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EXTREME RAINFALL INDUCED FLOOD RISK ASSESSMENT MODEL AND RESILIENCE ENHANCEMENT METHOD ON METRO NETWORKS

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In recent years, the global climate change-induced flood risk has posed great threats to the safety of the most important geotechnical infrastructure in mega-cities, namely the metro networks. A highly networked metro system will lead to a quicker spread of risks, and furthermore, the impact range of single-node accidents is nonlinearly amplified due to the complex underground interconnections of tunnels. This paper develops a method to assess the influence of extreme rainfall uncertainties on metro systems based on a multi-layer network model combining with Areal Reduction Factor. This method can not only analyse the uncertainties of rainfall centres and rainfall spatial distribution, but also can reflect the drainage conditions by runoff parameters in certain geotechnical sites. By incorporating rainfall intensity and spatial distribution parameters, taking Shanghai metro as an example, the method demonstrates how increased rainfall and spatial uncertainties amplify flood risks, particularly affecting central urban areas with higher station density and connectivity. This paper highlights the system's vulnerability to extreme rainfall events, characterized by the finding that nearly 50% of extreme rainfall events result in less than 5% network loss, whereas fewer than 5% of the events lead to more than 50% network loss. In order to enhance the resilience of metro networks, this paper also assessedstrategies to improve the drainage conditions. The resilience enhancement strategy aims to ensure the sustainability of geotechnical engineering and urban transportation in the long-term urban renewal process.

Keywords: Uncertainty analysis; Risk assessment; Resilience enhancement; Metro flooding; Extreme rainfall; Multi-layer network.

1. Introduction

Metro systems have become highlynetworked critical infrastructures, characterized by dense stations and complex interconnections. However, with the trending global urbanization and changing climate, the networked geotechnical infrastructure is becoming increasingly vulnerable to the impact of the increasing number of natural hazards, resulting in a significant risk to human society.Extreme rainfall is one of the most severe hazards affecting metro networks. Due to the high connectivity, flooding risks caused by extreme rainfall at a single point maybe nonlinearly amplified, leading to the failure or shutdown of connected stations or lines(Zhang et al. 2020). Recent instances of extreme rainfalls have provided significant lessons and posed serious threats to the lives and property of local residents. For example, in July 2021, Zhengzhou, the capital city of Henan province of China, was hit by extreme rainfall, which flooded two metro lines and killed 14 people(Chen et al. 2024).The incident in Zhengzhou was not merely a failure of a single-point geotechnical structure, but a disaster of the complex network formed by metro stations and lines. The networkexhibits more evident and non-negligible risk diffusion compared to the single geotechnical structure failure induced by the flood risk.

The purpose of this study is to develop a flood risk assessment model and assess resilience enhancement strategies for the metro network under extreme rainfall. An appropriate multi-layer model (De Domenico 2023)is first established. The corresponding multi-layer network efficiency metrics are formulated and the associated loss due to the flooding is thus evaluated. The multiple states of the stations and lines in the metro system can be simulated accurately under external disruptions, closely representing the real-life operations of metro stations and lines. The probabilistic-based characteristics of extreme rainfall are incorporated into the established multi-layer model as the external disruption on the metro network. The proposed method is then applied to the Shanghai metro as a case study both for overall risks.

2. Multi-layer network model for flood risk of metro system

This section outlines the development of a multi-layer network model for metro systems to assess flood risks. To capture the complexities of real-world scenarios, such as station closures due to extreme rainfall while trains continue running through tunnels, a multi-layer model is introduced. This model separates stations and lines into distinct layers, enhancing the representation of operational conditions and failure scenarios.In this multi-layer network, stations are a single layer of nodes symbolizing entrances and main halls, which also act as flood entry points during severe rainfall. Separate line layers represent platform areas, with edges between layers indicating pedestrian paths from entrances to platforms, while edges in line layers represent tunnels connecting platforms. This structure allows for a more precise depiction of the operational status and risk under extreme conditions.

