The network pattern of underground pedestrian system and its role to urban resilience

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Abstract: In recent years, underground pedestrian system (UPS) has been developed worldwide, especially within central megacity areas, but research on UPS characteristics is still in the qualitative description stage, and quantitative methods are lacking to assess the impact of UPS on resilience. Therefore, it is essential to quantitatively measure UPS resilience and thus be able to make decisions on how UPS can be improved. The authors propose topological analysis of UPS networks based on computational and functional graph representations, which represents a new approach to theoretical discussions and empirical evidence for planning and configuring a UPS, thereby contributing to urban resilience. These representations provide functional views in which nodes represent single underground spaces and links represent underground sideways. Various graph measures are computed for structural analysis, and results provide insights into the required physical properties for planning resilient UPS. Based on validations applied to two typical high-density areas in Nanjing Xinjiekou and Guangzhou Zhujiang New Town, China, the authors examine how different UPS network patterns influence resilience performance, then further discuss the social and economic factors affecting network patterns, and give suggestions.

1. Introduction
With the continuous development of urbanization in China, urban underground space (UUS) developed fast especially in urban centre direction. An area of nearly 100 million m² has been developed, and more than
2000 large-scale underground complexes have been constructed from 2011-2015 [1]. UUS development presents opportunities and challenges for achieving economic viability, environmental liveability and social equity and effectively contributes to sustainable urban development.

In the study of the development and utilization of the UUS contributing to urban resilience, most research suggests that many types of UUS can impact resiliency because of the protection provided by the soil or rock covering from catastrophic events that occur on the surface [2,3] (Sterling and Nelson, 2013; Qian, 1998), and this issue has been previously investigated by Bobylev, Hunt, Jefferson, and Rogers [4] and Hunt et al. [5]. However, the existing research work is still focused on qualitative analysis. As an underground space system of network state, underground pedestrian system (UPS) needs further study of the resilience characteristics under the network perspective.

2. Background

2.1 The UPS and its development in China

The modern UPS, which is an important urban infrastructure [6], includes, but is not limited to, the following functions and benefits: a direct link with many subway stations, i.e., separation of pedestrians from traffic, resulting in fewer accidents; avoidance of the unpleasant extremes of outdoor weather conditions; enhanced commercial activities, etc [7]. Given its many advantages, the UPS with multiple functions have been well established as an urban development phenomenon in recent decades.

From the perspective of the development time, the UPS development time in North America started the earliest, and North American cities have developed the most extensive UPSs worldwide. For example, the UPS in Chicago and Montreal are dozens of kilometres long and cover approximately 40 to 50 city blocks [8]. In addition, Toronto, Dallas, New York and other cities have developed and built large-scale UPS [9]. China’s urbanization occurred much later than in the West and Japan. While Toronto had constructed its UPS as one of the best globally, the urbanization process had just begun in China [10]. However, with the rapid urbanization process, the UPS development and utilization is also increasing. In China, there are basically two typical models of UPS development: one is the urban renewal in old central areas of cities, underground spaces are constantly being developed as part of development and renewal activities, and the use of UPS is actively promoted, such as UPS of the Shanghai People’s Square, Zikawei, Beijing Wangfujing Street, and Nanjing Xinjiekou. The other model is overall planning and construction in the development of new urban areas, such as the Beijing Tongzhou subcenter, Guangzhou Zhujiang New Town, Wuhan Optical Valley, and Nanjing Jiangbei New Area. With the continuous development of urban construction and investment in infrastructure, the scale of UPS will further increase in China.

2.2 The UPS and urban resilience

Underground structures typically provide excellent protection against catastrophic events, and there have been many cases across the world that prove that the UPS is a good and stable transportation system during disasters [11]. In addition, the UPS can be integrated in an urban disaster protection network, and it is
important to recognize the inherent merits of the UPS in offering protective spaces in the event of urban disasters [12]. However, so far, research has focused on the protective and stable properties of underground space structures, as well as their utilization as an emergency shelter. While form-based physical components may seem rigid and contradict resilience characteristics, their implications for achieving urban resilience may be significant [13]. As a transportation system, UPS can be used as an evacuation channel system in the event of a disaster and has an effective protective function in the urban centre area. The characteristics are closely related to the network form of the UPS. Based on these aspects, a framework can be developed to analyse the resilience of the physical components related to the UPS. It can be guided by 2 capabilities: (1) Providing reliable and efficient evacuation within the UPS network, and thereby focusing on the efficiency of passage between all underground spaces within the UPS network in the event of a disaster. (2) Providing reliable and efficient evacuation to critical evacuation areas (e.g., ground plazas and subway stations) connected with the UPS network in the event of a disaster. Clearly, these two capabilities are closely related to the network structure of the UPS, and different network pattern will affect the corresponding capacity.

