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Quantitative Study on the Waterlogging Resilience of Road Transportation System Based on the Validity View of System Functions

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Abstract

Waterlogging disasters cause significant threats to road transportation system. Scholars are currently focusing on the manner in which disaster resilience of road transportation system can be measured to improve the disaster control capability of an entire road transportation system. However, existing studies lack of quantitative analysis on the waterlogging resilience of road transportation system. This study analyzed the validity of network system structure by combining percolation theory on the basis of the validity view of system functions proposed by Pimm to construct a waterlogging resilience measurement model of road transportation systems and recognize the weak region of waterlogging resilience during a quantitative study. A resilience measurement model of an urban road transportation system in the context of waterlogging disasters was constructed. On this basis, the lost key connections, which were used as the weak region of waterlogging resilience in road transportation system, were recognized. Results demonstrated that the constructed waterlogging resilience measurement model could quantify the waterlogging resilience of the road transportation system throughout the process and highlight the dynamic features of waterlogging disasters. In the weak resilience region recognized in the quantitative study based on percolation theory, the percolation phenomenon of system network may disappear once the key connections are broken. Conclusions offset the shortcomings of previous resilience quantitative studies in the lack of waterlogging disaster analysis. The study results of waterlogging resilience of road transport system are applied directly to optimal decision making on resilience by combining the topology of system network and the post-disaster behavioral characteristics of users. This study provides a new method and decision-making idea to evaluate the disaster resilience of road transportation system.

Keywords: Road transportation system, Waterlogging disaster, Resilience

1. Introduction

Waterlogging disasters have caused considerable economic losses and ecological damages in developing cities [1]. As an important part of urban infrastructure, road transportation system is significantly affected by waterlogging disasters. Waterlogging has become the primary natural disaster that affects the normal operation of road transportation system. The resilience of road transportation system has attracted the attention of relevant scholars as an important attribute of urban infrastructure. This attribute is defined as a function of the number of reliable routes among all nodes in the system network [2] and it represents the capability of the system network structure to maintain functions after node loss or connection interruption [3]. A quantitative study on the waterlogging resilience of road transportation system is the basis for improving the disaster control capability of an entire road transportation system.

Existing quantitative studies on the resilience of road transportation system have mainly focus on the topological structural features of networks, as well as the role and characteristics of network topology in the responses of road transportation system to disasters [3]. These studies have estimated the resilience of urban nodes by the weighted average of reliable routes at an urban node in the network and calculate the network resilience by the weighted sum of resilience at all nodes [2]. However, they lack considerations to the dynamic features of resilience and fail to realize an integral study on the entire changing process of network topology. Alternatively, existing associated studies represent system adaptation to destructive events and recovery capability by users' responses. However, users' decision can affect their perception of the influences of destructive events on traffic conditions [4]. In addition, scenario analyses based on post-disaster recovery from the network perspective investigate disaster resilience [5], and attach significant attention to the resilience of road transportation systems to earthquake disasters [6]; however, they cover waterlogging resilience insufficiently. Generally, studies on the resilience of road transportation systems mainly focus on three aspects but lack the organic combination of these aspects. Resilience dynamics is also neglected in topological structural studies. Few scenario analyses based on waterlogging disasters have been conducted, and the quantitative analysis results of resilience are indirectly connected with the subsequent optimal decision making.

On this basis, a waterlogging resilience measurement model of road transportation system was constructed by combining scenario analysis and percolation theory based on Pimm's view that resilience is to maintain the validity of system functions. Real-time features of the waterlogging resilience of a road transportation system were characterized,

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and the post-waterlogging behavioral features of users were reflected in the topology of the system network. The dynamic characteristics of the waterlogging resilience of road transportation system were investigated.The topological structure of road transportation system was combined with post-waterlogging scenario analysis and user behavioral characteristics. The weak regions of waterlogging resilience of road transportation system were recognized during quantitative studies. Conclusions on resilience can provide beneficial references for follow-up optimal decision making and have important practical significance for waterlogging risk reduction in future.

2. State of the art

With respect to quantitative studies on the resilience of road transportation systems, many of existing studies have investigated the topological structural characteristics of road transportation system.

The topological attributes of road transportation systems influence their recovery from disasters significantly. Network topology is vital to the disaster resistance of road transportation system [3]. Wang Dingwei et al. proposed a quantitative assessment of resilience and claimed that the traffic viability of cities depends on the number of independent routes among them. The author assessed the resilience of urban nodes by the weighted average of reliable independent routes among all other urban nodes in the network and calculated the network resilience by the weighted sum of resilience of all urban nodes [2]. Cetinkaya et al. compared the standardized Laplace spectra of the physical and logical layer topologies of four Internet service providers and two research networks with that of the highway topology in the United States. They analyzed the structural similarity between the physical layer communication network and highway topology in the United States [7]. Moreover, system can be expressed as a group of nodes by the network, and these nodes connect mutually [8]. Testa et al. measured the topological characteristics of coastal transportation network to assess the resilience of the transportation network to extreme weather events. Nodes and connections in the network were eliminated to simulate faults and shutoffs caused by extreme climatic events [9]. In the same time, a transportation network was also developed by the GPS trajectories of taxis, and its topological characteristics were quantified. A temporal statistical monitoring of the topological characteristics of the transportation network was performed with a process control system, which could determine the abnormal mode caused by extreme events and analyze the resilience of the transportation network [10].

