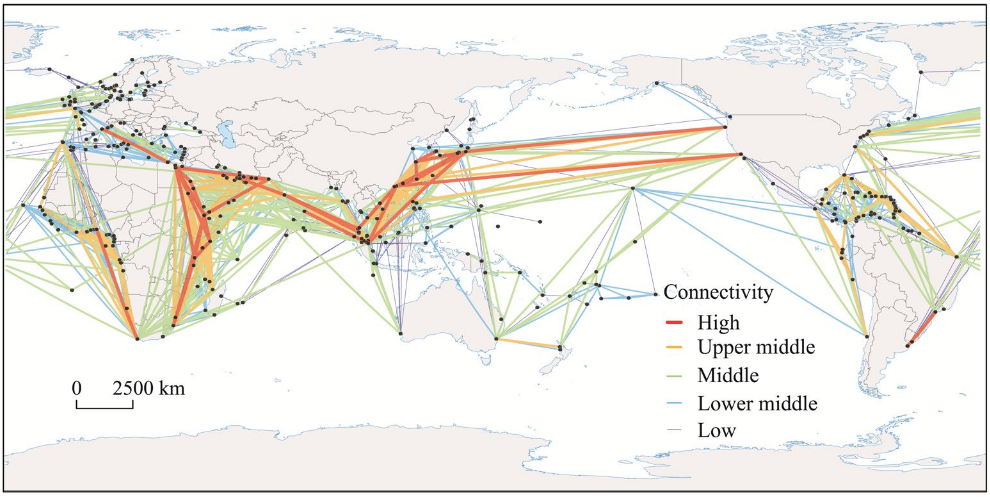


Figure 5 The connectivity of global submarine cable network between information ports

The connectivity indexes of all information ports are calculated and divided into five grades based on the natural fracture method to further analyze the individual differences in the connectivity level of information ports, as shown in Figure 6. Singapore, Djibouti, Hong Kong and Zafarana have the most prominent connectivity index, signifying that they have a large number of submarine cable systems connected with large capacity. The information ports with the second highest connectivity index are primarily distributed in the southern coastal zone of the Eurasian continent and the coastal areas of sub-Saharan Africa. Besides, their spatial distribution matches the "M" chain structure and the primary laying path of submarine cables discussed above. Generally, the connectivity index of information ports in Europe, North Africa, South America, Oceania and other regions is low.

Overall, the connectivity pattern of submarine cable network from the micro perspective is strongly related to the distribution of physical facilities. Moreover, the correlation can be traced back to the global geographical location of the information port, which reveals the primary reason for its spatial differences. In other words, at the micro scale, the connectivity level of the information port is affected by the agglomeration of submarine cables. The information port at the global hub node will connect additional submarine cables and have greater system capacity. It also explains why the United States, as a major information and communication country, does not have a prominent position on the micro scale. More specifically, the United States participates in the trans-Atlantic and trans-Pacific submarine cable systems through the East and West banks, respectively, and the connecting objects in the two directions are completely different. It has resulted in the formation of two information ports with secondary high-level connectivity in Florida on the east coast and California on the west coast from a micro perspective. Consequently, the concentration of submarine cables in the United States has been weakened from a micro perspective, and finally two information ports with secondary high-level connectivity have been established in Florida on the east coast and California on the west coast.

