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Network Characteristics and Vulnerability Analysis of Chinese Railway Network under Earthquake Disasters

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Abstract: The internal structure and operation rules of railway network have become increasingly complex along with the expansion of the network, putting a higher demand on the development of the railway and the reliability and adaptability of the railway under earthquake disasters. The theory and method concerning complex railway network can well capture the internal structure of railway facilities system and the relationship between subsystems. However, most of the research focuses on the vulnerability based on the logical network of railway, deviating from the actual spatial location of railway network. Additionally, only random attacks and deliberate attacks are factored in, ignoring the impact of earthquake disasters on actual railway lines. Therefore, this paper built a geographic railway network and analyzed topological structure of the network and its vulnerability under earthquake disasters. First, the geographic network of Chinese railway was built based on the methods of complex network, linear reference and dynamic segmentation. Second, the spatial distribution of railway network flow was analyzed by node degree, betweenness and clustering coefficient. Finally, the vulnerability of the geographic railway network in areas with high seismic hazards were assessed, aiming to improve the capacity to prevent and resist earthquake disasters.

Keywords: Chinese railway network; complex network; linear reference; earthquake disasters; vulnerability analysis

1. Introduction

Railway transportation, as the main artery of the national economy and one of the major means of transportation in the comprehensive transportation system, is characterized by huge carrying capacity, low operation cost, safety and punctuality, and low energy consumption [1–3]. In recent decades, China has actively implemented the strategy of building a sound railway transportation infrastructure, and has rapidly constructed a modern normal-speed railway network and a developed high-speed railway network. In 2004, the State Council approved the first "Medium and Long-Term Railway Network Planning" in the history of Chinese railway, which depicted a blueprint for a "four vertical and four horizontal" high-speed trunk network. In 2016, the revised "Medium and Long-Term Railway Network Planning" outlined a grand blueprint for an "eight vertical and eight horizontal" high-speed railway network [4,5]. In the meantime, the normal-speed railway has also undergone a speed-up transformation, electrification transformation and double-track transformation. As a result, the railway network coverage in the central and western regions has been expanded and the network layout in the eastern region has been optimized [6,7]. According to statistics, by the end of 2019, China's railway operating mileage had reached 139,000 km, of which the high-speed railway operating length reached 35,000 km, ranking first in the world [8]. With the planning, construction and operation of more railway lines, the railway network is becoming better and better, and the network scale is also expanding and making the network structure increasingly complex [9,10]. The complex network system does improve the operation efficiency of the whole network, but it has, meanwhile, brought various challenges [11,12].

Owing to its openness and complexity, the railway transport system is often subject to various internal and external interferences during its operation, resulting in disruptions to the railway network. Local disruption impedes the effective coordinated operation of the whole railway transportation network [13,14]. Various types of sudden geological disasters, including earthquake, mudslide, flood, tsunami, landslide and other frequently occurring natural disasters, make the railway transport system subject to threats and damage to varying degrees, which affect railway operations, cause train delays and cancellations in mild cases, paralyze the railway network structure, and seriously affect the production of the national economy and people's daily life and travel in severe cases [15–18]. Located in the two largest seismic belts in the world, i.e., the circum-Pacific seismic belt and Eurasian seismic belt, China suffers frequent and serious earthquake disasters. Many of the earthquakes happened in China are shallow-focus continental earthquakes with focal depth within 20 km [19]. For a railway, even a small-magnitude earthquake may result in accidents such as derailment and overturn, further causing casualty and economic loss [17,18]. However, it is impossible to completely stay away from seismic belt for railway design in China. With large-scale construction and operation of high-speed railway, the potential hazards of earthquake disasters are also increasingly prominent [20]. It may be necessary to pass through two or more seismic belts for long lines, which will pose serious threats to the operation safety of high-speed railways [3,21]. Although it is impossible to make accurate predictions for earthquakes by existing technology, obtaining a railway section and station that are susceptible to the earthquake through vulnerability analysis for railway network under impact of earthquake disasters can provide reference for the emergency management and rescue.

With the penetration of the theory on complex network into various disciplines, an increasing number of scholars have begun to study the complex characteristics of various transportation networks, and conducted relevant applied research from various perspectives such as urban road transportation network, rail transit network, railway network and public transportation network, providing a new research idea and orientation for the research on the reliability of railway network system [22–25]. However, two deficiencies exist in these studies: First, the vulnerability analysis of the railway network is mainly based on the logical network for railway, which is divorced from the actual spatial location of the railway network. Second, when analyzing the vulnerability of the railway network, only random attacks and deliberate attacks are considered, thereby ignoring the impact of disasters on the actual railway lines. However, in actual situations, railway lines are often greatly impacted by such factors as topography, landforms and sudden earthquake disasters. Therefore, based on linear reference and dynamic segmentation technologies, this paper constructs the actual geographic railway network to reveal the overall structure and properties of the current railway network, and identify important stations in the geographic railway network. On this basis, this paper evaluates the vulnerability of the geographic railway network under earthquake disasters conditions to provide a basis for railway emergency management and emergency rescue and reduce subjectivity and blindness in decision-making for the purpose of building a more reasonable, comprehensive, efficient and safe railway network.

2. Methods

2.1. The Geographic Railway Network Modeling

Due to the complexity of the railway network (including stations, bridges, tunnels and other infrastructure) in the real world, this paper made certain simplifications and assumptions:

(1) Based on the pair operation characteristics of railway trains, the direction of the railway was not considered.
(2) The station was abstracted as a node, and the railway line was abstracted as a simple line data connecting the stations.
(3) The number of train operations between station pairs was used as the edge weight of the train operation network.

On this basis, the geographic railway network model constructed in this paper is shown in Figure 1 and is divided into three layers: the first layer is the train operation network, created based on the complex network model, and is mainly used to study the topological characteristics of the train operation network; the second layer is a connection layer based on the linear reference system which maps the train operation network to the actual geographic railway network by means of events; and the third layer is the geographic network, composed of actual railway lines and providing the location basis for train operation.

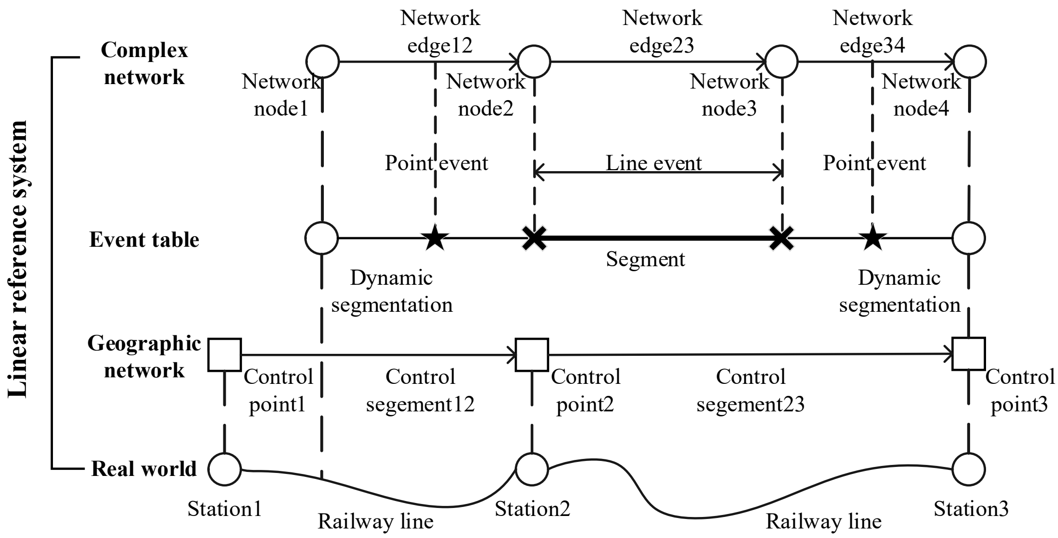


Figure 1. The geographic railway network conceptual model.