Moreover, some scholars have reported on the waterlogging resilience of road transportation system based on the post-disaster behavioral characteristics of users. Users are apt to change routes upon traffic congestion in one or more roads, bridges, or tunnels and even give up the travel plan for poor traffic conditions [11]. Therefore, the post-disaster behavioral characteristics of users can be used to represent the resilience of road transportation system. Users' response shall be considered in the resilience evaluation. Their response reflects the adaption to destructive events and main recovery capability from disasters of the system. Their decision may affect their perceptive to traffic conditions [4]. In view of users' behavior, Alderson et al. quantified the resilience of a road transportation system by the calculation model of the increased nonlinear traveling time caused by traffic congestion. This model showed the actual travel demands gained from a demographic census in the United States [11]. In view of the behaviors of passengers, Adjetey-Bahun et al. proposed a resilience quantification model based on a simulated large-scale railway transport system, in which the delay and loads of passengers were used as indexes of the system performance [12]. Donovan et al. developed a quantitative measurement method of the resilience of transportation systems by using the GPS data of detection vehicles, such as taxi. GPS data needed in this method included the beginning and terminal coordinates of the journey, metric distance, and total travel time. This method was applied to the traveling dataset of taxis in New York to analyze the resistance of urban traffic infrastructure to Hurricane Sandy [13]. Zhu et al. studied the effects of Hurricanes Sandy and Irene on traveling by taxis and subways on the basis of big data. They also discussed the recovery mode of road and subway systems in New York from natural disasters on the basis of traveling data by taxis and data on subway passenger flow [14].

In addition, waterlogging resilience has been studied by post-disaster scenario analysis. In the context of post-disaster recovery, disaster resilience has been analyzed from the network perspective [5]. Twumasi-Boakye et al. studied the resilience of a regional transportation network and proposed a scene-based traffic modeling and an assessment framework of regional network resilience based on GIS technology, given the damages of bridges by disasters [15]. Zhang and Miller-Hooks proposed a random time-varying integer programming method with a recursive function to assess the disaster resistance of a rail freight system [16]. Kilanitis et al. constructed a comprehensive multicriteria framework for earthquake disasters, considering the resilience of a road transportation system to earthquake loads; they also introduced a set of new time-varying indexes and evaluated the total losses in the entire recovery period using an accumulation index [6]. Alipour et al. concentrated on the earthquake resilience of a road–bridge network with considerations to the extensive social and economic consequences of network damages, given damages to roads and bridges after earthquakes might cause serious functional degeneration of the entire network [17]. Rural transportation networks are vulnerable to geological disasters, such as earthquake and landslide; therefore, Aydin et al. proposed a method to assess the resilience of road transportation system. This method evaluated the resilience of a road transportation system by the connections after blockage caused by earthquakes and earthquake-induced landslide [18]. In addition to earthquake disasters, Chan et al. studied Hurricanes Irene and Sandy and the snowstorm in New York. They proposed a graphic analytic index for the regular assessment of the resilience of road transportation system from weather-induced interruption [19].

To sum up, existing studies on the disaster resilience of road transportation system mainly focus on the topological characteristics of the network and post-disaster user behaviors, and post-disasterscenario analyses. IIbeigi and Mohammad [10] proposed a research method that combined the topological structure of a road transportation system and post-disaster user behavioral characteristics. The method proposed by Donovan [13] and Zhu [14] integrated the post-disaster user behavioral characteristics and post-disaster scenario analysis. However, few studies have combined two of three aspects, not to mention the combination of three aspects. Waterlogging disaster is also hardly applied in scenario analysis because it has dynamic features different from other geological disasters. As a result, previous quantitative studies on disaster resilience based on network topology have overlooked the dynamic features of resilience. Conducting an integral study on the entire process of changes in the network structure is impossible. Furthermore, a quantitative study on the resilience of a transportation system neither has direct connections with the follow-up optimal decision making nor discloses the relationship between research conclusions and the resilience improvement of road transportation system.

To address the shortcomings of the aforementioned studies, a reasonable entry point for study on the resilience of road transportation system was accordingly sought in the present work from the basic concept of resilience. Two different research modes exist on the concept of resilience; one is Holling's concept that resilience is to maintain the existence of system functions [20], and the other is Pimm's concept that resilience is to maintain the validity of system functions [21]. The latter concept is more applicable to engineering resilience. The waterlogging resilience of road transportation system belongs to the scope of engineering resilience. On this basis, Pimm's concept of resilience was used as the entry point in the present study. A waterlogging resilience measurement model of road transportation system was constructed on the basis of percolation theory, combined with the basic idea of Bruneau that the area between the system functional curve and the coordinate system is used to represent resilience [22]. In this model, post-disaster user behavioral characteristics were reflected in the topology of the road transportation system to investigate the dynamic features of the waterlogging resilience of the system. The lost key connections in the network were recognized as the weak regions of waterlogging resilience in the network by using percolation theory. This study could provide beneficial references to cope with dangerous waterlogging events and for optimal decision making over the resilience of road transportation system.

The remainder of this study is organized as follows. Section 3 introduces the research methods of the waterlogging resilience of the road transportation system, the determination of the threshold of road transportation system, the construction of the time history response function of the road transportation system to waterlogging disasters, and the recognition of weak resilience regions in the road transportation system from waterlogging disasters. Section 4 provides the result analysis. Section 5 presents the conclusions.

3. Methodology

3.1 Determining the threshold of the network structure of the road transportation system

In this study, the loss of validity of functions of the road transportation system indicates that the integral road transportation system has lost integrity of the entire region at one moment or in one period rather than the complete fragmentation of the network structure. On this basis, validity of the network topology was analyzed by percolation theory. The phase change process of a road transportation system fault was described by percolation theory, and the threshold P_c of this network was gained through its topological information. Whether the network breaks down was determined by this threshold.

In percolation theory, P_c is the critical probability for developing the main network cluster. In other words, the road transportation system network has a critical probability of P_c.

The road transportation system network is supposed to be a random network composed of N nodes, and each node is connected to surrounding nodes. The number of connections of one node with others is defined as the degree d_i, which can be expressed as

$$d_i = \sum_{i \neq j}^{n} a_{ij} \qquad i,j = 1,2,...n \tag{1}$$

where a_{ij} is the binary variable. When a connection exists between nodes i and j, a_{ij} =1; otherwise, a_{ij} =0. d_i is the degree of node i. On the basis of the degree of a node, the average degree of the network structure is calculated by:

$$\langle d \rangle = \sum_{i=1}^{n} d_i \Big/ N \tag{2}$$

where $\langle d \rangle$ is the average degree of all nodes. Finally, the P_c of the road transportation system network can be expressed as

$$P_c = 1 \big/ \langle d \rangle \tag{3}$$

3.2 Establishing the time history response function of the road transportation system network to waterlogging disasters

A time history response function of the road transportation system network was established to measure its resilience. With this time history response function, dynamic changes in waterlogging resilience throughout the process could be investigated.