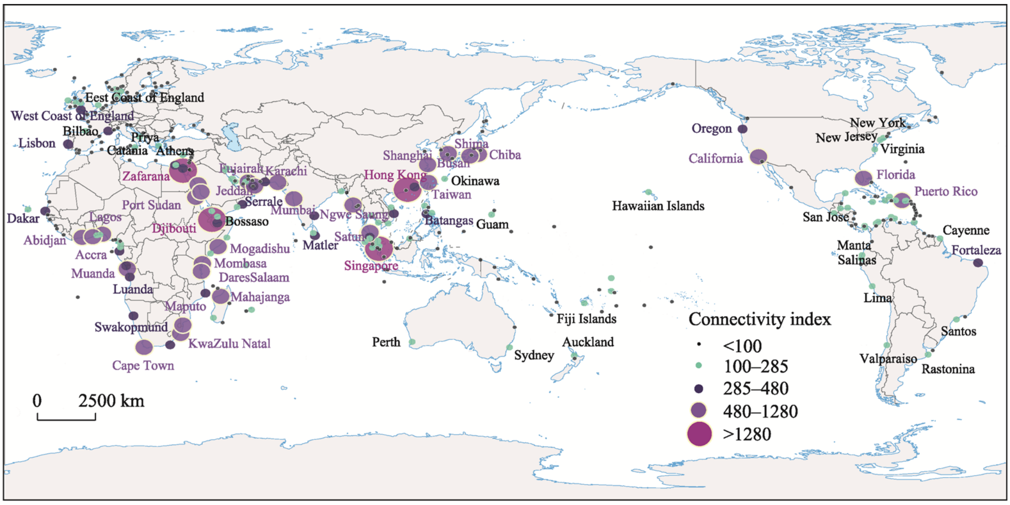


Figure 6 The connectivity index of information ports

Although the importance of geographical location and the agglomeration of physical facilities are the key factors for the spatial differences of connectivity patterns at the micro scale, from the perspective of its development motivation, the social, economic, policy and other internal factors in the hinterland of the information port also play crucial roles. For example, the Singapore government proposed the "Infocomm21" plan and the "connected Singapore" plan as early as the beginning of the 21st century, actively transforming it into a global information and communication hub. As a Special Administrative Region, Hong Kong has convenient customs clearance procedures, free financial policies and loose communication restrictions. Communication services in the Chinese mainland and many neighbouring countries and regions are retransmitted to the Americas and Europe via Hong Kong. Both of them are in the global leading position in the fields of scientific and technological innovation, such as financial technology, digital economy, artificial intelligence and blockchain, which is the internal motivation for their leading connectivity level. On the contrary, although India also has significant geographical advantages and is a necessary point to connect Europe and Southeast Asia, owing to multiple constraints of Indian laws, regulations and policies, it is difficult to approve the construction and maintenance of submarine cables (Sugadev, 2016). As a result, some submarine cable systems deliberately avoid landing in India's information port, so its connectivity level of information port is low.

3.2.2 Mesoscale: countries or regions

The research scale is scaled to the mesoscale and calculate the connectivity between any two countries or regions, as shown in Figure 7. Overall, the connectivity pattern between countries or regions presents a "cluster" structure. This phenomenon is particularly significant among countries or regions with high connectivity. Specifically, the connectivity among China, Hong Kong (China), Japan, Singapore, Malaysia, Thailand, India and other countries or regions are relatively high, forming a regional cluster of the "Asia Pacific Region"; the connectivity among Egypt, Djibouti, South Africa, Somalia, Madagascar, Pakistan and other countries or regions are relatively high, forming a regional cluster of the "West Bank of the Indian Ocean"; the connectivity among the United States, the United Kingdom, France, Spain, Portugal and other countries or regions are relatively high, forming a regional cluster of the "trans-North Atlantic". Additionally, the connectivity between Denmark and Norway is much higher than that of other countries or regions, which is the only high level. This is due to the data impact of a single ultra-high capacity submarine cable system.

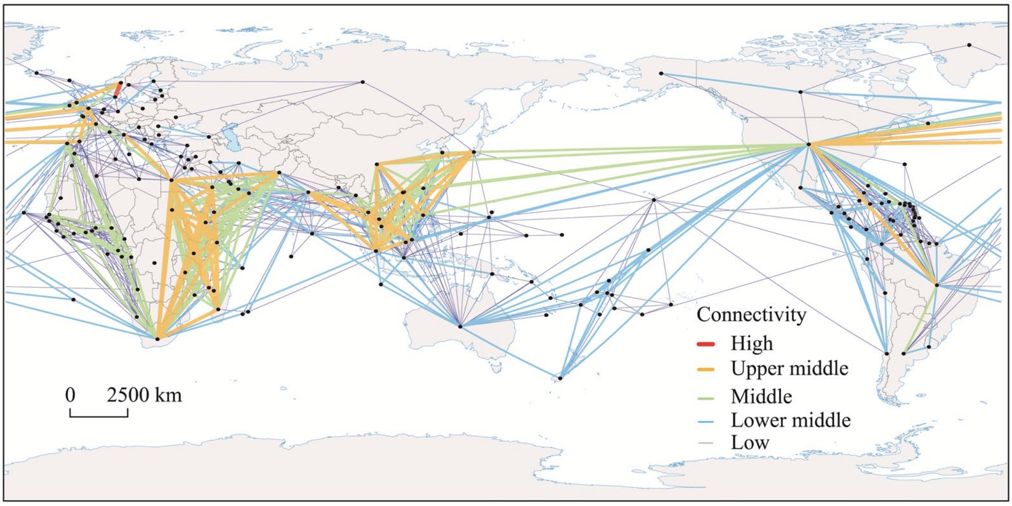


Figure 7 The connectivity of global submarine cable network between countries or regions