2.1.1. Complex Railway Network Modeling

The types of Chinese railway trains mainly include high-speed train, bullet train, non-stop train, express and fast train. According to speed, trains are divided into two types: high-speed and normal-speed trains, among which, high-speed and bullet trains are in the same group, while the rest of the non-stop trains, express trains and fast trains are in the other group. This paper used SpaceL method to establish two different Geographic Railway Network mentioned above. SpaceL modeling takes railway stations as nodes, and there is a connection edge between two nodes that the same train continuously stops on its travel line [26,27], as shown in Figure 2.

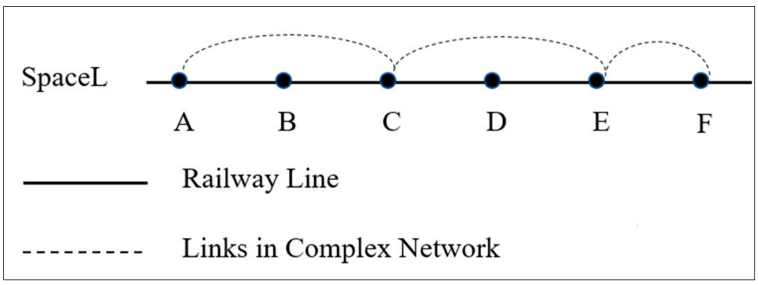


Figure 2. Complex railway network modeling.

Stations were used as network nodes and two stations through which trains operated were connected as an edge. Furthermore, the railway network can be regarded as an undirected graph G = (*V*, *E*) composed of N stations, and M edges, where V = $\{v_1, v_2, v_3, \ldots, v_N\}$ is a set of stations, E = $\{(v_i, v_j), i, j \in N, i \neq j\}$ is a set of line segments between Station v_i and v_j, and the weight of each edge is expressed by the number of trains passing Station v_i and v_j. The connection relationship between the stations can be represented by an $N \times N$ adjacency matrix A. a_{ij} represents the connection relationship between Station v_i and v_j. If Station v_i and v_j are connected, the value is taken as 1, otherwise, the value is taken as 0.

2.1.2. Connection Layer between Geographic Network and Railway Network

The complex network can well capture the connectivity between train operation networks. However, it is difficult for such a network to reflect the characteristics of spatial distribution as it is divorced from the geographic location of the railway. Therefore, the linear reference and dynamic segmentation technology were adopted in this paper to realize the mapping connection between the train operation network and geographic network to reflect the distribution and characteristics of railway network in geographic space [28–30]. This paper mainly found the corresponding coordinates in the geographic network through station node in the complex network; obtained mileage information list of station node in the complex railway network through information separation and integration; and finally achieved a segmented display of the railway network in the geographic network through linear reference system.

Line information that station node pairs pass through was realized through the following principles:

(1) If there is only one line connecting the station node pair, then the mileage position of the station node pair on the line can be directly calculated, as shown in Figure 3a.
(2) If there is one extra line connecting the station node pair, then the line corresponding to the station node can be determined according to the type of train and the lines of the previous and next station, as shown in Figure 3b.
(3) If there is no corresponding line passing between the station node pair, the intermediate node station between the stations are determined according to the shortest path principle based on the second principle, and the original Start Station-End Station node pair is transformed into Start Station-New Station and New Station-End Station node pair, as shown in Figure 3c.

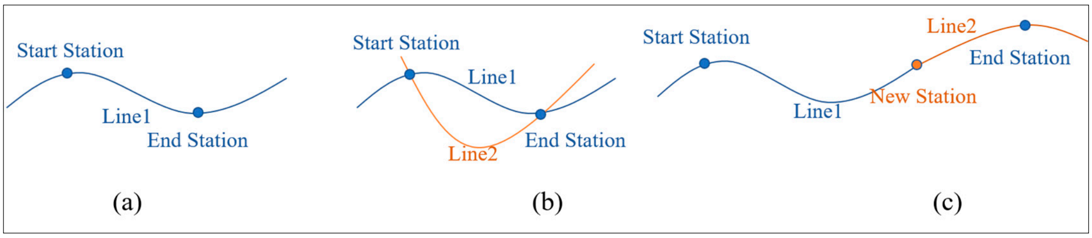


Figure 3. Line information of the station. (**a**) Only one line connecting the station node pair. (**b**) Two lines connecting the station node pair. (**c**) No corresponding line passing between the station node pair.

2.1.3. Geographic Network Modeling

The geographic network is the network composed of actual railway lines. It is the basis of the spatial location of the train operation network and mainly consists of three layers: station data, line data and city data, as shown in Figure 4. The station data includes location information and attribute information, which includes station grade, route and mileage. Line data also includes location information and attribute information, which includes line name, design speed and line type. The city data is composed of the location information and attribute information of the city center. The attribute data of the station can be associated with the line data and city data through the foreign key.

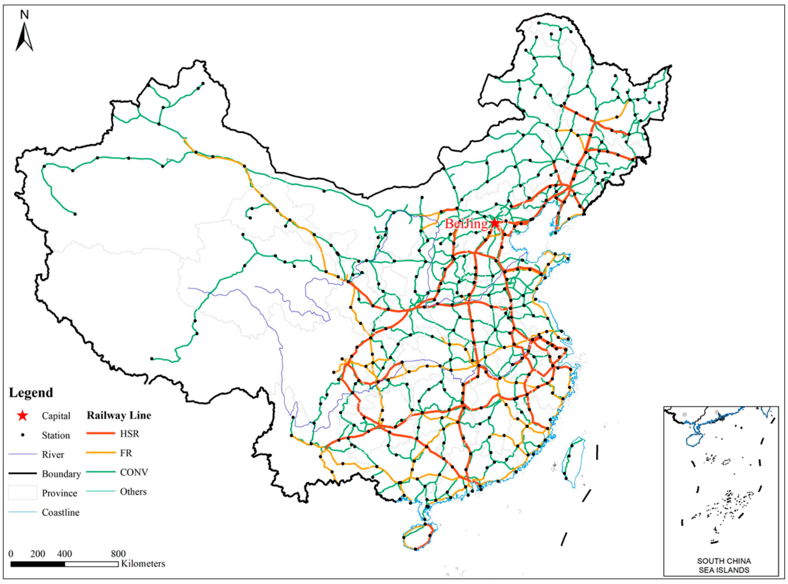


Figure 4. The geographic network.

2.2. *Topological Statistical Characteristics of the Geographic Railway Network*

The statistical property of a network, also called static geometric quantity of the network, refers to the statistical distribution or macro statistical mean of microscopic quantities of a network, mainly including statistical quantities such as degree distribution, betweenness, clustering coefficient, etc. [31–34]. The calculation formulas are as follows:

(1) Degree: the degree k_i of the node i is defined as the number of other nodes connected to the node i. Generally speaking, the larger the node degree, the greater its role in the network. The mean of all node degrees in the network is called the average degree of the network, and is recorded as $<k>$. N is the total number of nodes.

$$\langle k \rangle = \frac{\sum_i k_i}{N} \tag{1}$$

(2) Betweenness: An important global geometric quantity, related to path length, reflects the effect and influence of nodes or edges on the entire network. The calculation formula is:

$$B = \frac{1}{n} \sum_i \left(\frac{b}{B} \right)_i \tag{2}$$

where B represents the betweenness value of the node i, and b/B represents the contribution degree of the node i to the betweenness of these two nodes. The calculation method is as follows: If there are N different shortest paths between two nodes, of which n paths need to pass through the node i, then the contribution rate of the node i to the betweenness of the two nodes is b/B.