A road transportation system is a system composed of N units. The road transportation system network topology is a network system composed of N nodes and segments. Moreover, the road transportation system and its units have the following properties:

(1) Nodes in the system only have two states, namely, valid and invalid;

(2) State of the system is completely determined by its structure and state of nodes.

The state of node i is described by a binary variable x_i. If node i is in G, then the node is valid; otherwise, it is invalid. G is the largest cluster in the network.

$$x_i = \begin{cases} 1, node \quad validity \\ 0, node\, invalidity \end{cases} \quad i = 1,2,...,N \tag{4}$$

where i reflects any node. x_i is the binary variable used to describe the state of node i. Therefore, the time history response function of the road transportation system is defined as

$$Q_{tm} = \sum_{i=1}^{N} x_i \Big/ N, m = 1,\ 2,\ \ldots, n \tag{5}$$

where Q_{tm} is the time history response function of the road transportation system. t_m denotes the moment m. The road transportation system is composed of *N* different nodes, which are connected through routes. These connections are destroyed upon the occurrence of waterlogging disaster, and increasing nodes are isolated continuously. Nodes that are separated from the largest cluster are viewed as invalid nodes, whereas nodes that remain in the largest cluster are viewed as valid ones. The number of valid nodes in the road transportation system at each moment is recorded to represent the functional validity of the system. The study period is divided into n ($t_1 < t_2 < ...t_m... < t_n$) on the basis of the interval of Δt. If the number of invalid nodes at one moment is *a*, then the corresponding Q_{tm} is *a*/*N*. This functional value is placed in the *m*-th interval.

In this manner, *a* valid nodes exist in the *m*-th interval, which implies that the largest cluster contains *a* valid nodes at this moment. The frequency histogram of the time history function is shown in Fig. 1.

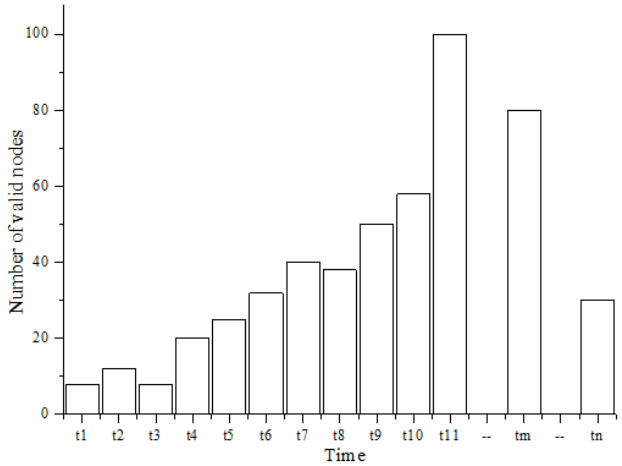

Fig. 1. Frequency histogram of the time history function of the road transportation system

One moment t_m was selected for observation. The sum of all functional values before t_m is $Q(t)$, which can be expressed as follows:

$$Q(t) = \sum_{m=1}^{n} \Delta t \times Q_{tm} \tag{6}$$

The time interval decreases with the increase of the selected moments. In other words, when $n \to \infty$ and $\Delta t \to 0$, $Q(t)$ can be approximately expressed as

$$Q(t) = \int_0^n Q_{tm} dt \tag{7}$$

Pimm deemed that resilience refers to the system resistance to disturbances. The expression of resilience is to measure the speed or time for a system to recover the original equilibrium state after disturbance. Bruneau et al. emphasized that the resilience of key urban infrastructure systems is a concept that can be measured quantitatively. They illustrated such quantitative measurement from four dimensions and four features of resilience. On this basis, the resilience quantitative measurement model of urban infrastructure was proposed. In accordance with the curve model of the functional response process of a road transportation system, Ouyang M, Duenas-Osorio L and Min X constructed the "three-stage" resilience analysis framework for infrastructure [23]. The ratio between the area closed by post-disaster functional curve and the time axis to the area closed by the functional curve under normal conditions and the time axis was used as the measurement standard of resilience.

On this basis, the time history response function of the road transportation system Q'_{tm} is

$$Q'_{tm} = 100\% \tag{8}$$

Therefore, the sum of all functional values before t_m is $Q'(t)$, as expressed as follows:

$$Q'(t) = n \times \Delta t \times 100\% \tag{9}$$

where Δt is the time interval. On the basis of the aforementioned constructed waterlogging scenario, the time history response function of the road transportation system views resilience as the ratio between $Q(t)$ after the occurrence of waterlogging and $Q'(t)$ under normal situations in the study period, which can be expressed as follows:

$$R = Q(t) / Q'(t) \tag{10}$$

Invalid nodes are constantly changing; hence, $Q(t)$ is more accurate when Δt is smaller, and the actual response can be reflected better. This condition can be understood as the integration of Q_{tm} in the study period *T*, which is divided into *n* parts equally.

$$R = \int_0^n Q_{tm} dt \Big/ n \times \Delta t \tag{11}$$

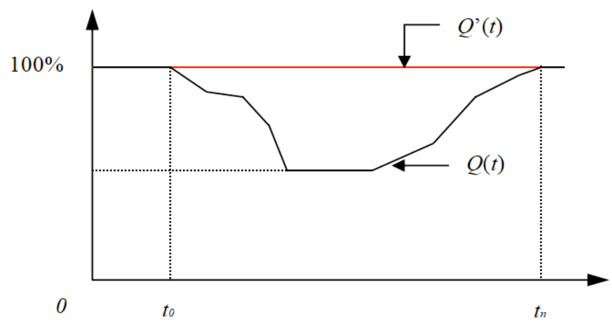

Fig. 2. Conceptual graph of waterlogging resilience of the road transportation system

The aforementioned condition only depicts the validity of nodes in a system. The functional validity of a road transportation system changes accordingly with the decrease of valid nodes and the increase of invalid nodes. This process pertains to the quantitative change that triggers qualitative change. The moment of system failure is determined combined with the preceding P_c.