This study further analyzes the differences of connectivity indexes among countries or regions, as shown in Figure 8. Norway, Denmark, Egypt, South Africa, the United States, Djibouti, Singapore, Thailand, Hong Kong (China) and other countries or regions have the highest connectivity index. The connectivity index of China, Japan, the Philippines, Malaysia, India, Pakistan, Oman, the United Kingdom and other countries or regions are at the second highest level. Russia, Turkey, Israel, Lebanon, Algeria, Libya, Mauritania and other countries or regions have the lowest connectivity index. Overall, the connectivity level of each country or region is characterized by "regional identity", that is, countries in adjacent regions often have similar connectivity levels, which also supports the "cluster" structure mentioned above and fully reflects the degree of social and economic ties between countries or regions.

The conclusion at mesoscale is not only an extension of the results of microscale analysis, it is also a reversal. On the one hand, if the connectivity level of the information port is high, the connectivity level of the country or area where it is located is high. The research results of East African countries effectively reflect this feature. On the other hand, the connectivity level of the United States is very high; however, from a micro perspective, the connectivity level of its information port is not outstanding. In contrast, the connectivity level of Puerto Rico, Côte d'Ivoire, Ghana, Nigeria and other countries is low; however, from the micro perspective, the connectivity level of its information port is high. This contrast is due to the "cumulative effect" in the process of scale rise. As a typical multi information port country, the United States has a large territory, rich coastlines, many information ports in space and a clear division of labor among the information ports. More specifically, the connected target areas have significant differences. Therefore, when the research scale rises from micro to meso, the United States, which lacks an information port with a high connectivity index, has a very high connectivity level, which further reflects the important position of national sea power in the mesoscale.

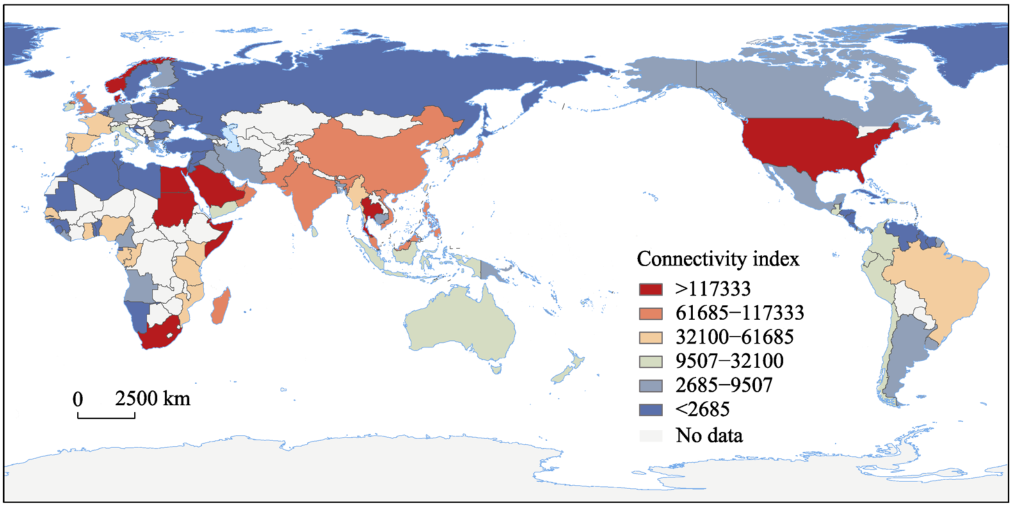


Figure 8 The connectivity index of countries or regions

3.2.3 Macroscale: regions

This study continues to raise the research scale to the macro scale, screen each submarine cable system involved regionally, and obtain the connectivity between any two regions and the connectivity index of each region, as depicted in Figure 9. On the whole, the inter-regional network connectivity pattern presents a "hub-spoke" structure. Specifically, Europe and North America are the two most prominent regions, which match their social and economic development status in the world and the close social and economic ties between Europe and America. Moreover, with Europe and North America as the core hubs, it radiates each region of the eastern and western hemispheres, respectively, forming a network organization with a macro connectivity pattern. Among them, South and Southeast Asian regions have become the third largest core pole, which is consistent with their global hub location. To the west, it connects West and Central Asia, North Africa, sub-Saharan Africa and other regions mainly radiated by Europe. To the east, it connects East Asia, Oceania and other regions mainly radiated by North America.

