セル・オートマトンを用いた山岳都市における歩行空間の連続性評価に関する研究

米, 暁燕
九州大学大学院人間環境学府都市共生デザイン専攻 : 博士後期課程

趙, 世晨
九州大学大学院人間環境学研究院都市・建築学部門

ラディヤ プラテウィ, アンディニ
九州大学大学院人間環境学府都市共生デザイン専攻 : 博士後期課程

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The Evaluation of Connectivity for Pedestrian Network in Mountainous City Using Cellular Automata

米　曉燕*，趙　世晨**，アンディニ・ラディシャ・プラティウィ*
Xiaoyan MI*, Shichen ZHAO** and Andini Radisya Pratiwi*

Walking is the main mode of moving in the urban cluster of mountainous cities. Connectivity of pedestrian space plays a vitally important role in people's daily life. The purpose of this study is to analyze the connectivity in mountainous pedestrian networks by an analytical method based on cellular automata (CA). Firstly, distinctive features of pedestrian network in mountainous cities are clarified. Accordingly, the method of CA is identified to apply to connectivity analysis according to their characteristics. Secondly, an analytical method is proposed by a combination of the method of CA, the algorithm of Fowler and Little, and the impacting analysis of vertical transportation. Lastly, the characteristics of connectivity in mountainous pedestrian networks are presented. As a result, this study provides the usability and rationality of the method. Furthermore, it shows off influencing factors on the connectivity of mountainous pedestrian networks.

Keywords : *Connectivity, Mountainous City, Pedestrian Network, Cellular Automata, City Center*
連続性，山岳都市，歩行空間，セル・オートマトン，都心

1. INTRODUCTION

1.1 Background

Mountainous terrain in broad definition is known as mountains, hills and rough plateaus in geography. Mountainous city is the city that is grown up on the mountainous terrain. Meanwhile, it creates the urban form and living environment which is different from the one at the city on the plain terrain[1]. Since the 1970s, it has become an issue of concern world-wide with global eco changes[2]. The urban construction of mountainous city is unique existing through compact centralization and organic distribution due to the particular geographical environment, altitude difference, terrain change, climate and other natural conditions[3]. City clusters have become the most developed and active areas in the mountainous regions. Nevertheless, the development is restricted by the scarcities of land resources, traffic problems and indistinctive spaces. Street as one of the core spatial elements in mountainous cities plays a significant role in urban functions and cityscape systems. Walking is the main mode of moving in the urban clusters of mountainous cities for the inhabitants. However, the construction of pedestrian space in mountainous city is restricted by the distinctive landform conditions. One of the most important objectives of the pedestrian space is to improve its connectivity. Especially, the connectivity is more complicated and more difficult in mountainous city than it in flat city due to the complexity of mountain terrain. The connectivity of pedestrian network has become one of the principle issues for pedestrian in mountainous city, at the same time, it should be more carefully considered by urban researchers. This study aims to analyze the connectivity quantitatively in mountainous pedestrian networks and try to show its characteristics in order to exert an effect on pedestrian network connectivity improvement.

* 都市共生デザイン専攻博士後期課程
** 都市・建築学部門

1.2 Research Objectives

The study on the connectivity of pedestrian network in mountainous cities is rarely shown in the most existing researches. This study aims to analyze the connectivity in mountainous pedestrian networks by an analytical method based on CA.

There are three objectives:

Firstly, we clarify the distinctive features of pedestrian network in mountainous cities, then we identify the method of CA to apply to connectivity analysis according to their characteristics.

Secondly, an analytical method is proposed by a combination of the method of CA, the algorithm of Fowler and Little[4)5)] and the impacting discussions of vertical transportation.

Furthermore, this study shows off the characteristics of connectivity and influencing factors in mountainous pedestrian networks.

2. CHARACTERISTICS OF RESEARCH FACTORS

2.1 Distinctive Features of Pedestrian Network in Mountainous Cities

According to the 'pedestrian space network data development specification'[note1], the pedestrian road is classified into two types. There are the road and corridor as the first type, and the square and park as the second one. In this research, mountainous pedestrian networks include the previous two types.

The features of pedestrian network in mountainous cities are unique, while compared with it in flat cities. First of all, the geographical terrain is distinct due to the altitude differences. Next difference is shown on by spatial structure which changes from only growing in horizontal direction in flat cities to growing in elevation direction as well in mountainous cities. Then, different connecting relations of road appear along with vertical transportation; for instance, stairway, which is the most common type. Furthermore, the changes of pedestrian's behaviors are reflected in walking speed, walkability[6] and choice of routes.

Altitude difference is the original feature which raises the distinctive spatial structure. And then, the vertical transportation is the primary factor for the different characteristics of connectivity which show in mountainous pedestrian networks comparing to it in flat pedestrian spaces. Alternatively, pedestrian's behaviors have influences upon accessibility of pedestrian networks[7].