(3) Clustering coefficient: It is an index parameter describing the clustering of nodes in a network, and is recorded as C_i. The node i with a degree of k_i has k_i edges connecting it with other k nodes, and the ratio of the actual number of edges n_i between these k nodes to the total number of possible edges is the clustering coefficient of the node i.

$$C_i = \frac{2n_i}{k_i(k_i - 1)} \tag{3}$$

2.3. *Vulnerability Assessment of the Geographic Railway Network under Earthquake Disasters*

China suffers frequent and serious earthquake disasters. If the speed of a train exceeds 200 km/h, even a small-magnitude earthquake will result in serious impacts on the roadbed, track and bridge, which is extremely threatening to its operation safety. According to the related literature, earthquakes with 4.5-magnitude and above may have influence on the railway system [21]. Therefore, only earthquakes with 4.5-magnitude and above were studied in this paper. In addition, the mechanism of earthquake disasters was overlooked, which was useful for studying characteristics of the railway network itself. First, the data of station, line and operating train that are susceptible to earthquake disasters in geographic railway network were obtained through assessing hazard of earthquake disasters. Then, these stations were removed successively to analyze changes of the network efficiency as a whole, and assess the vulnerability of the geographic railway network under earthquake disasters.

2.3.1. Hazard Assessment of Earthquake Disasters

According to the historical data of earthquake disasters, this paper firstly calculated the maximum possible destruction range by the attenuation relationship of the earthquake and obtained seismic intensity of the earthquake through transformation; it then calculated the possibility of seismic hazards at each station of the geographic railway network by kernel density estimation function; finally it comprehensively analyzed the seismic intensity and kernel density distribution together and obtained the hazards of earthquake disasters in the geographic railway network.

(1) Seismic Intensity

The seismic wave energy or amplitude will be smaller if the seismic wave is further away from the energy release zone during its transmission from the rupture unit. The seismic attenuation relationship can better reflect energy attenuation rules of the seismic wave during transmission. Therefore, it is feasible to calculate the maximum possible destruction range based on known the seismic attenuation relationship equation of the region after determining the epicenter and earthquake magnitude. This paper calculated Peak Ground Acceleration (PGA) at each position of the geographic railway network by the mid-value equation as follows [21,35]:

$$\begin{aligned} ln(median\ PGA) = 2.20 + 0.81 \times (M-6) - 1.27 \times ln\left(\sqrt{Repi^2 + 9.3^2}\right) \\ +0.11 \times \max\left[ln\left(\frac{Repi}{100}\right), 0\right] - 0.0021\sqrt{Repi^2 + 9.3^2} \end{aligned} \tag{4}$$

where *Repi* is epicentral distance and *M* is magnitude of the earthquake.

The earthquake can be measured by seismic magnitude and intensity. The seismic magnitude measures seismic release energy, while seismic intensity measures the destruction degree of the earthquake. Table 1 shows the transformation relationship between PGA and seismic intensity. Generally, only influences of the earthquakes with intensity VI and above are collected, namely, PGA is 0.05. If PGA is 0.2 g, then it is a severely afflicted area with seismic intensity VIII. According to the mechanism of earthquake disasters, if a position once suffered an earthquake with a certain magnitude, then it will be struck by earthquake with same magnitude in the future. Therefore, this paper calculated the seismic distribution within the geographic railway network by PGA mid-value model based on historical earthquake data.

Table 1. Transformation comparison between seismic intensity and Peak Ground Acceleration (PGA) [36].

***PGA* Value**	**<0.05**	**0.05**	**0.1**	**0.15**	**0.2**	**0.3**	**≥0.4**
Seismic intensity	<VI	VI	VII	VII	VIII	VIII	≥IX

(2) Kernel Density Estimation

Generally, the geographic structure of a certain region will not experience great changes within a short time scale (<100 a), therefore the seismic activity level of a region remains consistent within a certain time range [37]. In addition, according to the elastic rebound hypothesis, the earthquake is periodical, that is to say, if earthquake frequency in a region is high, then the possibility to be struck by earthquake in this region will also be high [38]. The kernel density analysis is to estimate the possibility of a same accident at different positions based on existing accident records. If a similar accident occurs in a region, then the possibility of suffering from the same accident is higher compared to other regions [39]. Therefore, the kernel density method is used to estimate the possibility of earthquakes at each position of the geographic railway network, with calculation equation as follows [40]:

$$KDE(x) = \frac{1}{nh}\sum_{i=1}^{n} K\left(\frac{x - x_i}{h}\right) \quad (5)$$

where $KDE(x)$ is the 'kernel', and h is the 'bandwidth'. Some popular choices for the kernel are epanechnikov, triangular and gaussian. x_i ($i = 1 \rightarrow n$) is a set of n measurements.

2.3.2. Vulnerability Assessment of the Geographic Railway Network

As a passenger flow center and train workplace, the station node is an important part of the geographic railway network. This paper took the station as the vulnerability analysis object for geographic railway network and overall network efficiency as a main indicator of the vulnerability analysis to analyze the vulnerability of each station in the geographic railway network under earthquake disasters. First, the hazard assessment result of earthquake disasters is mapped to the geographic railway network, and the data of station, line and operating train that are susceptible to earthquake disasters are obtained through overlap analysis. Then, these station nodes are removed successively to analyze the change of the overall network efficiency, and the vulnerability of geographic railway network is assessed. Finally, key points of the geographic railway network are selected as subjects for protection based on vulnerability analysis results.

The overall network efficiency is the average value of reciprocal sum of the distance between all node pairs in the network, with value range from 0 to 1. If the overall efficiency is 0, then all important nodes in the geographic railway network are isolated and separated and the network reliability is the worst. If the overall network efficiency is 1, then all important nodes are connected. The overall network efficiency is calculated as per the equation as follows [41]:

$$E_{global} = \frac{1}{N(N-1)}\sum_{i \neq j}\frac{1}{d_{ij}} \quad (6)$$

where E_{global} is overall network efficiency; N is the number of nodes in network; d_{ij} is the shortest distance between node i and j.

Through removing the station node, the change of overall network efficiency is calculated, and important station nodes are determined. The calculation equation is shown as follows [41]:

$$V_i = \frac{E_{global} - E'_{global}}{E_{global}} \quad (7)$$

where V_i is importance of station in network; and E'_{global} is overall network efficiency after removing station i.

3. Results and Analysis

3.1. Research Data

This paper collected train operation data from 20 June 2019 to 20 July 2019 and for 31 days through the CHINA RAILWAY website (https://www.12306.cn), and obtained information on 12,000 passenger train numbers of mainland China. Based on this, the spatial location and attribute information of stations and railway lines were searched through the Catalogue Service for Geographic Information, CHINA RAILWYAY MAP website, Baidu Map, OpenStreetMap and other sources. The geographic railway network was obtained after spatial arrangement in ArcMap software. This paper collected information on a total of over 3000 stations and over 400 railway lines. The geographic network of Chinese railway was built based on complex network, linear reference and dynamic segmentation. Due to the lack of freight train data, the geographic network of Chinese railway constructed in this paper refers to the passenger railway network. The topological structure, operating condition, evolution behavior of the railway network and accessibility of the node were discussed.

China suffers frequent and serious earthquake disasters. According to related literature, earthquakes with 4.5-magnitude and above may have influences on the railway system. Therefore, with the historical data of over 7900 earthquakes with 4.5-magnitude and above from the Resource and Environment Data Cloud Platform, including focal position, focal depth, and seismic magnitude, this paper conducted a vulnerability study on the geographic network of Chinese railway under earthquake disasters, providing reference for railway emergency management and rescue.