3 Methodology

3.1 Network abstraction

UPS resilience can be examined using the graph theory, by which the network topology is represented in a simple manner. A graph is an abstract representation of the pairwise relations between a set of elements in a network. These elements are called nodes (also vertices or points), and the connections between them are called links (also edges or lines). A graph defined as \( G = \{N, E\} \) contains \( N \) vertices and \( E \) edges representing the relations between pairs of vertices.

In this paper, the nodes in the UPS network represent underground spaces with independent functions, which include commercial premises, subway stations, and sunken squares. Whether an underground space is considered a node follows the criterion of whether it is a freely accessible space. This consideration is primarily based on the fact that people choose accessible spaces when evacuating refugees. The edge of the UPS network represents a direct connection between two nodes. After establishment of the vertices, the connections are identified by determining whether two nodes are directly connected by underground walkways. The connecting procedure follows two major criteria: (1) if there is a unique underground walkway between the two nodes, it can be used as a link between them, and (2) when there are more than two nodes connected by a walkway, these nodes are considered to be interconnected, and each two nodes have links. The length of links is measured based on the actual length between nodes. With the above modelling method, the underground space network can be abstracted into an inward-weighted network, and the corresponding calculations can be conducted based on network feature parameters. Optimal functioning of UPS networks hinges on the number of nodes and links, their capacity, and how they are located with respect to each other [14]. In measuring UPS resilience, centrality and connectivity
are major intertwined measures related to the network topology that are commonly used for examining the performance of UPS network systems.

3.2 Coefficient computation

3.2.1 Connectivity

Connectivity measures are commonly adopted to examine the functionality of an urban system under normal or emergency conditions [15]. Connectivity can be studied in terms of the movement of humans/vehicles, as well as the movement of species. Under normal conditions, a well-connected UPS is expected to reduce the travel distance and improve accessibility to services and utilities in a timely, efficient, equitable manner. Under emergency circumstances caused by disasters or man-made hazards, redundant connections are needed to maintain system functionality and service accessibility [16]. Appropriate connectivity is critical for facilitating effective and efficient access to safe places of refuge.

The average node degree, the average segment length, and the characteristic path length are commonly adopted connectivity measures. The average node degree is the mean number of internally node-disjoint paths between each pair of nodes, and in a graph, a high average node degree indicates better connectivity and contributes to resilience of the UPS network. The average segment length is the average length of all segments. The characteristic path length is the average length of the shortest paths between separate nodes, and lower values indicate a higher connectivity. The characteristic path length in graph \( G = \{N,E\} \) is defined as:

\[
L = \frac{1}{N(N-1)} \sum_{i \neq j \in G} d_{ij}
\]

where \( L \) is the characteristic path length, \( N \) is number of nodes, \( d_{ij} \) is the shortest distance in graph \( G \) between a given vertex \( i \) and every other vertex \( j \).

3.2.2 Closeness centrality

The closeness centrality is an indicator of the ability to reach a location (from other places in the network) within a reasonable time and distance [17], based on the average distance of all shortest paths from a particular vertex to every other reachable vertex in the network. That is, this indicator measures the minimum steps required to access every other vertex from a given vertex. The closeness centrality of a vertex in graph \( G = \{N,E\} \) is defined as [18]:

\[
C_i = \frac{N-1}{\sum_{i \neq j \in G} d_{ij}}
\]
where $C_i$ is the closeness centrality of vertex $i$, $N$ is number of nodes, $d_{ij}$ is the shortest distance in graph $G$ between a given vertex $i$ and every other vertex $v$. Vertices that have a short average length to every other reachable vertex have a high closeness centrality.

To augment the urban form resilience in terms of accessibility, it is essential to consider the closeness centrality when making decisions about the locations of services and amenities [19]. In urban centres, it is critical to place evacuation areas and emergency service facilities such as squares, green fields, and metro stations near nodes with high closeness centrality values to improve their accessibility at times of disasters.

In relation to the placement of emergency service facilities, Novak and Sullivan [20] argued that the significance of each link (its associated nodes) in the graph is dependent on the relative importance of nodes (determined by factors such as a commercial centre and shelter), the number of shortest-distance connections facilitated by the link, and whether the link is an isolating link.

### 3.2.3 Network efficiency

The network efficiency is a measure of information propagation across the entire network, which is based on the assumption that one travels along the shortest routes in graph $G$ [21]. The network efficiency is defined as the average sum of the inverses of the shortest distances in graph $G=(N,E)$ between vertices $i$ and $j$ [22]:

$$E(G) = \frac{1}{N(N-1)} \sum_{i<j \in E} \frac{1}{d_{ij}}$$

(3)

where $E(G)$ is global efficiency of network communication, $N$ is number of nodes, $d_{ij}$ is the shortest distance in graph $G$ between a given vertex $i$ and every other vertex $j$.