The study employs a defined risk assessment framework, leveraging classical risk equations to quantify the potential losses in metro networks due to flooding. The risk is modelled as a function of the probability and loss caused by flood events, with calculations performed using MonteCarlo simulations to estimate average losses. This approach integrates the probability density distribution (PDF) of losses to better reflect their uncertainty and the network's response to extreme rainfall, ultimately enhancing the realism and accuracy of the risk assessments. The framework of risk assessment is illustrated in Fig 1.

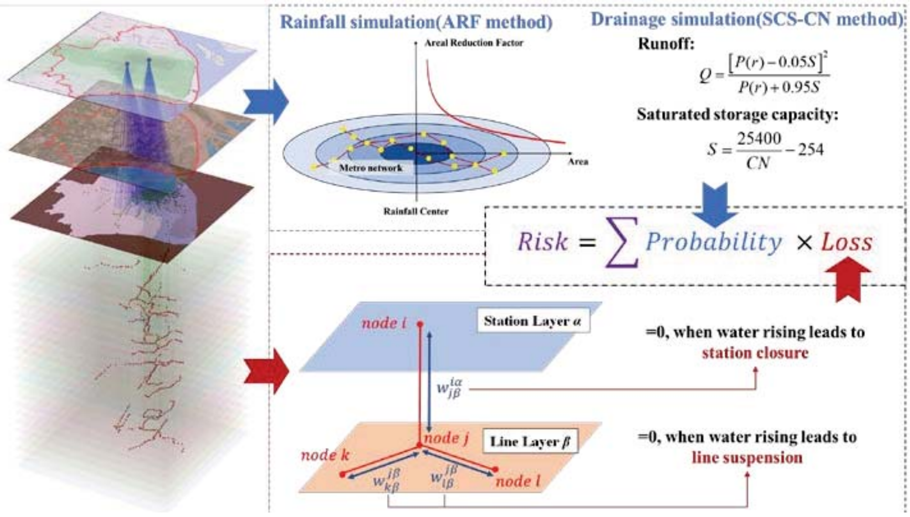


Fig. 1.The proposed risk assessment framework of multi-layer metro network under extreme rainfall

3. Flood risk simulationmethodology

This section introducesthe simulation of extreme rainfall for estimating station flooding probabilities andhow to measure the loss of flooding metro network.

3.1.*Spatial simulation of extreme rainfall and its uncertainty*

For metro networks, extreme rainfall that has short duration but wide coverage is difficult to manage. It needs emergency response in terms of rapid deployment and extensive area coverage, which is a big challenge for mega cities. In view of this circumstance, this study focuses on the short-duration, wide-area extreme rainfall events. Because of the wide extent of extreme rainfall areas, it is assumed that rainfall is spatially unevenly distributed andthe characteristics of rainfall's spatial distribution will be represented using the Areal Reduction Factor (ARF) method(Flammini et al. 2022). Surface water accumulation is calculated using the Soil Conservation Service Curve Number (SCS-CN) method(Mishra et al. 2018).The basic concepts of ARF method and SCS-CN method are shown in Fig.1.

The uncertainty of extreme rainfall is reflected by the ARF method. Firstly, the rainfall center is randomly distributed within the research area. This is because the rainfall centers are primarily uniformly distributed in the urban area of Shanghai. Secondly, Gaussian white noise is introduced to the rainfall. This is because the ARF is only suitable for large-scale regional rainfall estimation and represents a statistical characteristic, and it is inappropriate to directly use the ARF to characterize the rainfall per unit area. Due to the uncertainty of the rainfall process (Kim et al, 2019), the rainfall per unit area within one hour can be modeled with superimposed normalized white Gaussian noise with a mean of zero.

3.2. *Metro network loss model*

The concept of network efficiency (Latora and Marchiori 2001) is used as the performance indicator for evaluating the loss of metro network. Multi-layer network efficiency for metro system is expressed as follows:

$$E_f = \frac{1}{N_\alpha (N_\alpha - 1)} \sum_{i,j \in N_\alpha, i \neq j}^{N_\alpha} \frac{1}{p_{ij}^{weighted}} \tag{1}$$

where ±represents the station layer and$N_{\pm}$ is the number of nodes in layer ±, which is also equal to the number of stations. Specially, let $p_{weightedij}$denote the shortest weighted path length from node *i* to node *j* in the station layer. It is the sum of the weighted lengths of all edges that a passenger passes through when entering the metro system at node *i* and exiting the system at node *j*.In multi-layer network, the shortest weighted path length$p_{weightedij}$ from node *i* to node *j* consists of two kinds of edges. The first kind includes the edges connecting a node in the station layer and a node in a line layer. The second kind includes the edges connecting two nodes in the same line layer. The calculation method of $p_{weightedij}$isrelated to length and ridership as detailed in(Zhang et al. 2020).