3.2. Spatial Distribution Analysis of the Geographic Railway Network

According to the linear reference and dynamic segmentation technology, the railway network is mapped onto the actual geographic network to obtain an analysis of spatial distribution characteristics of the geographic railway network, as shown in Figure 5. Figure 5a is the geographic network of high-speed railway. High-speed railway lines are mainly concentrated in the eastern and central regions in China. Figure 5b is the geographic network of normal-speed railway. The geographic network of normal-speed railway covers a wider range, especially in the northern and western regions where the coverage of high-speed railway is insufficient, and plays an important role in passenger transportation. Lanzhou-Xinjiang Railway in the west region is the main railway connecting Xinjiang to mainland China, and a main component of the railway network in Northwest China.

On this basis, the lines with the most operating trains in the geographic railway network were counted in this paper, as shown in Table 2. The lines with the largest number of trains are Shanghai-Kunming High-speed Railway, Beijing-Shanghai High-speed Railway, Beijing-Shanghai Railway, Beijing-Guangzhou Railway and Beijing-Jiulong Railway. The average workload (9129) of the high-speed railway network is nearly three times (3296) that of the normal-speed railway network, indicating that China's high-speed railway has become the backbone of the national comprehensive transportation system. In the geographic network of high-speed railway, the busiest lines are the vertical Beijing-Guangzhou High-speed Railway, Beijing-Shanghai High-speed Railway, the horizontal Fuzhou South-Zhangzhou section of the Fuzhou-Xiamen Railway along the coastal high-speed channel, Shanghai Hongqiao-Huaihua South section of Shanghai-Kunming High-speed Railway, Shangqiu-Xi' and North section Xulan High-speed Railway, etc. High-speed railways in Northeast China include Beijing-Harbin High-speed Railway, Xi'an-Chengdu High-Speed Railway connecting Sichuan, Chongqing and Guizhou, Shanghai-Kunming High-speed Railway and Chengdu-Chongqing High-speed Railway, with a medium passenger transport volume. Lanzhou-Wulumuqi High-speed Railway, a high-speed railway in Northwest China, connects Xinjiang with other provinces and cities. However, its passenger transport volume is relatively small. In the geographic network of normal-speed railway, busy normal-speed railway lines include vertical Beijing-Guangzhou Railway, Beijing-Jiulong Railway, Beijing-Shanghai Railway and Beijing-Harbin Railway in the Northeast direction, and horizontal Shanghai-Kunming Railway and Lanzhou-Lianyungang Railway in the horizontal direction.

3.3. Topological Analysis of the Geographic Railway Network

3.3.1. Analysis of Node Degree

In the geographic railway network, if the degree of a certain node is k, it means the number of stations that a passenger can reach with only one stop from the station. Figure 6a shows the distribution of node degrees in the geographic network of high-speed railway, with average node degree of 7.0. That is to say, every station in the network is directly connected with about seven stations on average. The stations with a node degree of 30 and above include Guangzhou South Railway Station (43), Chengdu East Railway Station (43), Nanjing South Railway Station (38), Hangzhou East Railway Station (37), Wuhan Railway Station (34), Guiyang North Railway Station (34), Zhengzhou East Railway Station (34), Shenyang Railway Station (31), Shenyang North Railway Station (31) and Chongqing West Railway Station (30). Figure 6b shows the node degree distribution in the geographic network of normal-speed railway, with an average node 4.3. That is to say, any station in the network is directly connected with about four stations on average. The stations with a node degree of 30 and above include Beijing Railway Station (54), Jiujiang Railway Station (39), Harbin Railway Station (37), Xi'an Railway Station (36), Tianjin Railway Station (36), Fuyang Railway Station (34), Wuchang Railway Station (34), Nanchang Railway Station (34), Zhengzhou Railway Station (33), Shenyang Railway Station (33), Shenyang North Railway Station (31) and Xuzhou Railway Station (30).

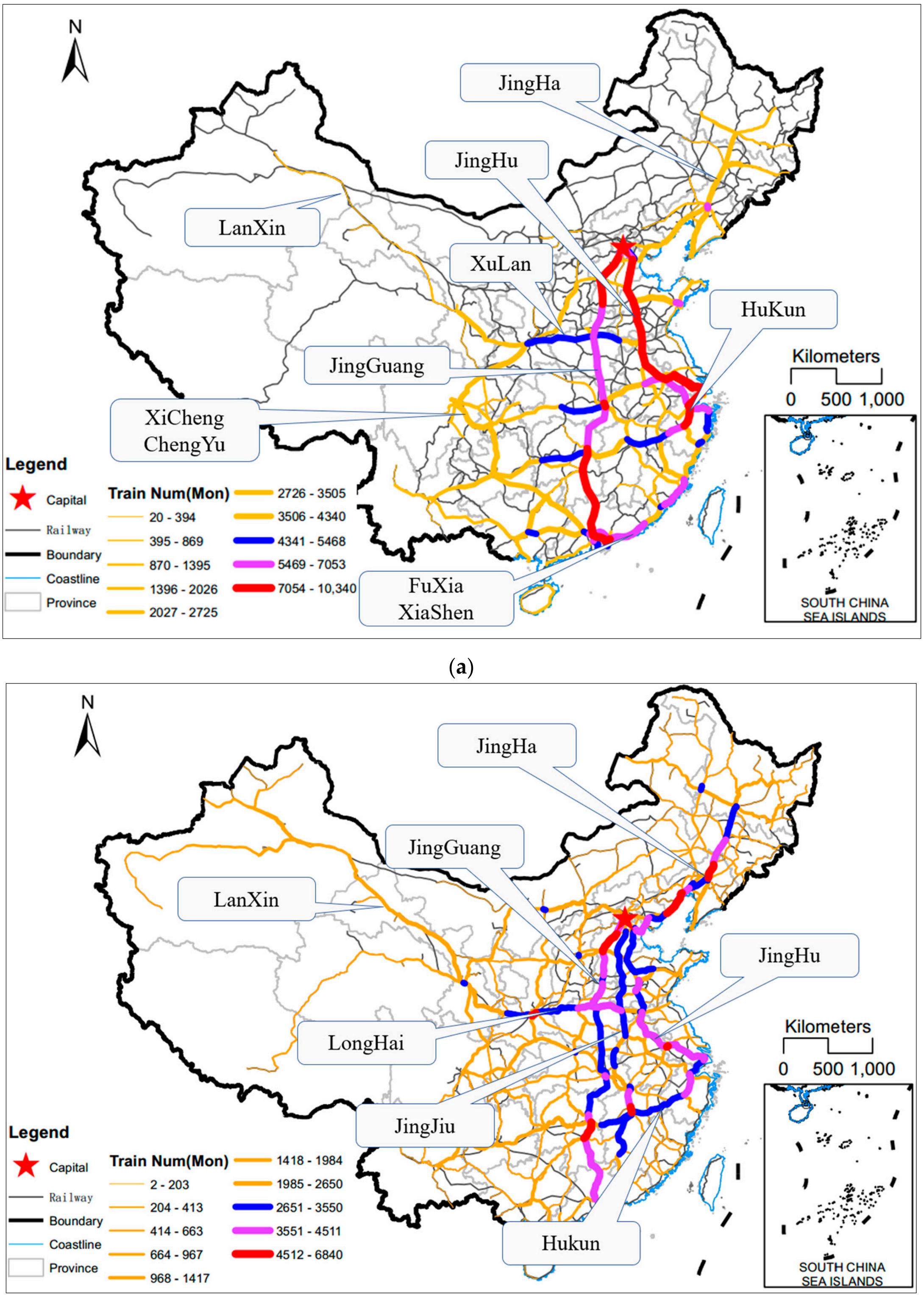
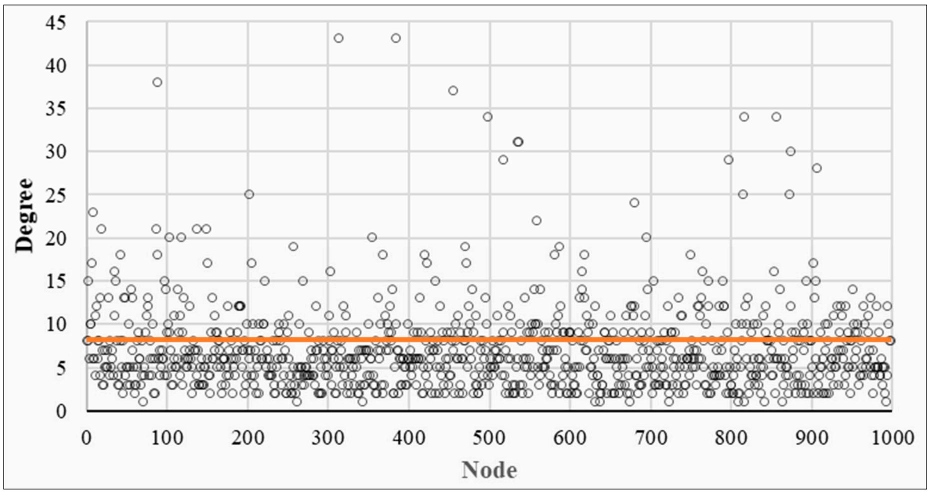