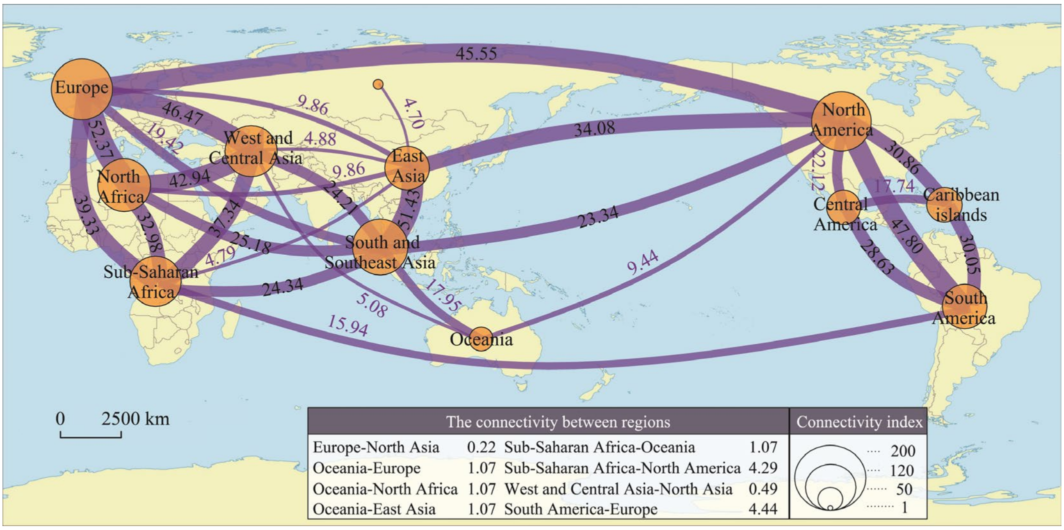


Figure 9 The connectivity of global submarine cable network between regions and the connectivity index of regions

The scale accumulation effect is further manifested during the rising process of the macroscale. Europe, which does not have outstanding connectivity at micro and meso levels, has become the region with the highest connectivity index at the macro level. It is primarily because European countries neither lack information ports with high connectivity nor belong to multi information port countries with large territory and rich coastlines. However, there are a large number of countries connected by submarine cables in Europe, and the target regions connected by these countries have obvious preference differences, covering most regions worldwide. Therefore, the level of connectivity in Europe is very prominent at the macroscale. In brief, different conclusions are obtained through multi-scale analysis, highlighting that the connectivity pattern of the global submarine cable network has a significant scale accumulation effect.

Combined with the meso and micro scale research conclusions, it is evident that the United States and Singapore are actually the core members leading North America, South and Southeast Asia. Therefore, it can be considered that Europe, the United States and Singapore are the three key hubs in the connectivity pattern of the global submarine cable network, which are connected in pairs globally, forming a triangular network core connectivity framework. This conclusion reflects three connotations. First, the cumulative effect of scale runs through the global submarine cable network. Whether it is a small information port, a vast country, or a regional community of multi-national alliances, it can constitute a critical node of the global submarine cable network. The research on communication network should consider the combination of different scales. Second, society, economy and policy are the internal causes of network connectivity. In this regard, Europe and the United States have strong advantages and needs, which makes them occupy the core position of the network. Third, geographical location is an external factor for network connectivity. Singapore has continued exploiting its regional advantages in the global maritime connectivity path, becoming a key hub in the network.

3.3 Identification of strategic pivot and strategic channel and analysis of network security risk

3.3.1 Strategic pivot

The top 30 information ports of the System Centrality are obtained through calculation and screening, and are divided into four grades by using the natural fracture method, as shown in Figure 10. It is not difficult to find that the hierarchical structure of the strategic pivot of the global submarine cable network presents a typical pyramid structure. The number of strategic pivots at levels 1, 2, 3 and 4 correspond to 1, 4, 8 and 16, respectively, that is, the higher the level, the less the number.