The state of the road transportation system is described by a binary function $\delta(X)$ as follows:

$$\delta(X) = \delta(x_1, x_2, ..., x_n) = \begin{cases} 1, & system \quad validity \\ 0, & system \ invalidity \end{cases} \tag{12}$$

where X is the n-dimensional vector $X = (x_1, x_2, \ldots, x_n)$. The binary function $\delta(X)$ is defined as the structural function of a road transportation system. For a random network involving N nodes, the system fails when the number of valid nodes is lower than $N \times P_c$. This condition can be expressed as

$$\delta(X) = \delta(x_1, x_2, \ldots, x_n) = \begin{cases} 1, \sum_{i=1}^{n} x_i \geq N \times P_c \\ 0, \sum_{i=1}^{n} x_i < N \times P_c \end{cases} \quad (13)$$

3.3 Recognizing the weak regions of waterlogging resilience of the road transportation system

Complicated correlations of nodes exist in the road transportation system, and most of them have significant nonlinear features. Thus, interruption or breakdown of one key connection can affect the connections of other nodes that are closely related with the failed node. This phenomenon will produce a domino effect on the functions of the entire road transportation system and intensify the influence of waterlogging. In percolation theory, *SG* can be used as the failure indicator of the road transportation system network. This indicator can be used to recognize key connections and determine their importance in the entire network, thereby enabling the weak regions of waterlogging resilience to be recognized. Hence, results of resilience are directly connected with the optimal decision making of resilience.

In topology, the road transportation system network is a random network composed of N nodes and P sides. The network is expressed as a weighted undirected graph G= (N, P) (Fig. 3).

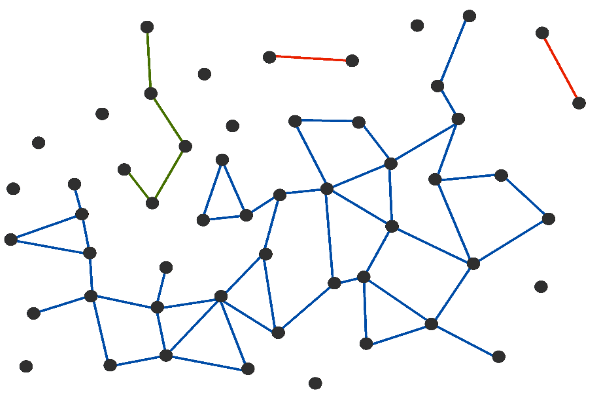

Fig. 3. Structure of the road transportation system network

Percolation state refers to the occurrence of a large cluster in the system to connect and infiltrate the left and right boundaries or the upper and lower boundaries of the system.

Different colors of clusters are observed in Fig. 3. The same color of clusters denotes nodes in the same group of connection, and any node in the same cluster can be connected through routes. G is the largest cluster in the network, followed by *SG*. As time goes by, connections between one node and others are broken successively, thereby narrowing G and changing *SG* continuously. On the basis of percolation theory, when *SG* reaches the maximum size, the network structure will be broken. This *SG* can be used as the failure indicator of the road transportation system network.

In percolation, some connections play an important role in the network structure. If G loses these connections, then the network structure is broken and *SG* reaches the maximum size. Moreover, the network functions are changed considerably, and the road transportation system becomes invalid once key connections between *SG* and G are lost. These key connections are defined as the weak regions of waterlogging resilience in the network. The spatial distribution of these key connections is analyzed (Fig. 4).

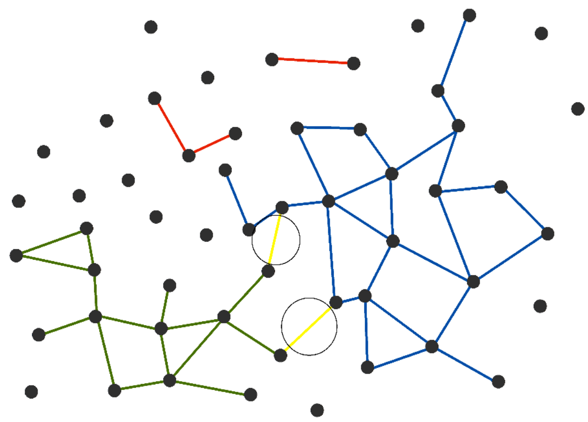

Fig. 4. Recognition of the weak regions of waterlogging resilience in the road transportation system network

As shown in Fig. 4, two marked connections are weak regions. After G loses these two connections, the network structure breaks down suddenly. At this moment, *SG* reaches the maximum size, which proves the key role of the two connections in *SG* and G. Once the two connections are lost, functions of the entire road transportation system network will also be lost.

4 Result analysis and discussion

Nanjing City was selected as the study object in this case study to validate the constructed model. A rainstorm occurred in Nanjing on May 25, 2018. According to the weather forecast on that day, the rainfall started from 14:30 and lasted for 270 min. Data were collected every 10 min from 14:30 to 19:00 to analyze the traffic congestion in Nanjing. The waterlogging resilience of the road transportation system in Nanjing City was investigated and weak regions were recognized on the basis of these data. The waterlogging resilience distribution of the road transportation system in Nanjing City was drawn by combining the time history response function.

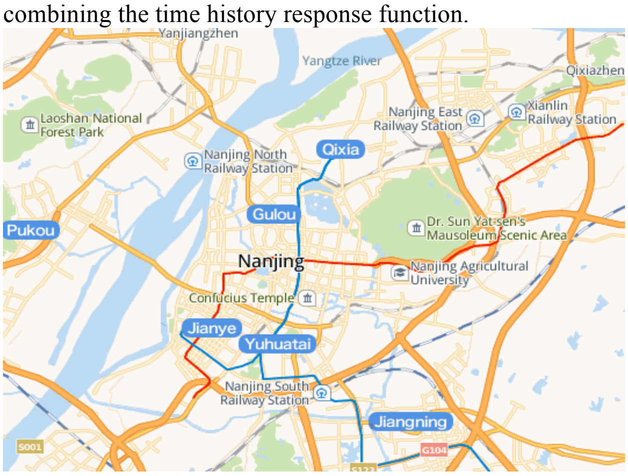

Fig. 5. Waterlogging resilience of the road transportation system in Nanjing City

4.1 Calculating the threshold of the road transportation system

The P_c in the road transportation system in Nanjing City was calculated by the method in Section 3.1. The real-time traffic congestion of the road transportation system in Nanjing City was comprehended combined with one rainfall process. The spatial network topological model of the road transportation system in Nanjing City was drawn on the basis of the simulation platform of GIS. Moreover, the percolation conditions of the road transportation system in Nanjing City were presented on the basis of percolation theory. In the study area, the road transportation system is a random network composed of 212 nodes. The network topology of the road transportation system in Nanjing City at the initial moment (t_0) is shown in Fig. 6, where G is the cluster formed by green lines, and SG is the cluster formed by red lines.