The loss model is crucial for analyzing the network's performance after disturbances.In a multi-layer network, considering emergency plans, the loss model for metro systems under extreme rainfall can be developed into two conditions.The first condition is water rising leading to station closure. In this condition, passengers cannot enter or exit the closed station, so the ridership of the edge between the station layer and line layer is set to zero. The second condition is water rising so high that the station is flooded and leads to metro line suspension. In this condition, trains cannot carry passengers along the metro lines, so the ridership of edges in the suspended line layer is also set to zero.

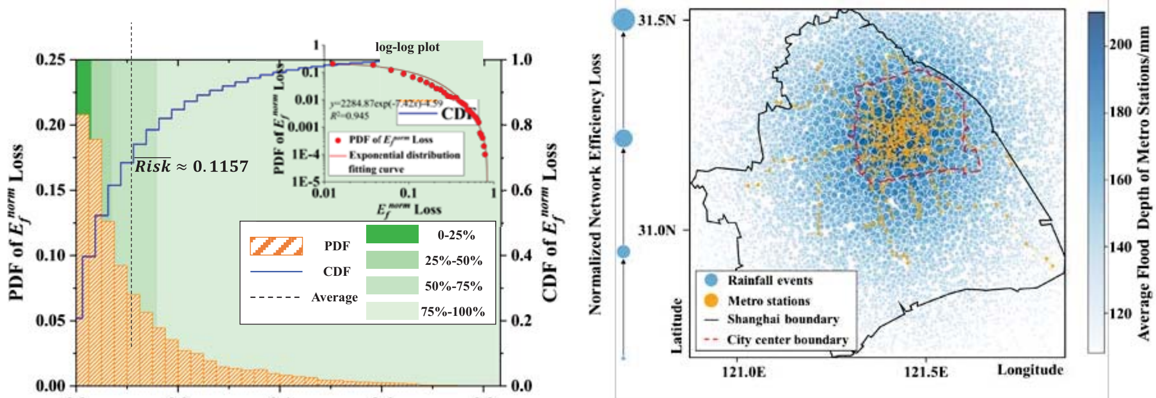
With the above metro network loss model and rainfall simulations, the average of metro network loss can be calculated by Monte Carlo simulations. In each sample of rainfall simulations, the rainfall center is generated randomly in the study area to account for the unpredictable nature of extreme rainfall events, where the location and intensity of rainfall can vary significantly.

4. Case study and results

This study takes Shanghai metro network as an application example.The study area is a quadrilateral area from the westernmost to the easternmost and from the southernmost to the northernmost in Shanghai, excluding Chongming Island. Fig. 2 shows the flooding risk of Shanghai metro network under 10 thousand extreme rainfall simulations with hourly rainfall set to 201.9 *mm/h* (the most extreme rainfall record in Zhengzhou, China, July 2021, which frequency is lower than that of a 1000-year event), as well as shows the Probability Density Function (PDF) and Cumulative Distribution Function (CDF) of normalized network efficiency (E_f^{norm}) loss.

The flooding risk of Shanghai metro network shows a feature of exponential distribution. This type of distribution indicates that the probability of low-loss events is relatively high, while the probability of high-loss events is low.Theaverage of E_f^{norm} loss is 0.1157 and nearly 50% of rainfall events have a loss less than 0.05, while fewer than 5% rainfall events have a loss more than 0.5.