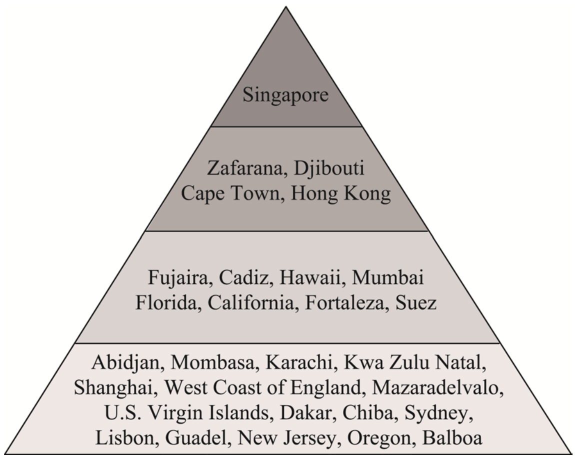


Figure 10 Hierarchical structure of strategic pivots of global submarine cable network

Among them, Singapore has the most prominent System Centrality and has the information port with the highest strategic pivot status, which conforms with the previous description of distribution pattern and connectivity pattern. Among all information ports, Singapore ranks first, third and first in terms of direct accessibility, relative accessibility and transit functions, which fully illustrates its crucial role in the global submarine cable network. The secondary strategic pivot is Cape Town, Djibouti, Zafarana and Hong Kong. These four information ports also have critical strategic positions, and have a high level in terms of direct accessibility, relative accessibility and transit functions. There is a large number of strategic pivots in levels 3 and 4, and the coverage is wide. Although the overall impact of these information ports on the submarine cable network is slightly lower than the strategic pivots of levels 1 and 2, they often have crucial strategic significance for regional network security. For instance, Hawaii and Guam have important transit and routing functions in the North Pacific; Shanghai, New Jersey and West Coast of England are crucial portals of China, the United States and the United Kingdom, respectively, with relatively open geographical advantages. The four levels of strategic pivots constitute the core “Acupoint” of the global submarine cable network. Once they fail or become restricted, the global submarine cable network will be affected regionally, or even globally.

3.3.2 Strategic channel

The top 18 sea areas with the average change rate are selected as the maritime strategic channel by simulating the change of eigenvalues of the global submarine cable network under the restriction of each sea area, and are divided into four grades according to the natural fracture method, as listed in Table 1. It is evident that the strategic channels of the global submarine cable network also have a pyramid-like hierarchical structure. The number of strategic channels at levels 1, 2, 3 and 4 correspond to 2, 3, 5 and 8, respectively.

Table 1 Hierarchical structure of strategic channels of global submarine cable network

Strategic channel level	No.	Sea area	*L*		*E*		*D*		ΔN	Average rate of change
			Value	Rate	Value	Rate	Value	Rate		
Level 1	1	Gulf of Aden	4.680	0.063	0.018	0.143	6.183	0.137	0.034	0.377
	2	Strait of Malacca	4.887	0.110	0.019	0.095	6.391	0.108	0.051	0.365
Level 2	3	South China Sea	4.612	0.048	0.019	0.095	6.295	0.121	0.040	0.304
	4	Red Sea	4.589	0.043	0.019	0.095	6.308	0.119	0.037	0.295
	5	Caribbean Sea	4.597	0.045	0.019	0.095	6.419	0.104	0.040	0.284
Level 3	6	Singapore Strait	4.830	0.097	0.019	0.095	6.608	0.078	0.040	0.263
	7	Arabian Sea	4.500	0.022	0.019	0.095	6.395	0.107	0.031	0.256
	8	Gulf of Oman	4.483	0.019	0.019	0.095	6.454	0.099	0.040	0.253
	9	Mediterranean Sea-Eastern Basin	4.583	0.041	0.020	0.048	6.452	0.099	0.057	0.245
	10	Strait of Gibraltar	4.824	0.096	0.020	0.048	6.901	0.037	0.026	0.206
Level 4	11	South Pacific Ocean	4.472	0.016	0.020	0.048	6.649	0.072	0.051	0.187
	12	Indian Ocean	4.743	0.078	0.020	0.048	6.926	0.033	0.026	0.184
	13	Celtic Sea	4.642	0.055	0.020	0.048	6.810	0.049	0.031	0.183
	14	North Atlantic Ocean	4.606	0.047	0.020	0.048	6.805	0.050	0.031	0.176
	15	Gulf of Suez	4.557	0.035	0.020	0.048	6.706	0.064	0.029	0.175
	16	North Pacific Ocean	4.589	0.043	0.020	0.048	6.845	0.044	0.026	0.160
	17	South Atlantic Ocean	4.577	0.040	0.020	0.048	6.869	0.041	0.029	0.157
	18	Philippine Sea	4.495	0.021	0.021	0.000	6.904	0.036	0.026	0.083