In this paper, the network efficiency can be expressed as the evacuation efficiency of any node along the shortest path. As a central characteristic of resilient systems, improving network efficiency contributes to the adaptive resilience of the UPS form. Closely related to the closeness centrality, the efficiency of a UPS network is an indication of the extent of directness of links between network nodes. The network efficiency of a UPS is maximized when the average shortest distance between all pairs of nodes is comparable to their average Euclidean distance [23].

### 4 Case study and results

#### 4.1 Case selection and introduction

In this article, the UPS in Xinjiekou and Zhujiang New Town are adopted as examples, and the two regions are the Central Business Districts (CBDs) of Nanjing and Guangzhou in China.

Xinjiekou has been the earliest commercial centre of Nanjing City since the 1930s, and after many years of development, it is still the core area of City [24]. Until now, the underground space in the Xinjiekou area is mainly composed of the basements of surface buildings, which are generally cattered and sparse. Since 2000, the UPS has been established by the gradual construction of underground cross-street passages and subway
stations. Thus far, the current UPS network in Xinjiekou is a radial star-like structure with the central junction and subway station as its centre (Fig. 1).

In contrast to the long-term urban renewal development of Xinjiekou, Zhujiang New Town has been planned since the 1990s. The development scale and connectivity of underground spaces have been designed in a unified and synchronous manner, and a grid-like network structure is presented overall. According to the abovementioned characteristics of evacuee travel behaviour in underground spaces, the underground space of the commercial office building and other non-accessible spaces are not included (Fig. 2).

4.2 UPS network models

![Figure 3. UPS network topology map of Xinjiekou.](image)

![Figure 4. UPS network topology map of Zhujiang New Town.](image)
After considering the connectivity of the underground spaces, a network topology map of the UPS network in Xinjiekou is obtained (Fig. 3). The UPS network in Xinjiekou has a total of 8 nodes, and node 1 is a transportation facility, i.e., the central cross-street passage, while the rest of the nodes are commercial places. Nodes 2, 7, and 8 connect node 1 via individual underground walkways. Nodes 1, 3, 4, 5, and 6 are connected by north-south underground streets, and they are interconnected in their topological relationship.

In the UPS network in Zhujiang New Town (Fig. 4), there are 12 nodes in total. However, there are only 5 nodes in the commercial underground spaces (nodes 4, 6, 7, 11, and 12); in addition to 2 transport facilities, nodes 3 and 5 represent subway and APM stations, respectively, and there are 5 sunken squares (nodes 1, 2, 8, 9, and 10). Compared with Xinjiekou, the number of nodes of the UPS network in Zhujiang New Town is larger, and the diversity of the node functions is higher.

4.3 Results and analysis

4.3.1 Connectivity

By abstracting the UPS network into an inward-weighted network, geospatial data are obtained from online digital maps (Baidu map: http://map.baidu.com) and calculated, and the results are as follows (Table 1).

| UPS in Xinjiekou | UPS in Zhujiang New Town |
|------------------|--------------------------|
| Number of nodes  | 8                        | 12                       |
| Number of edges  | 13                       | 17                       |
| Average degree   | 3.25                     | 2.83                     |
| Average segment length (m) | 283                     | 194                     |
| Characteristic path length (m) | 403                     | 417                     |
| Diameter (m)     | 810                      | 720                      |
| Total path length (m) | 3680                    | 3300                    |

The total number of nodes (12) and edges (17) of the UPS network in Zhujiang New Town is larger than those of the UPS network in Xinjiekou (8 and 13, respectively), and in terms of the characteristic path length, the Xinjiekou (403 m) is slightly lower than that of the Zhujiang New Town (417 m), so the Zhujiang New Town has a larger network size. On the other hand, the average segment length of the network in Xinjiekou (283 m) is larger than that in Zhujiang New Town (194 m), and in terms of the total path length, that in Xinjiekou (3680 m) is larger than that in Zhujiang New Town (3300 m), and the network diameter is also
larger (the Xinjiekou has a diameter of 810 m, and that of the Zhujiang New Town is 720 m). Overall, the UPS network in Zhujiang New Town is more compact.