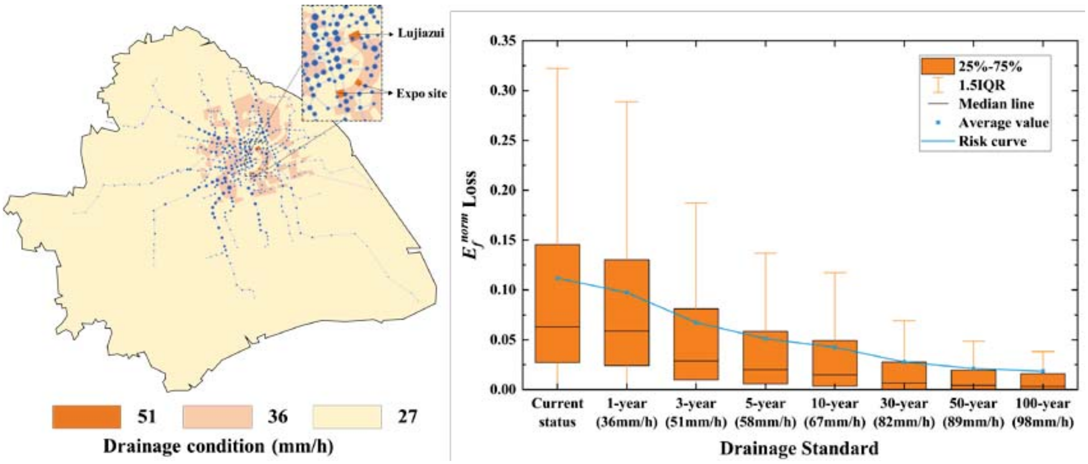
Based on the 10 thousand simulations, the results are recorded as shown in Fig. 2(b). The results show that the closer the rainfall center is to city center, the greater the impact it causes. Each blue bubble represents a sample of extreme rainfall. The location of the bubble center represents the location of extreme rainfall center, the size of the bubble indicates the E_f^{norm} loss caused by the rainfall, and the color gradient reflects the average flood depth of the metro stations. Incorporating Shanghai urban planning, it is observed that the rainfalls in city center have a higher E_f^{norm} loss and more severe average flood depth. This is attributed to the dense distribution and high connectivity of metro stations in the city center, which also means the metro network center and city center are almost in the same area. It leads to a greater likelihood of critical minority of stations being threatened by flooding when the center of extreme rainfall is near this region.



(a) (b)

Fig. 2Results of risk assessment (P=201.9 mm/h). (a) PDF and CDF of normalized network efficiency loss under extreme rainfall; (b) Extreme rainfall impact on Shanghai metro network

In this case study,the model shows its ability to analyze the risk levels of metro networks.From the perspective of this model, the way to reduce metro flood risks and enhance resilience is by improving the drainage conditions around the metro network as modeled in the SCS-CN method. The drainage conditions of Shanghai, as shown in Fig.3(a), are as follows: the general urban area has a design standard of 36mm/h, key urban areas have 51mm/h (like Lujiazui and Expo site), and other areas have 27mm/h. If the drainage conditions around the metro network can be improved, the risk of extreme rainfall will be reduced, as shown in Fig. 3(b). In the figure, as the drainage design standards increase from 1-year to 100-year, it is evident that the risk gradually decreases, although the rate of decrease becomes smaller. It can be observed that as the design standards increase, the frequency of high-loss events decreases, while the frequency of low-loss events increases, thereby enhancing resilience. Considering the diminishing marginal returns, it is equally important for urban managers to select an appropriate flood protection standard based on the city's economic situation and flood control needs.



(a) (b)

Fig. 3(a) Current drainage condition in Shanghai (He et al. 2017); (b) Risk of Shanghai metro network with different flood protection standards

5. Conclusion

This study presents a comprehensive flood risk assessment model and resilience enhancement strategies for metro networks under extreme rainfall conditions, incorporating a multi-layer network approach and rainfall simulations. Using the Shanghai metro as a case study, the results highlight the risk follows the characteristics of an exponential distribution. Theaverage of loss is 0.1157 and nearly 50% rainfall events have a loss less than 0.05, while fewer than 5% rainfall events have a loss more than 0.5.Additionally, the resilience enhancement method underscores the importance of improved drainage systems to safeguard urban transportation and infrastructure in the face of evolving climatic challenges. This research provides valuable insights for advancing metro network resilience in rapidly urbanizing regions.

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