2.2 Differences between Network Connectivity and Pedestrian Accessibility

Despite the distinction between connectivity and accessibility measures is sometimes hard to discern[8], their characteristics are clearly different. Network connectivity, generally defined with respect to the directness of routes to destinations[9], is mainly focus on the spatial structures and road connections. On the other hand, pedestrian accessibility is a function of proximity to destinations and connectivity to those destinations. It is also called an important aspect of walkability which is the ability of pedestrian to access their destinations. Thus, it pays closer attention to pedestrian's behaviors.

Current researches of connectivity for bicycling and walking are focused on network structure primarily in grid networks[10]. In addition, some of the measures are calculated by land use, such as block density[11], percent grid[12] and pedestrian route directness[13]. Another part is discussed from an aspect of road proportion; for instance, intersection density[14], street density[15], percent four-way intersections[16], connected intersection ratio[17] and link-node ratio[18]. The third part is considered with the length of road and walking distance; for instance, block length[19], block size[20] and walking distance to activities[21]. According to the point of view that there are restrictions on road shape, road size and connecting direction in mountainous pedestrian network under terrain complexity, a method for connectivity should be discussed with consideration not only on connection and length but also on width and range of network. For this reason, an analytical method is identified based on Cellular Automata.

2.3 The Method of Cellular Automata

Cellular Automata (CA) is generally defined as discrete dynamic system in which local interactions among components generate global changes in space and time[22]. Four fundamental properties are, firstly, consisting of a regular grid of cells. Next, each cell is able to be in one of a finite number of states. Thirdly, a new generation is created, according to some fixed rules which determine the new state of each cell in terms of the current state of the cell and the states of the cells in its neighborhood. Furthermore, the rule for updating the state of cells is the same for each cell and does not change over time, and is applied to the whole grid simultaneously[23]. It is wildly applied to many fields; for instance, biology, chemistry, traffic, economy, and so on. With regard to the field of urban planning, it is applied to model urban growth, land use and population distribution in general. With respect to connectivity, the application of CA is hardly found in the aspect of transportation network, however, several researches on forest networks have appeared[24][25].

3. ANALYTICAL METHOD OF CONNECTIVITY FOR PEDESTRIAN NETWORK IN MOUNTAINOUS CITY

This study approaches to the analysis method through three phases. As the first phase, CA is presented to analyze connecting relations of pedestrian network with consideration not only on connection and length but also on width and range of roads. Secondly, the algorithm of Fowler and Little is applied to calculate the quantity of peaks in each cell state in order to confirm the specific time step which is used to express the connectivity score. As the third phase, vertical transportation should be examined in the procedure of calculation and simulation in order to illuminate its impacts on mountainous pedestrian networks.

3.1 Definition of CA

A CA model consists of a discrete cell space, in which states characterize every cell[26]. Moreover, the state of each cell depends on its previous state and on the state of its neighboring cells according to a set of transition rules. One particular representation of components according to the research objects leads to a particular CA model.

1) Cell space and cell state

A cell-space is composed of square cells with a specific resolution. In view of the width of passage for one person which is from 0.75m to 1m[27], the resolution in this study is considered to be 1 meter. Meanwhile, with a view to the cell state, binary values are considered to simulate the transitions from non-pedestrian to pedestrian road. Alternatively, if the proportion for pedestrian road in one cell is more than 50%, it is considered to be the state of pedestrian road, and vice versa.

2) Neighborhood

There are two kinds of most commonly used neighborhood which are the Moore Neighborhood and the Von Neumann

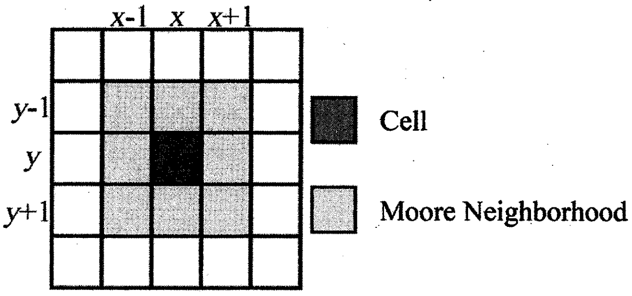

Fig. 1 A Cell and Its Moore Neighborhood

Neighborhood in the previous researches. The Moore neighborhood (Fig.1) comprises the eight cells surrounding a central cell on a two-dimensional square lattice. Meanwhile, the Von Neumann neighborhood comprises the four cells orthogonally surrounding a central cell on a two-dimensional square lattice. The Moore neighborhood is the most frequent neighborhood and it also applied in this study.