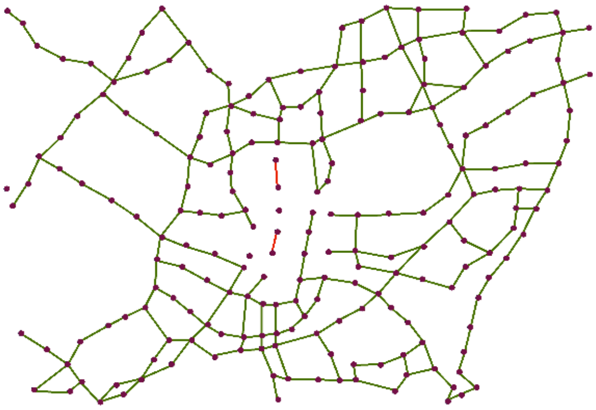

Fig. 6. Network topology of the road transportation system in Nanjing City (t_0)

The distributions of the degree of nodes d_i in the network are shown in Fig. 7.

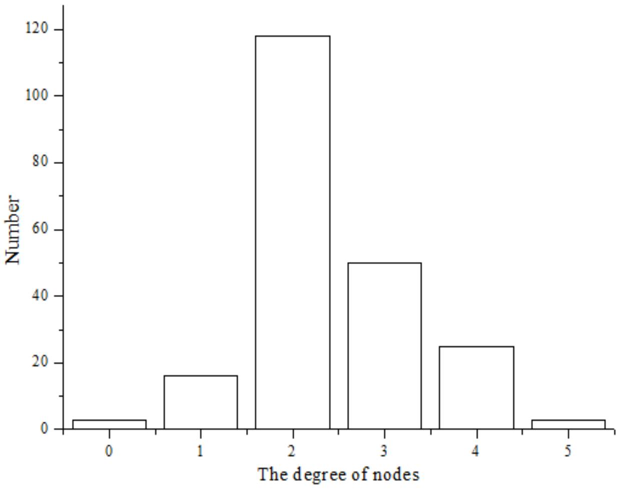

Fig. 7. Distributions of degree of nodes

The average degree of nodes of the road transportation system was calculated from Eq. (2) as $<d>=517/212=2.4387$. Finally, the percolation threshold was calculated from Eq. (3) as $P_c = 1/2.4387 = 0.4101$.

4.2 Calculating the waterlogging resilience of the road transportation system and recognizing weak regions

The waterlogging resilience of the road transportation system in Nanjing City was analyzed in this section on the basis of the time history response function of the waterlogging resilience of the road transportation system in Section 3.2 and weak regions were recognized in Section 3.3, waterlogging resilience of road transportation system in Nanjing City was analyzed in this section.

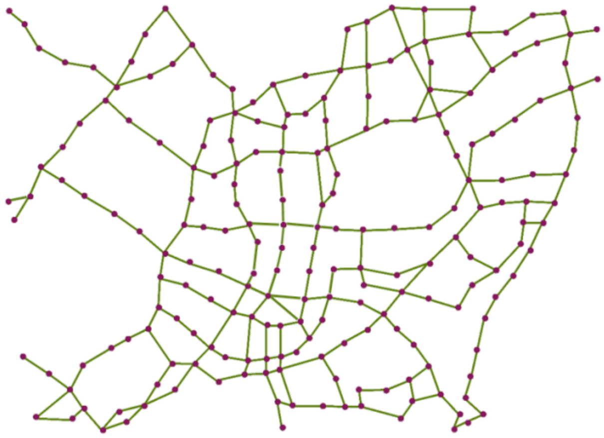

Fig. 8. Road network in the study area

The ideal road transportation system in Nanjing City is shown in Fig. 8. The topological structure of the road transportation system in Nanjing City was drawn. No isolated nodes and region existed in the entire network. Therefore, the road network connected the entire study area.

For the road network in the study area, N=212, and the initial time was recorded as t_0. The time interval was Δt =10 min. Moreover, T=270 min and n=27.

After the rainfall, the network structure was changed. The largest cluster G lost some connections, and isolated nodes and clusters began to be produced. However, these isolated nodes and clusters were extremely small to influence the entire road network.

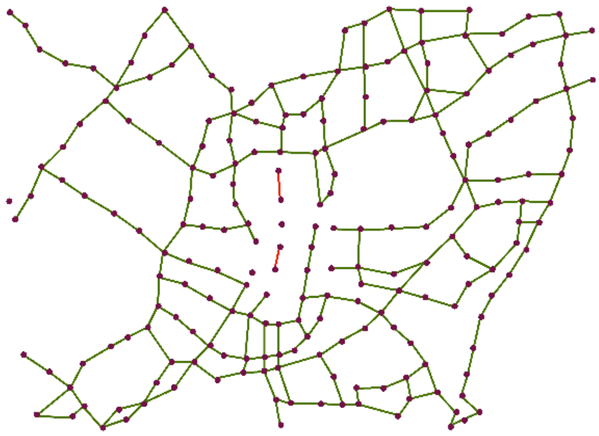

Fig. 9. Percolation chart of the road network (t_1)