Figure 5. Spatial distribution of the geographic railway network. (**a**) The geographic network of high-speed railway. (**b**) The geographic network of normal-speed railway.

Table 2. Top 20 lines with most operating trains.

Train Number	Line	Train Number	Line
1000	Shanghai-Kunming High-speed Railway	604	Nanjing South-Chengdu East Railway Nanjing South-Chongqing Section
935	Beijing-Shanghai High-speed Railway	589	Beijing-Harbin Railway
840	Beijing-Shanghai Railway	585	Guangzhou-Shenzhen Railway
835	Beijing-Guangzhou Railway	575	Wuhan-Guangzhou Passenger Dedicated Railway
711	Beijing-Kowloon Railway	562	Xuzhou-Lanzhou High-speed Railway
709	Shanghai-Kunming Railway	510	Beijing-Shijiazhuang Passenger Dedicated Railway
683	Guangzhou-Shenzhen-Hong Kong High-speed Railway	453	Fuzhou-Xiamen Railway
675	Shiwu Passenger Dedicated Railway	413	Guiyang-Guangzhou Passenger Dedicated Railway
659	Xiamen-Shenzhen Railway	388	Liuzhou-Nanning Intercity Railway
624	Lanzhou-Lianyungang Railway	363	Shenyang-Dalian High-speed Railway



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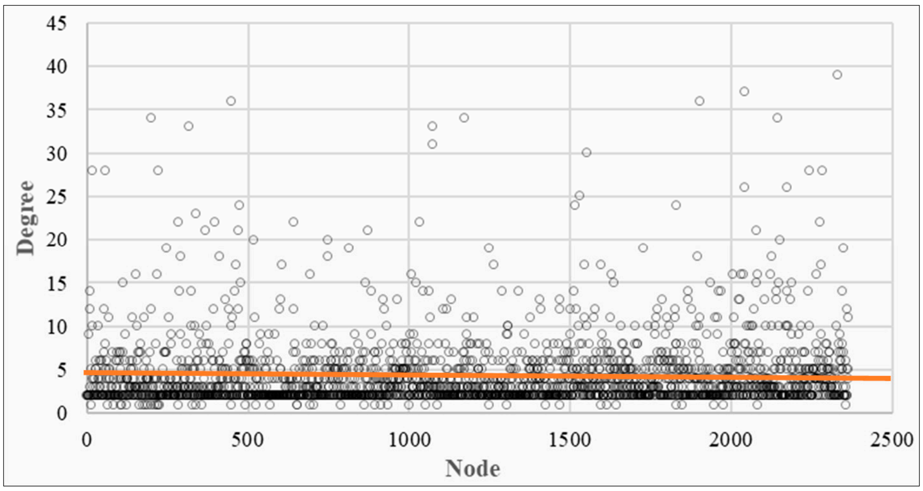


(**b**)

Figure 6. Node degree statistics of the geographic railway network. (**a**) Degree distribution of the high-speed railway network. (**b**) Degree distribution of the normal-speed railway network.

Compared with the geographic network of normal-speed railway, the connection among stations in the geographic network of high-speed railway is closer with a better accessibility. The stations with large node degree in the geographic network of high-speed railway are mainly located in the eastern and central provincial capitals or municipalities. This indicates that early construction of Chinese high-speed railway network starts from Eastern and Central China and focuses on connection with major cities. Besides which, cities in western China are in a relatively inferior position in the geographic network of high-speed railway. The stations with large node degree in the geographic network of normal-speed railway are mainly located in western, central and northeast China. This indicates that these regions still play an important role in the geographic network of normal-speed railway and are important places for construction and renovation of the high-speed railway in the future. As cooperation and connection among regions become closer, it is urgent to improve the high-speed railway between western region and other regions. In addition, Wuhan and Zhengzhou have a larger node degree in both the geographic network of high-speed railway and normal-speed railway, connecting multiple railway lines because they are located in central China and are important hubs connecting other part of China.

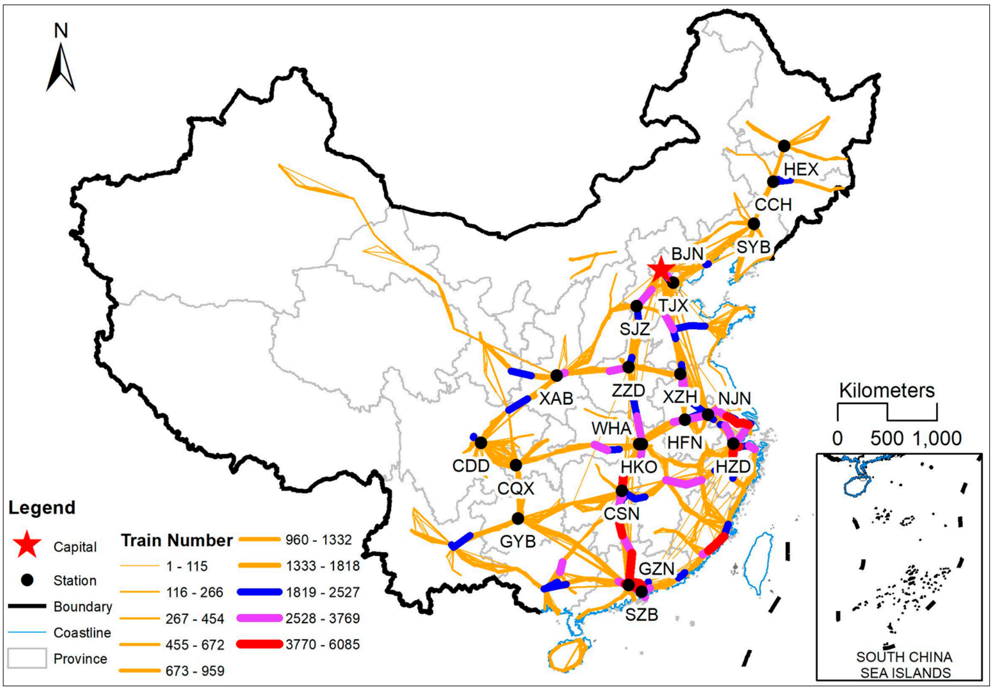
3.3.2. Analysis of Betweenness

The distribution characteristics of betweenness in the geographic railway network reflect the pivotal role of different stations in the network. Table 3 shows the top 20 betweenness values in the geographic railway network and Figure 7 shows the spatial distribution of the station. The important stations in the geographic network of high-speed railway are mainly located in provincial capital and municipalities. The top five stations with maximum betweenness value include Zhengzhou East Railway Station, Guangzhou South Railway Station, Beijing South Railway Station, Xi'an North Railway Station, and Shenyang North Railway Station. They are important traffic hubs in Central China, Southern China, North China, the Northwest, and Northeast of China. Some important stations in the geographic network of normal-speed railway are located in non-provincial cities. The top five stations with maximum betweenness value include Beijing Railway Station, Harbin Railway Station, Xi'an Railway Station, Fuyang Railway Station, and Lanzhou Railway Station.