In the simulation, the average change rates of the Gulf of Aden and the Strait of Malacca are the highest, indicating that they are the most prominent strategic channels and form the artery of the global submarine cable network. More specifically, these two maritime strategic channels correspond to the two corridors with the densest distribution of submarine cable lines in the previous article, and are the most critical components. By decomposing each network eigenvalue, it can be found that the Gulf of Aden and the Strait of Malacca are of great strategic significance to the integrity, security and operation efficiency of the network. The secondary strategic channels are the South China Sea, the Red Sea and the Caribbean Sea. The South China Sea and the Red Sea have close spatial correlation and comparable strategic significance with the two primary strategic channels. As the most vital maritime passage in the Americas, the Caribbean Sea holds the cable link between South and North America and between the Atlantic and Pacific oceans, and is of independent strategic importance. There is a large number of level 3 and level 4 strategic channels with a wider spatial coverage, including the sea areas closely related to level 1 and level 2 strategic channels, such as the Singapore Strait, the Gulf of Suez and the Mediterranean Sea-Eastern Basin; and including the sea areas with strong spatial independence and differences in strategic significance, such as the North Pacific, the North Atlantic and the Indian Ocean. The four levels of strategic channels constitute the main "Meridians" of the global submarine cable network. Once they are blocked or become restricted, it will have a regional or even global impact on the global submarine cable network.

3.3.3 Network security risk

Considering the geographical proximity, correlation and similarity of strategic pivot and strategic channel, and in combination with the laying path and spatial distribution of submarine cable lines, this study divides the global submarine cable network into six strategic areas: Southeast Asia Strategic Area, Gulf of Aden and Mediterranean Strategic Area, Trans-North Pacific Strategic Area, Trans-North Atlantic Strategic Area, Persian Gulf Strategic Area and Caribbean Strategic Area. Important strategic pivots and strategic channels co-exist in these areas, as shown in Figure 11. Accordingly, this study analyzes the network security risk of each strategic area.

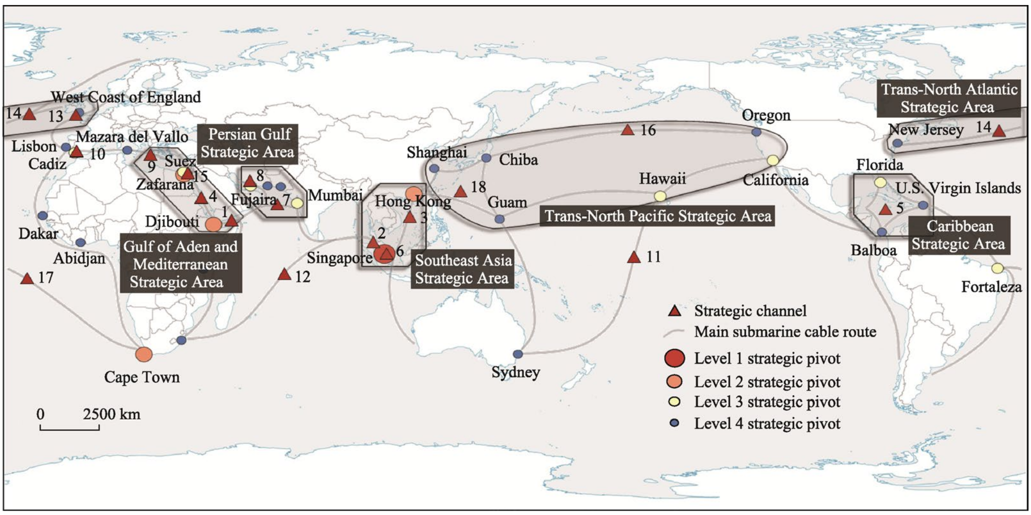


Figure 11 Strategic areas of global submarine cable network

i) Southeast Asia Strategic Area. Includes two strategic pivots of Singapore and Hong Kong, and three strategic channels of the Malacca Strait, the South China Sea and the Singapore Strait. It is the heart of maritime information security. Once this area is blocked, the loop structure of the global submarine cable network will breakdown. In particular, for China, Japan and South Korea, all direct submarine cable links with Southeast Asia, South Asia, West Asia, East Africa and the Mediterranean and Europe will be blocked. However, both the marine geographical environment and the geopolitical pattern of the Southeast Asia strategic area are very complex. On the one hand, the region is located at the junction of the Eurasian seismic belt and the circum-Pacific seismic belt. Therefore, frequent earthquakes places the region at risk of random damage by natural factors. On the other hand, Western hegemonic powers pose a continuous threat to the security of information transmission in the region, seeking various excuses to undermine multilateral security cooperation in the region. Therefore, the network security risk of Southeast Asia Strategic Area deserves the high attention of China and even the world.