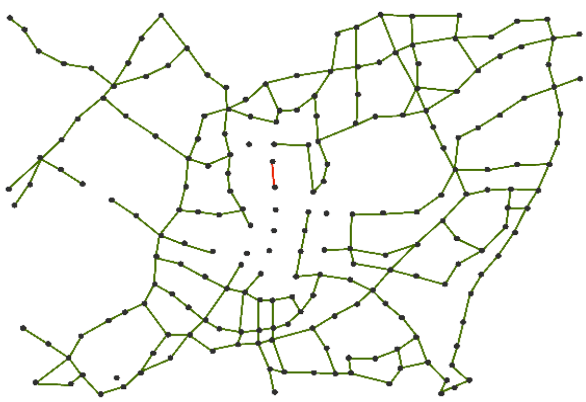

Fig. 10. Percolation chart of the road network (t_2)

Rainfall just began at t_1 and t_2. The network began to have isolated nodes and clusters. The isolated region was in the intersection of Gulou, Xuanwu and Qinhuai Districts. Zhongshan Road, Hanzhong Road, Zhongshan South Road and Zhongshan East Road were affected significantly, and nodes on these trunk roads were lost. The entire road transportation system is generally complete. Observation showed that the largest cluster in the network could connect and percolate the left and right boundaries or the upper and lower boundaries of the study area. The road transportation system was still in the percolation state.

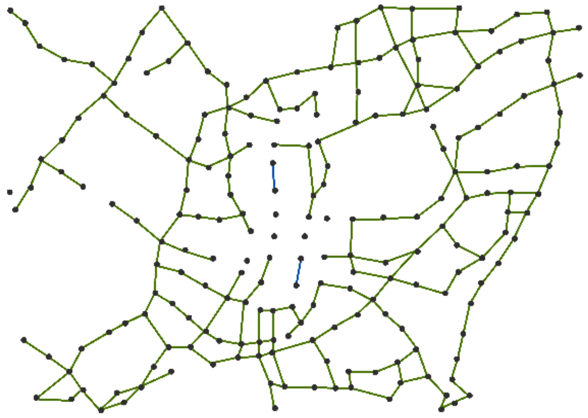

Fig. 11. Percolation chart of the road network (t_6)

At 60 min of rainfall (t_6), *G* lost numerous nodes. The south line of the Inner Ring, Fengtai South Road and Ningluo Highway were isolated in addition to Zhongshan Road, Hanzhong Road, Zhongshan South Road and Zhongshan East Road.

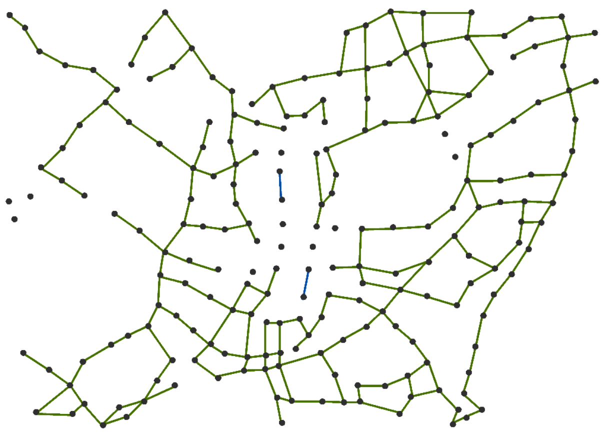

Fig. 12. Percolation chart of the road network (t_{10})

At 90 min of rainfall (t_{10}), *G* lost important nodes, which brought it a risk of being broken. Particularly, the isolation of the Express Way of Jaingbei Road, Hurong Highway, and Mufu West Road intensified the weakness of the road network. However, *G* could still connect and percolate the left and right boundaries or the upper and lower boundaries of the study area. The road transportation system remained in the percolation state.

At 150 min of rainfall (t_{15}), *G* lost important nodes again, and *SG* (orange cluster in Fig. 13) was expanded into a cluster composed of several nodes rather than a cluster involving two or three nodes. The isolated nodes increased and scattered. The formation of *SG* was mainly caused by traffic congestion in the Yangtz River Channel in Nanjing. However, *SG* still had not reached the maximum, and the weak regions were not recognized.

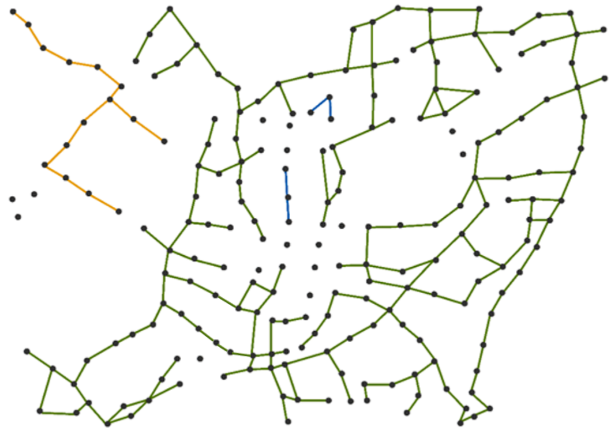

Fig. 13. Percolation chart of the road network (t_{15})

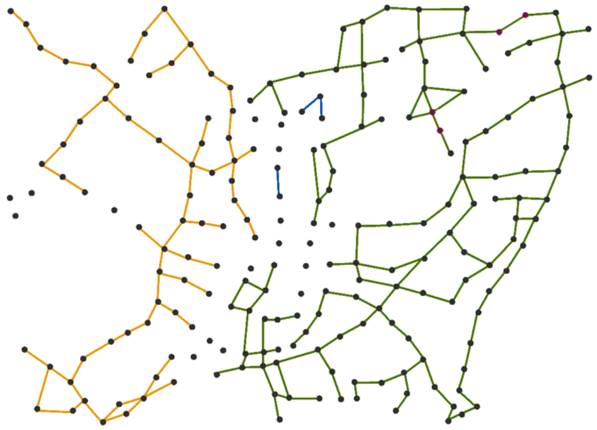

Fig. 14. Percolation chart of the road network (t_{16})

SG reached the maximum at 160 min of rainfall (t_{16}). The weak regions of waterlogging resilience of the road transportation system in Nanjing City were recognized, which were Zhenhe North Road, Mengdu Street and Hexi Street. The road network was broken after *G* lost these connections and *SG* reached the maximum. *G* could not connect and percolate the left and right boundaries of the study area. The road transportation system was out of the percolation state.

The numerical values of Q_{tm} at different moments were calculated according to Eq. (5). The results are shown in Table 1.