3) Transition rules

The cell space is considered to be a two-dimension coordinate system with each cell corresponding to a set of coordinate values. $P_{xy}(t)$ represents the state of the cell which is located in (x,y) in coordinate system at the time step '*t*'.

Firstly: The initial state (t=0)

$$P_{xy}(0) = \begin{cases} 1, & if\ (x,y) = \text{pedestrian road} \\ 0, & if\ (x,y) = \text{non pedestrian road} \end{cases} \quad \text{Eq. (1)}$$

Secondly: The transition rules (t≥1)

$$P_{xy}(t) = \begin{cases} \sum_{i=x-1}^{x+1} \sum_{j=y-1}^{y+1} P_{ij}(t-1), & if\ P_{xy}(t-1) > 0 \\ 0, & if\ P_{xy}(t-1) = 0 \end{cases} \quad \text{Eq. (2)}$$

The value of *P* for the cell of non-pedestrian road is 0, and is immune to the time step. Conversely, the value of *P* for the cell of pedestrian road at the time step *t* is the sum of the value of its Moore neighborhood and the value of itself at the time step *t*-1 on the premise of t≥1 (Fig.2). The same computation procedures also show in the method of CON[28] which is applied to analyze the connectivity of forest network.

Thirdly: The value of *Q*

The method of Multi-linear Connected Matrix[29] is considered to investigate the results from last computation procedure. The value of *P*, which is under our transition rules, is practical to analyze the connectivity based on the theory of Multi-linear Connected Matrix that a great value of *P* represents high connectivity. Obviously, with the step *t* increasing, the value of *P* is becoming huge. $Q_{xy}(t)$ is thus proposed to support the discussion.

$$Q_{xy}(t) = \frac{P_{xy}(t)}{P_{max}(t)} \times 100 \quad \text{Eq. (3)}$$

$P_{max}(t)$ is the maximum value of *P* at the time step *t*. $Q_{xy}(t)$ is regarded as the connectivity score of cell (*x*, *y*) at the time step *t*. Meanwhile, the mean value of *Q(t)* is considered to be the connectivity score of pedestrian network at the time step *t*.

3.2 Consideration on the Time Step

The quality of connectivity is closely connected with the distribution of the value of *P(t)*. The proportion of greater value of *P(t)* is bigger, the analysis of connectivity is closer to practice. Consequently, the algorithm of Fowler and Little is applied to calculate the quantity of peaks in each cell state in order to confirm the specific time step which contains the greatest number of peaks. If the value of the central cell is the greatest in a square grid with 3×3 cells, the central cell is defined as a peak. The mean value of *Q(t)* in the time step *t* in which contains a greatest number of peaks is considered to be the representation of connectivity score.