The top 20 stations are very different in geographic network of normal-speed railway and high-speed railway. The important stations in geographic network of high-speed railway are mainly distributed along the "four-vertical and four-horizontal" passenger railway line, because stations and distribution of railway line in this region are denser. However, in the geographic network of normal-speed railway, there are no particularly important stations along the southeastern coastal area. However, there are multiple important stations in the west, especially Sichuan. Lanzhou Railway Station in Gansu is an important station that connects the central and western regions. In addition, the ranking of betweenness value of Changsha, Hangzhou and Zhengzhou is higher in the geographic network of high-speed railway, but lower in the geographic network of normal-speed railway. This indicates that they are important hub cities in the overall operation of the high-speed railway network, providing reference for the future line planning and station protection.

Table 3. Top 20 railway stations with largest betweenness.

High-Speed				Normal-Speed			
Station	**Sequence**	**Station**	**Sequence**	**Station**	**Sequence**	**Station**	**Sequence**
Zhengzhou East	1	Shenzhen North	11	Beijing	1	Guiyang	11
Guangzhou South	2	Chengdu East	12	Harbin	2	Shenyang	12
Beijing South	3	Xuzhou	13	Xi'an	3	Chengdu	13
Xi'an North	4	Hankou	14	Fuyang	4	Ankang	14
Shenyang North	5	Changsha South	15	Lanzhou	5	Dazhou	15
Nanjing South	6	Wuhan	16	Shijiazhuang	6	Guangyuan	16
Hangzhou East	7	Hefei South	17	Huaihua	7	Suihua	17
Shijiazhuang	8	Chongqing West	18	Tianjin	8	Taiyuan	18
Guiyang North	9	Changchun	19	Beijing West	9	Liupanshui	19
Tianjin West	10	Harbin West	20	Zhuzhou	10	Wuchang	20



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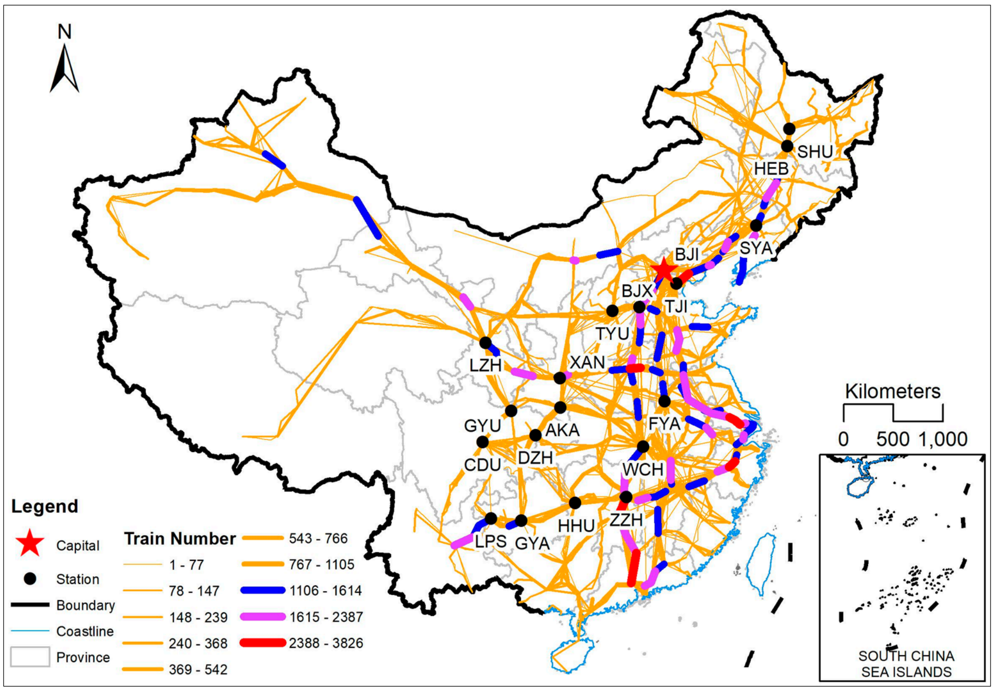
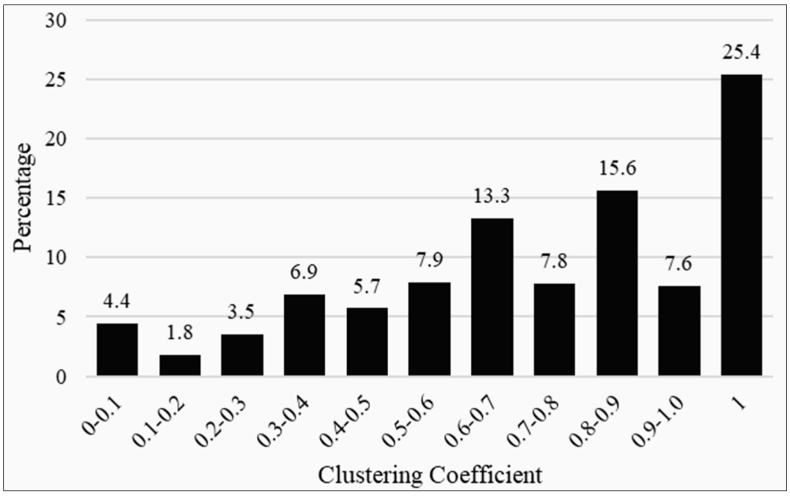


(**b**)

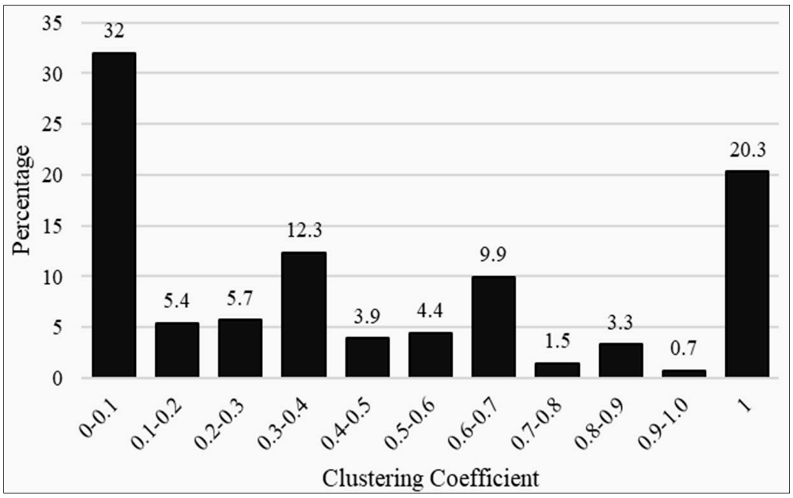
Figure 7. Distribution of stations with largest betweenness in the geographic railway network. (**a**) Station with the largest betweenness in high-speed railway network. (**b**) Station with the largest betweenness in normal-speed railway.