ii) Gulf of Aden and Mediterranean Strategic Area. This strategic area is composed of three strategic pivots of Djibouti, Zafarana and Suez, and four strategic channels of the Gulf of Aden, the Red Sea, Suez Canal and the Mediterranean Sea-Eastern Basin. It forms the throat of maritime information security. Once the region is blocked, the loop structure of the global submarine cable network will be seriously damaged, and the submarine cable links between East Asia, Southeast Asia, South Asia, East Africa and the Mediterranean and Europe will be blocked. However, there are complex ethnic and religious issues among countries in the Gulf of Aden and Mediterranean Strategic Area, such as wars, terrorist activities and piracy, which can directly threaten the information security transmission situation. Therefore, the network security risk of the Gulf of Aden Mediterranean strategic area requires long-term focus.

iii) Trans-North Pacific Strategic Area. It is composed of six strategic pivots and two strategic channels, of which Shanghai and Chiba are crucial continental portals in East Asia; California and Oregon are crucial continental portals of North America; Hawaii and Guam are important relay pivots connecting the two ends. This region is the main artery of the global submarine cable network. Once restricted, it will seriously threaten the global network security. In particular, for China and the United States, economic and trade cooperation, social exchanges, political mutual trust and many other aspects will be damaged. However, the security risk of the Trans-North Pacific Strategic Area is not only related to the operation safety of the existing submarine cable, but also related to the combat readiness competition of governments, enterprises, consortiums and market technologies in the new era. For instance, with the support of Australia and Japan, the United States has for long excluded the participation of Chinese suppliers on the grounds of national security, and even obstructed the connection of submarine cables with China. Overall, the network security risks in the Trans-North Pacific Strategic Area are extremely complex and vital. In particular, for China, the construction and operation of submarine cables in the region should be strengthened from a national level.

iv) Trans-North Atlantic Strategic Area. It includes two strategic pivots of New Jersey and West Coast of England, as well as two strategic channels of the North Atlantic and Celtic Sea. This region constitutes another major artery of the global submarine cable network. Once blocked, the submarine cable links between North America, Europe, North Africa and even the Middle East will be blocked, and the links between Western Europe and Asia will also be seriously affected. Recently, the crisis of geopolitical and economic in European countries poses the main threat to the Trans-North Atlantic Strategic Area.

v) Persian Gulf Strategic Area. It includes four strategic of Fujaira, Mumbai, Gwadar and Karachi, and two strategic channels of the Arabian Sea and the Gulf of Oman. Although the region is close to the Gulf of Aden and Mediterranean Strategic Area, they have different strategic significance. On the one hand, the Persian Gulf Strategic Area is a vital channel for the East-West connection of the Indian Ocean, and the Arabian Sea and Mumbai are crucial locations for most cross Indian Ocean submarine cables. On the other hand, the Persian Gulf

Strategic Area constitutes the information portal of Central Asian countries. Among them, the Gulf of Oman almost guards all the submarine cable systems connecting Central Asian countries. Therefore, not only is the connectivity between Asia, Africa and Europe constrained by the Persian Gulf Strategic Area, but also the external submarine cable links of Central Asian countries are completely dependent on it.

vi) Caribbean Strategic Area. This strategic area is composed of three strategic pivots of Florida, the U.S. Virgin Islands and Balboa, and one strategic channel of the Caribbean Sea. The Caribbean Strategic Area acts as a transit hub in the global submarine cable network, similar to a crossroads. It connects the Atlantic Ocean and the Pacific Ocean from east to west, and connects the North America and the South America from north to south.

4 Conclusions and discussion

Submarine cable network is regarded as the "central nerve" of the ocean and plays an extremely important role in the fields of national defense, telecommunications, social economy and even energy. As network security has gradually become the focus of the international community, and the protection of key infrastructure has been raised to a prominent position involving national security, submarine cables have become a new field of international competition and superpower game. There is abundant research on similar large-scale connectivity infrastructure networks. However, there is limited literature discussing the spatial pattern of submarine cable networks. Accordingly, this paper analyzed the distribution pattern and connectivity pattern of the global submarine cable network, quantitatively identified the strategic pivot and strategic channel, and discussed the security risks of the network.