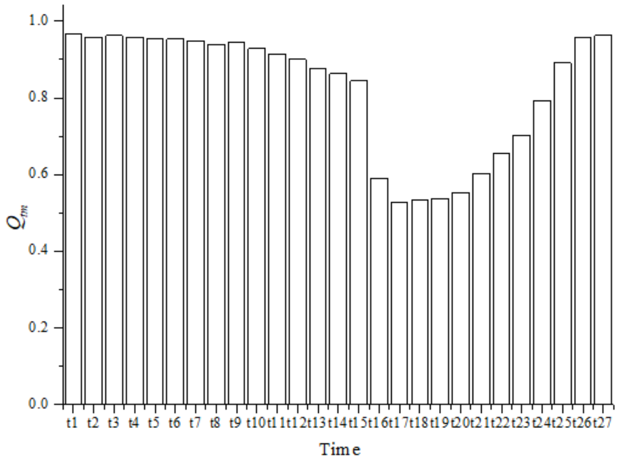

Fig. 15. Frequency histogram of the waterlogging resilience of the road transportation system in Nanjing City

On the basis of Eq. (6), $Q(t)$=222.168, $Q'(t)$=270 according to Eq. (9), and *R*=0.8228 according to Eq. (10). The occurrence of waterlogging (t_1) to the recovery of the waterlogging resilience of the road transportation system from normal level stably (t_{27}) needed 270 min. *SG* reached the peak at t_{16}. Zhenhe North Road, Mengdu Street, and Hexi Street were recognized as the weak regions of waterlogging resilience in the road transportation system.

Table. 1. Numerical values of Q_{tm}

Number	Time	Number of valid nodes	Q_{tm}
1	t_1	205	0.9670
2	t_2	203	0.9575
3	t_3	204	0.9623
4	t_4	203	0.9575
5	t_5	202	0.9528
6	t_6	202	0.9528
7	t_7	201	0.9481
8	t_8	199	0.9387
9	t_9	200	0.9434
10	t_{10}	197	0.9292
11	t_{11}	194	0.9151
12	t_{12}	191	0.9009
13	t_{13}	186	0.8774
14	t_{14}	183	0.8632
15	t_{15}	179	0.8443
16	t_{16}	125	0.5896
17	t_{17}	112	0.5283
18	t_{18}	113	0.5330
19	t_{19}	114	0.5377
20	t_{20}	117	0.5519
21	t_{21}	128	0.6038
22	t_{22}	139	0.6557
23	t_{23}	149	0.7028
24	t_{24}	168	0.7925
25	t_{25}	189	0.8915
26	t_{26}	203	0.9575
27	t_{27}	204	0.9623

4.3 Result analysis

The waterlogging resilience of the road transportation system in Nanjing City was quantified on the basis of the constructed measurement model, through which percolation threshold was determined in the waterlogging scenario. From Eq. (13), the number of valid nodes in the system at failure was calculated as $N \times P_c = 212 \times 0.4101 = 86.9412$. This value was compared with the minimum number of valid nodes at t_{17}, which indicated that it was lower than the actual minimum number of valid nodes. This result reflected that the road transportation system in Nanjing City remained valid after waterlogging. The system could recover to normal state only when it was kept valid or the system collapsed. Quantitative study on the resilience of road transportation system based on the validity perspective was meaningless. The waterlogging resilience R of the road transportation system in Nanjing City was calculated as 0.8228, which indicated that $Q(t)$ after the occurrence of waterlogging accounted for 82.28% of $Q'(t)$ under normal conditions. This result indirectly proved the good performance of the road transportation system in Nanjing City in maintaining node validity. Next, Zhenhe North Road, Mengdu Street and Hexi Street were recognized as the weak regions of waterlogging resilience based on percolation theory. The results provide references for optimizing the waterlogging resilience of the road transportation system.

Nanjing is a city with frequent occurrence of waterlogging. Attention shall be given to recognize weak regions of waterlogging resilience, determine the optimization goal, and formulate the optimization strategy of waterlogging resilience to improve the capability of Nanjing City to cope with waterlogging. Prevention and effective post-disaster recovery activities shall be taken positively to assure connection of Zhenhe North Road, Mengdu Street, and Hexi Street, which are the weak regions of waterlogging resilience. Advantage resources shall be collected to improve the overall resilience level of the road transportation system. This recommendation not only can prevent excessive resource input but can also improve the overall waterlogging resilience effectively.

Except for Nanjing City, many cities are suffering from losses caused by waterlogging. Waterlogging increasingly becomes a barrier against urban development. The waterlogging threat in Nanjing City is a universal problem against urbanization. Many other cities are facing waterlogging threats. Moreover, waterlogging control does not consider the input–output relations fully. Many cities have invested considerably to cope with waterlogging disasters but failed to achieve satisfying outcomes, except resource and human waste. The constructed waterlogging resilience measurement model of the road transportation system realized visualization of waterlogging resilience and could provide an intuitive exhibition of the resilience level of the road transportation system. The overall waterlogging resilience of the road transportation system was improved significantly at a small input on the basis of the recognized weak regions. Studying problems in urban development can arouse high attention of cities on these problems, strengthen waterlogging prevention and governing, reduce losses caused by waterlogging, and protect sustainable economic and social development.

5. Conclusions

For a quantitative study of the waterlogging resilience of road transportation system, a waterlogging resilience measurement model of road transportation system was constructed from the perspective of system validity and percolation theory by combining the post-disaster scenario analysis of the network topology and post-disaster user behavioral characteristics. This model realized a quantitative study on waterlogging resilience of road transportation system and reflected the dynamic changes in waterlogging resilience. Moreover, weak regions of waterlogging resilience of road transportation system were recognized. The major conclusions are drawn as follows.

(1) The waterlogging resilience measurement model of the road transportation system, which is constructed from the perspective of system validity and percolation theory, can realize quantitative studies on waterlogging resilience of the road transportation system and reflect the dynamic changes in waterlogging resilience of the system in the entire process.

(2) The waterlogging resilience measurement model of the road transportation system can evaluate the validity of the road transportation system accurately. If the minimum number of valid nodes in the road transportation system in the context of waterlogging is not lower than the threshold of the network, then the road transportation system has strong waterlogging resilience.