3.3.3. Analysis of Clustering Coefficient

A larger clustering coefficient indicates a closer connection between a node and its neighboring nodes. It is then easier to get to other stations from one station in the geographic railway network. When a node fails, the geographic railway network can still be connected and maintained. As shown in Figure 8a, the overall clustering coefficient of the high-speed railway network is relatively high in that station nodes with a coefficient of above 0.5 account for the vast majority, with an average clustering coefficient of 0.70. As shown in Figure 8b, the overall clustering coefficient of the normal-speed railway network is relatively low in that station nodes with a coefficient of below 0.5 account for the vast majority, with an average clustering coefficient of 0.42.



(**a**)



(**b**)

Figure 8. Percentage distribution of clustering coefficients of the geographic railway network. (**a**) Clustering coefficients of the high-speed railway network. (**b**) Clustering coefficients of the normal-speed railway network.

The geographic network of high-speed railway shows relatively high clustering because of two reasons. On one hand, the improvement of the high-speed railway network has enhanced the connection among cities. On the other hand, increased numbers of running high-speed trains, bullet trains, and non-stop trains has connected multiple inter-district urban nodes and improved connection among cities. Due to low accessibility of geographic network of normal-speed railway, transfer can be completed only at important hubs. This is because the normal-speed railway network is designed vertically and horizontally and there is no triangle and enclosed access among three adjacent nodes in the network. Therefore, it is necessary to increase lines among diagonal nodes in cross-shaped road network, and improve clustering degree of the network, thus ensuring a higher stability even under the attack of disaster.

3.4. Vulnerability Analysis of the Geographic Railway Network

The maximum possible destruction range under different seismic magnitude is calculated by the seismic attenuation equation. The equivalent intensity value at different positions in the geographic railway network is obtained through overlap analysis of the network in ArcGIS to measure the degree of seismic impact. Moreover, historical seismic point (ms ≥ 4.5) is used to calculate kernel density value which is classified into four levels by the natural fracture method to measure the possibility of earthquakes in different regions. As a result, equivalent intensity value and kernel density value are superposed to obtain the hazards diagram of the geographic railway network under earthquake disasters, and it is classified into five levels, as shown in Figure 9. Type I hazardous zone indicates that the railway line will be hardly influenced by the earthquake. Type II hazardous zone indicates that the railway line will be influenced by the earthquake, but degree of impact and possibility of earthquake are relatively low. Type V hazardous zone indicates that the railway line is susceptible to earthquake disasters and seismic destruction degree is very high. Type III & IV hazardous zones indicate conditions between the two. The railway lines in the geographic railway network that are greatly affected by the earthquake are mainly located in northwest, southwest, northeast and northern China, corresponding to Region 1, Region 2, Region 3 and Region 4 in the Figure. Besides which, the impacts are relatively small in southeast region.

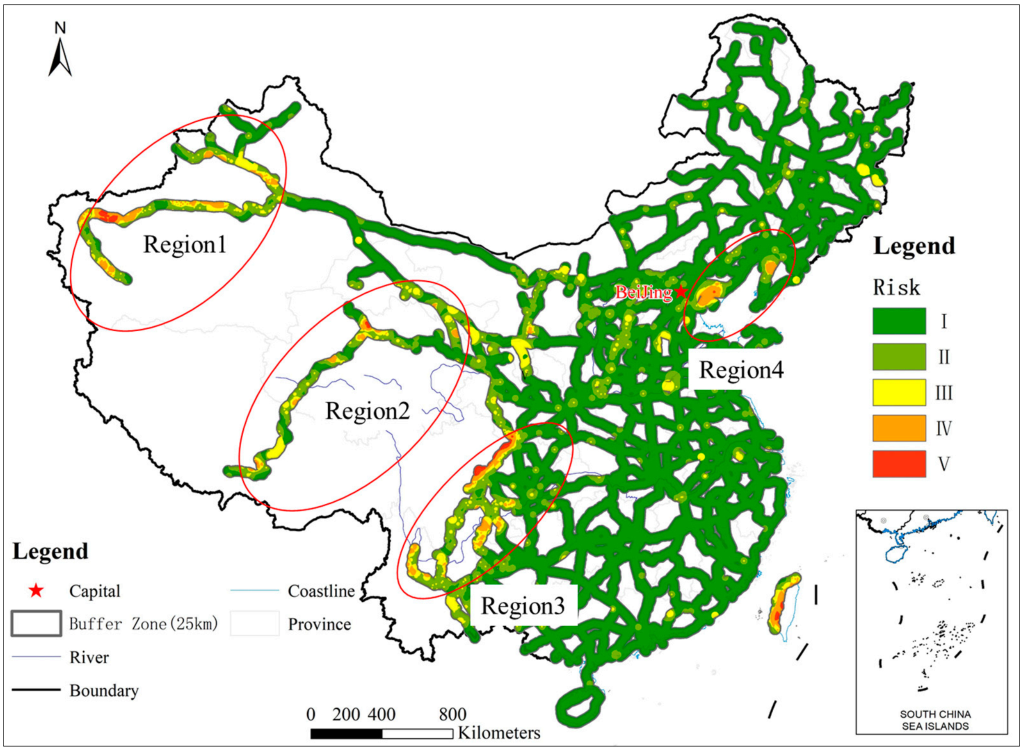


Figure 9. Hazard assessment of earthquake disasters.

Figure 10 shows the impacts of earthquakes on railway lines within the four regions. In Region 1, railway lines affected mainly include Southern Xinjiang Railway, Kashi Railway, and Lanzhou-Xinjiang Railway. In Region 2, railway lines affected mainly include Qinghai-Tibet Railway, and Lanzhou-Xinjiang High-speed Railway. In Region 3, railway lines affected mainly include Dali-Lijiang Railway, Neijiang-Liupanshui Railway, Chengdu-Guiyang High-speed Railway, Baoji-Chengdu Railway, Xi'an-Chengdu High-Speed Railway, Chengdu-Ya'an Railway, Chengdu-Chongqing Railway, and Chengdu-Chongqing High-speed Railway. In Region 4, although the areas affected are relatively small, more railway lines are affected due to dense railway line, including Beijing-Harbin Railway, Tianjin-Qinhuangdao High-speed Railway, Tianjin-Shanhaiguan Railway in Beijing-Tianjin-Hebei region, and Shenyang-Dalian High-speed Railway, Shenyang-Dalian Railway, Panjin-Yingkou High-speed Railway, and Goubangzi-Haicheng Railway in Liaoning Province. Table 4 shows the number of trains and railroad sections under impacts of earthquakes within the four regions.