The conclusions are as follows: (1) The spatial distribution of global submarine cables is significantly unbalanced. The landing stations are unevenly distributed along the coastline, forming several agglomeration zones; submarine cables are primarily concentrated in five corridors that are connected end-to-end, forming a closed loop around the world, and are very similar to the path of global maritime shipping lines. (2) The connectivity pattern of the global submarine cable network has a significant scale accumulation effect. For the microscale, the connection between information ports presents a "chain" structure, and the connection pattern has a strong correlation with the distribution of physical facilities; for the mesoscale, the links between countries or regions presents a "cluster" structure, and the connectivity pattern reflects the closeness of the links between countries or regions; for the macroscale, the connection between regions presents a "hub-spoke" structure, and the connectivity pattern reflects the network hub status among regions. (3) The strategic pivot and strategic channel of the global submarine cable network present typical pyramid structure, in which Singapore has the highest strategic pivot position and the Gulf of Aden and the Strait of Malacca have the highest strategic channel position. Accordingly, six strategic areas can be further divided, which have different strategic significance and security risks, and need special attention and vigilance.

As mentioned above, the spatial pattern of the global submarine cable network is not only the spatial mapping of the international communication network, but also inextricably linked with the complex international socio-economic and geopolitical relations. Therefore, combined with the spatial pattern of the global submarine cable network and its possible impacts and constraints, this paper proposes the following suggestions to help China timely optimize the development strategy of the submarine cable network: (1) Accelerate the layout of global submarine cables. Currently, China's overall strategic position in the global submarine cable network is not prominent. China should plan new submarine cable systems and appropriately add new landing stations to increase the number of areas directly connected to China and enhance the core position of the network. (2) Prioritize the dividends of Hong Kong's network centre position. The above research shows that Hong Kong has a core position in the global submarine cable network. Although there are obstacles in the construction, operation and service of submarine cable systems in the Chinese mainland and Hong Kong (China), the two places can still make full use of the dividends of Hong Kong's network centre position and actively participate in the construction of landing submarine cables in Hong Kong to maximize the advantages of China's submarine cable network layout. (3) Cooperate to develop submarine cable network pivot countries. According to the identified strategic pivot, the Chinese government should focus on strengthening cooperation with strategic pivot countries to jointly build international submarine cable transit points to improve the convenience of China's submarine cable network organization. (4) Actively participate in the construction of trans-Arctic submarine cables. With the opening of the Arctic channel, the construction of the trans-Arctic submarine cable system will be mark a crucial event to change the pattern of the global submarine cable network in the future. China should exploit its good geopolitical relations with Russia and actively participate in the trans-Arctic submarine cable to enhance the resilience of network security.

The main transmission content of submarine cable has developed from the original Morse telegraph password to voice and image, and has been occupied by a large amount of Internet information. In particular, the global epidemic in 2020 has driven the society to move online, and also led to a surge in Internet traffic. The construction subject of submarine cable is also changing from national telecom operators to large Internet enterprises. Internet giants, such as Facebook, Google and Microsoft are not only the leaseholders and buyers of submarine cable bandwidth, but also the leading force in international submarine cable construction. All the above can explain that the global submarine cable is inseparable from the world Internet. Therefore, new infrastructure, such as data centres and root servers, which are closely related to the Internet, also deserves high attention from the global information network security. For example, in the IPv4 era, there were 13 root servers worldwide, with the United States accounting for one main server and nine auxiliary servers, and the remaining two in Europe and one in Japan. The governance system formed by this has not only caused an extreme imbalance in the management and distribution of global Internet resources, but also brought great hidden dangers to the information security of China and other countries. The "Yeti DNS Project" based on the global next generation Internet (IPv6) root server test and operation experiment project broke this dilemma. 25 root servers in the IPv6 era are more evenly distributed in 16 countries worldwide, of which one primary root and three secondary roots are deployed in China, breaking the pattern of the United States dominating the Internet and laying a foundation for the establishment of a multilateral, transparent and secure global information network. The future research on submarine cable network and global strategic pattern should be combined with new infrastructure to realize the integrated research on global information transmission network.

The transport geography in the post Fordism era conforms with the transportation attribute of communication facilities; however, lacks empirical research. While, information geography attaches significance to the key role of communication facilities, it is mostly limited by virtual information flow. Based on submarine cable–the most important communication infrastructure in the world, this study explores the global strategic pattern and national strategic decisions from the perspective of transport geography and information geography, which can provide scientific support for China's participation in the construction of the global submarine cable network while promoting the theoretical development of transport geography and information geography. In future research, the combination of submarine cable network and Internet urban network will provide a new impetus for the development of transportation geography and information geography theory.

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