4.3.2 Closeness centrality

In closeness centrality analysis, the selected computation nodes are divided into two categories. One category refers to subway stations. In the event of a surface disaster prohibiting evacuation, the subway (or subway tunnel) can be transferred to other areas. The other category includes nodes directly connected to aboveground open space. In case of subsurface disasters (e.g., an underground fire), or when disasters occur and the underground space is not suitable as a shelter (e.g., an earthquake), surface open spaces are suitable refuge locations. In the nodes of the first category, there is only one key node in the UPS network in Xinjiekou, the Xinjiekou subway station, and Zhujiang New Town UPS network has two nodes of the Zhujiang New Town subway station and Flower City Avenue APM station. In the second category, there are five nodes (sunken squares) connecting aboveground Square in Zhujiang New Town, but none in Xinjiekou.

Table 2. Summary of the network efficiency and closeness centrality indicators

| Indicator                  | UPS in Xinjiekou | Indicator         | UPS in Zhujiang New Town |
|----------------------------|------------------|-------------------|--------------------------|
| Network efficiency         | $E(G) = 1.589 \times 10^{-3}$ | $E(G) = 1.630 \times 10^{-3}$ |
| Closeness centrality       |                  |                   |
| (the first category)       | $C_1 = 3.825 \times 10^{-3}$ | $C_3 = 3.354 \times 10^{-3}$ |
|                            |                  | $C_5 = 2.254 \times 10^{-3}$ |
|                            |                  | $C_f = 3.503 \times 10^{-3}$ |
|                            |                  | $C_2 = 3.207 \times 10^{-3}$ |
| Closeness centrality       | NA               |                   |
| (the second category)      |                  | $C_8 = 2.111 \times 10^{-3}$ |
|                            |                  | $C_9 = 2.111 \times 10^{-3}$ |
|                            |                  | $C_{10} = 2.376 \times 10^{-3}$ |

Based on the closeness centrality value of a single node (Table 2), the subway station (node 1) in the Xinjiekou UPS network has the highest value ($3.825 \times 10^{-3}$), which indicates that in a single-core star-like network structure, for the key nodes with high values, their accessibility is notably better. In the UPS network in Zhujiang New Town, the closeness centrality values of the Zhujiang New Town metro station (node 5) and APM Flower City APM station (node 3) are slightly lower than that of the Xinjiekou subway station ($2.254 \times 10^{-3}$ and $3.354 \times 10^{-3}$, respectively), but if viewed in terms of the whole pedestrian system, these two sites constitute an effective backup system and have higher weighted values.
In terms of space accessibility for underground disaster prevention, there are no data for this indicator due to the lack of open spaces in Xinjiekou. Nevertheless, there are 5 sunken squares connected UPS in Zhujiang New Town.

### 4.3.3 Network efficiency

In the conducted network efficiency analysis (Table 2), although the scale of the UPS network in Xinjiekou is smaller, its network efficiency \((1.589 \times 10^{-3})\) is lower than that in Zhujiang New Town \((1.630 \times 10^{-3})\). This indicates that the star-like network structure has disadvantages compared with the grid-like network structure in this respect. The difference in network efficiency implies that when considering evacuation through the UPS, the efficiency of evacuation to underground spaces via the connecting structures of the UPS must be improved.

### 5 Discussion

Overall, in terms of resilience-related indicators, the UPS in Zhujiang New Town has better resilience characteristics, which is mainly due to its grid-like network structure and compact spatial form. The UPS in Xinjiekou is affected by many constraints in the development and utilization of the underground space, such as the built environment that is not conducive to development. Therefore, the UPS construction strategy in Xinjiekou is passive, that is, on the basis of the existing underground space pattern, public underground pedestrian channels are subsequently constructed to realize connection to other underground spaces.

Similar to Xinjiekou, many of the other old commercial centres in the city also face the problem of how to develop the underground space under the existing space pattern. The usual feasible approach is to connect the existing underground spaces by constructing underground pedestrians. To further improve UPS resilience, the following planning measures should be implemented in the next step: (1) The connectivity between underground spaces should be further promoted, which means improving the average node degree. (2) The number of key nodes in the UPS network should be further increased by building underground pedestrian channels to connect more subway stations and surface plazas.

Furthermore, aboveground open spaces are very scarce resources in urban central areas. Zhujiang New Town planned a large-scale square (Flower City Square) and used the UPS to connect the underground spaces below the square and buildings. This not only has good environmental and transportation benefits but is also very conducive to the construction of effective three-dimensional disaster prevention spaces. In Xinjiekou, due to its long development history and built-up environment, it is unable to develop large-scale open space, which is also a common problem in many other old central areas. This problem should be considered and solved in future urban renewal activities, such as following the example of the Boston Big Dig, by constructing underground traffic facilities while also providing open and green spaces on the surface for pedestrian transportation and recreation, and building a more resilient spatial system.

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