(3) The model can recognize weak regions of waterlogging resilience of the road transportation system. Once the key connections in weak regions are broken, the

network structure fails and the percolation phenomenon disappears in the road transportation system.

(4) The waterlogging resilience measurement model realizes an organic combination of post-disaster scenario analysis of the network topology and post-disaster user behavioral characteristics.

In a word, the study method of waterlogging resilience of road transportation system from the perspective of system validity and percolation theory can realize quantitative studies on the resilience of road transportation system. The post-disaster user behavioral characteristics are reflected onto the network topology to represent the dynamic features of waterlogging resilience. The network percolation disappears once key connections in the recognized weak regions are interrupted. Therefore, weak regions must be focused on, and corresponding optimization strategies must be formulated to improve the waterlogging resilience of road transportation system.

The conclusions are based on the waterlogging resilience measurement model of a road transportation system constructed from the perspective of system validity and percolation theory. This model realizes quantitative study on waterlogging resilience, recognizes weak regions, provides beneficial references for optimal decision making on resilience, and connects the results with resilience improvement of the road transportation system. However, further studies are needed on how to improve the waterlogging resilience of road transportation systems and determining what optimal decisions of resilience shall be made to improve the disaster-controlling capability of road transportation system.

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References

1. Liu, J., Shi, Z., Wang, D., “Measuring and mapping the flood vulnerability based on land-use patterns: a case study of Beijing, China”. *Natural Hazards*, 83, 2016, pp.1545-1565.
2. Ip WH., Wang D., “Resilience evaluation approach of transportation networks”. *Proceedings of the international joint conference on computational sciences and optimization*, 2, 2009, pp. 618–22.
3. Zhang X., Miller-Hooks E., Denny K., “Assessing the role of network topology in transportation network resilience”. *Journal of transport geography*, (46), 2015, pp.35-45.
4. Nogal, M., Honfi, D., “Assessment of road traffic resilience assuming stochastic user behaviour”. *Reliability Engineering & System Safety*, 185, 2019, pp.72-83.
5. Do, Myungsik; Jung, Hoyong., “Enhancing Road Network Resilience by Considering the Performance Loss and Asset Value”. *Sustainability*, 10(11), 2018.
6. Kilanitis, I., Sextos, A., “Integrated seismic risk and resilience assessment of roadway networks in earthquake prone areas”. *Bulletin of earthquake engineering*, (17), 2019, pp.181-210.
7. Cetinkaya, EK., Alenazi, MJF., Peck, AM., Rohrer, JP., Sterbenz, JPG., “Multilevel resilience analysis of transportation and communication networks”. *Telecommunication Systems*, 60(4), 2015, pp. 515-537.
8. Wu, JJ., Gao, ZY., Sun, HJ., Huang, HJ.. “Urban transit system as a scale-free network”. *Mod. Phys. Lett. B*, 18, 2004, pp.1043-1049.
9. Testa, AC., Furtado, MN., Alipour, A., “Resilience of Coastal Transportation Networks Faced with Extreme Climatic Events”. *Transportation Research Record*. (2532), 2015, pp.29-36.
10. Ilbeigi, M., “Statistical process control for analyzing resilience of transportation networks”. *International journal of disaster risk reduction*, (33), 2019, pp.155-161.
11. Alderson, DL., Brown, GG., Carlyle, WM., Wood, RK., “Assessing and Improving the Operational Resilience of a Large Highway Infrastructure System to Worst-Case Losses”. *Transportation Science*, 52(2), 2018, pp.1012-1034.
12. Adjetey-Bahun, K., Birregah, B., Chatelet, E., Planchet, JL., “A model to quantify the resilience of mass railway transportation systems”. *Reliability Engineering & System Safety*, 153, 2016, pp.1-14.
13. Donovan, B., Work, DB., “Empirically quantifying city-scale transportation system resilience to extreme events”. *Transportation Research Part C-Emerging Technologies*. 79, 2017, pp.333-346.
14. Zhu, Y., Ozbay, K., Xie, K., Yang, H., “Using Big Data to Study Resilience of Taxi and Subway Trips for Hurricanes Sandy and Irene”. *Transportation Research Record*, (2599), 2016, pp.70-80.
15. Twumasi-Boakye, R., Sobanjo, JO., “Resilience of Regional Transportation Networks Subjected to Hazard-Induced Bridge Damages”. *Journal of Transportation Engineering Part A-systems*, 144(10), 2018.
16. Zhang, XD., Miller-Hooks, E., “Scheduling Short-Term Recovery Activities to Maximize Transportation Network Resilience”. *Journal of Computing in Civil Engineering*. 29(6), 2015.
17. Alipour, A., Shafei, B., “Seismic Resilience of Transportation Networks with Deteriorating Components”. *Journal of Structural Engineering*. 142(8), 2016.
18. Aydin, NY., Duzgun, HS., Heinimann, HR., Wenzel, F., Gnyawali, KR., “Framework for improving the resilience and recovery of transportation networks under geohazard risks”. *International Journal of Disaster Risk Reduction*, 31, 2018, pp.832-843.
19. Chan, R., Schofer, JL., “Measuring Transportation System Resilience: Response of Rail Transit to Weather Disruptions”. *Natural Hazards Review*, 17(1), 2016.
20. Holling, CS., “Resilience and stability of ecological systems”. *Annu Rev Ecol Syst*, 4, 1973, pp.1-23.
21. Pimm, SL., “The complexity and stability of ecosystems”. *Nature*, 307, 1984, pp.321-326.
22. Bruneau, M., Chang, SE., Eguchi RT., Lee, GC., O'Rourke, TD., Reinhorn, AM., Shinozuka, M., Tierney, K., Wallace, WA., von Winterfeldt, D., “A framework to quantitatively assess and enhance the seismic resilience of communities”. *Earthq Spectra*, 19(4), 2006, pp.737-8.
23. Ouyang, M., Duenas-Osorio, L., Min, X., “A three-stage resilienceanalysis framework for urban infrastructure systems”. *Structural Safety*, (36), 2012, pp.23-31.