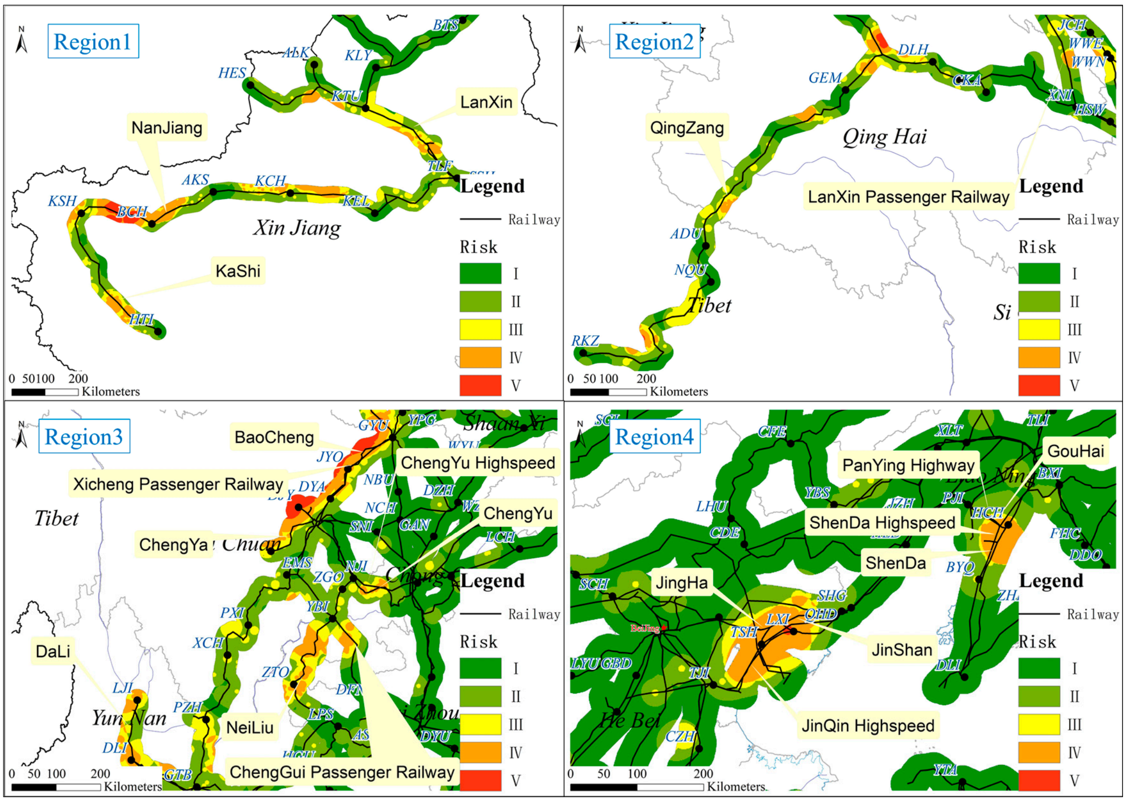


Figure 10. Railway lines under impacts of earthquakes within the four regions.

Table 4. Number of trains and railroad sections under impacts of earthquake disasters within the four regions.

No.	Railway	Segment	Trains Affected (Day)	Type
1	Beijing-Harbin Railway	Yutian County-Changli	143	High-speed
2	Chengdu-Chongqing High-Speed Railway	Rongchang North-Dazu South	135	High-speed
3	Shenyang-Dalian High-speed Railway	Haicheng West-Gaizhou West	126	High-speed
4	Tianjin-Shanhaiguan Railway	Lulong-Binhai North	125	Normal-speed
5	Xi'an-Chengdu High-Speed Railway	Guangyuan-Deyang	117	High-speed
6	Chengdu-Dujiangyan Railway	Hongguang Town–Qingcheng Mountain	116	Normal-speed
7	Tianjin-Qinhuangdao High-speed Railway	Beidaihe-Binhai North	101	High-speed
8	Shenyang-Dalian Railway	Haicheng-Gaizhou	76	Normal-speed
9	Lanzhou-Xinjiang Railway	Urumqi South-Kuitun	66	Normal-speed
10	Chengdu-Ya"an Railway	Chongzhou-Xilai	45	Normal-speed

Earthquakes have different impacts on the geographic network of national railway. This paper mainly selected train stations in type IV & V regions with high seismic hazards and analyzed the influences on the overall network efficiency through removing the network edge connected with stations. If all stations in the region with high seismic hazards are attacked and cannot work normally, overall network efficiency will decline by 7.5% for the geographic network of high-speed railway and 7.2% for the geographic network of common-speed railway. This indicates that although the earthquake happened in the local region, it will have serious impacts on the geographic network of the railway system as a whole. Table 5 shows the important stations in the geographic railway network.

Table 5. Important stations in the geographic railway network.

High-Speed			Normal-Speed		
Station	V_i	**Class of Station**	**Station**	V_i	**Class of Station**
Yingkou East	0.0047	First-grade station	Dashiqiao	0.0050	Second-grade Station
Tangshan	0.0029	First-grade station	Tangshan	0.0043	First-grade station
Binhai North	0.0024	NA	Kashgar	0.0042	First-grade station
Longchang North	0.0024	Third-grade station	Panzhihua	0.0032	NA
Rongchang North	0.0024	Third-grade station	Zhaotong	0.0029	Third-grade station
Dazu South	0.0024	NA	Tongxin	0.0024	Fourth-grade Station
Haicheng West	0.0024	Second-grade Station	Yingxiang street	0.0022	Fourth-grade Station
Raoping	0.0023	Fourth-grade Station	Longchang	0.0018	NA
Zhao'an	0.0023	Fourth-grade Station	Pishan	0.0017	NA
Tangshan North	0.0023	Second-grade Station	Tangshan North	0.0016	Second-grade Station

According to the management characteristics of railway stations in China, the emergency rescue resources are distributed as per grade of station in the railway network. Although some stations have low grade, they play important roles in the railway network. Besides which, these second and third-grade stations are not distributed with enough resources due to grade limitation; once an emergency occurs, it is difficult to ensure the safe operation of the railway network and to meet the requirements for emergency rescue. Therefore, it is necessary to provide some stations with professional rescue resources in a proper manner and improve supported emergency service facilities to provide rapid rescue in case of emergency, enhance the response capacity of emergency management systems, and guarantee the safe operation of the railway network in China.

4. Conclusions and Prospects

In order to solve problems in existing studies, such as inconsistency between logical network and real-world spatial position, and the negligence of actual impacts from earthquake disasters in vulnerability analysis of railway line, this paper implemented a vulnerability analysis of the geographic railway network under earthquake disasters. First, this paper built a geographic network of the actual railway and analyzed characteristics of topological structure of the geographic railway network based on complex network theory, linear reference, and dynamic segmentation. Although the geographic network of the high-speed railway is mainly located in the eastern and central region, their connection is closer, showing better accessibility. The important stations are mainly distributed along the "four-vertical and four-horizontal" passenger railway line. Although the geographic network of normal-speed railway with wide coverage range plays an important role in passenger transport, especially in the northern and western region, they have low connection and poor accessibility, and transfer can be completed only through important hubs. Second, this paper collected data of national earthquake points and conducted vulnerability analysis of geographic railway network under earthquake disasters. The lines that are greatly influenced by earthquake disasters in the geographic network of railway are mainly located in northwest, southwest, northeast, and northern China. If all stations in high hazardous zones are attacked and therefore cannot work normally, then the overall network efficiency will decline. Therefore, it is necessary to design railway stations for rescue resources in a rational manner and improve supported railway emergency service facilities.

There is also some literature on the vulnerability of railway network in Europe. These studies focus on the mechanism of disaster occurrence, and the vulnerability of transportation network is obtained through overlap analysis of hazardous areas and transportation network under a single network [42–44].

Compared with these studies, the method proposed in this paper can quickly realize the association of logical network and geographical network. On this basis, the vulnerability assessment of the railway network under earthquake disasters is implemented. Of course, there are some defects in this paper. First, data of earthquake disasters points in this paper were all collected from public information and resources on the Internet, which will inevitably cause missing and erroneous data. Therefore, it is necessary to build a complete and accurate database for earthquake data. Second, existing data of earthquake points are nationwide, and there is no data of earthquake disasters specialized in railway lines. Therefore, related data can be collected for further analysis. Third, due to the lack of freight train data, this paper only focuses on the passenger railway network in mainland China. The freight railway data can be added to construct a more perfect geographic railway network in further study. Finally, this paper only considered the vulnerability of the geographic railway network under earthquake disasters. In fact, the railway system may suffer from various disasters. Therefore, it is necessary to improve the dataset of geological disasters and further discuss the vulnerability of the geographic railway network under various disasters.

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