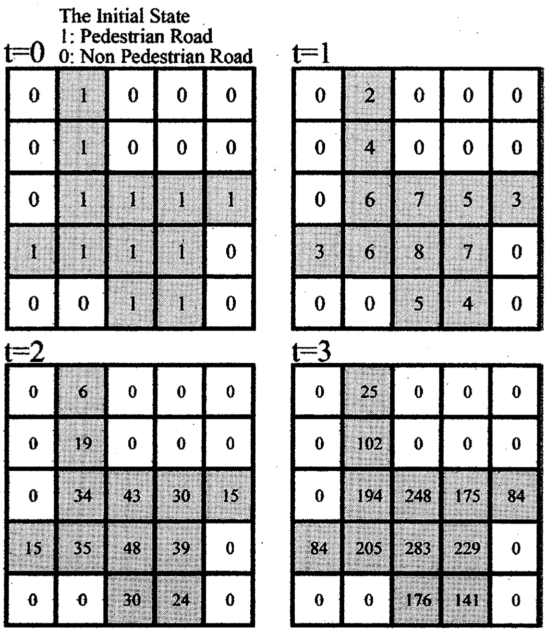

Fig. 2 Transition Rules for Pedestrian Networks

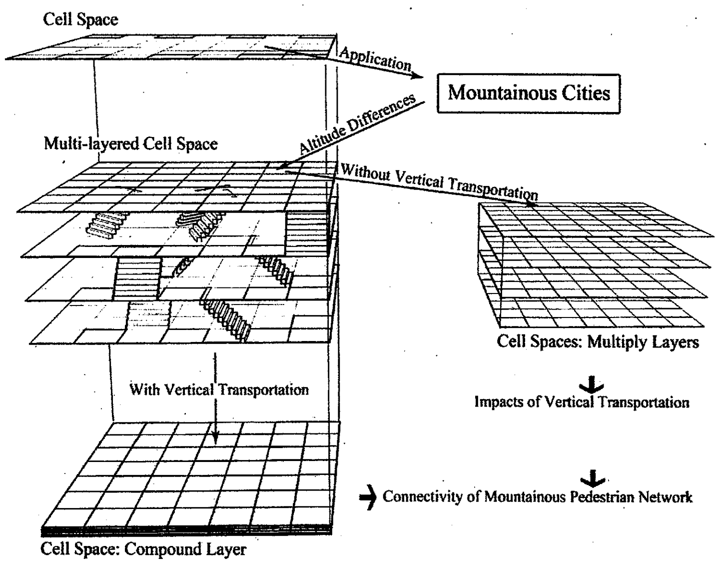

Fig. 3 Consideration of a CA Model on the Mountainous Pedestrian Network

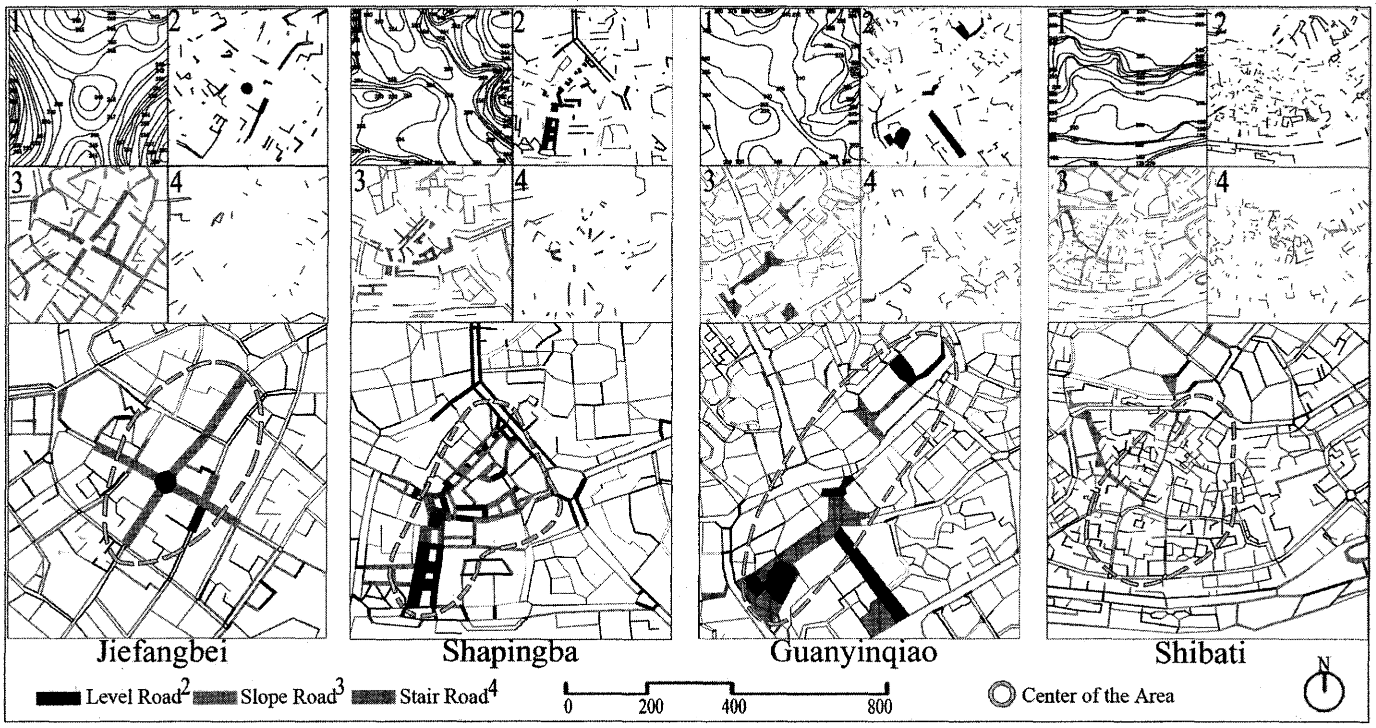

Fig. 4 The Characteristics of the Four Mountainous Pedestrian Networks

3.3 Impacts of Vertical Transportation

In the mountainous pedestrian network, there are two connection patterns expressed by three shapes of road. The first pattern, called direct-connection which grows along with the mountainous terrain, includes level roads and slope roads. The second one, called indirect-connection which connects with two layers in different altitudes, is represented by vertical transportation in which stairway is the most common shape. The mountainous pedestrian network could be regarded as a multi-layered CA[30] model with the vertical transportation being the connection among each layer. For one thing, multi-layer can be transformed into a compound layer during the computation procedure for mountainous network by means of vertical transportation. For another, to investigate the impacts of vertical transportation, the computation for each layer is exhibited, and then the comparison of connectivity scores between multi-layer and the sum of layers is shown off (Fig.3).

4. CHARACTERISTICS OF CONNECTIVITY FOR PEDESTRIAN NETWORK IN MOUNTAINOUS CITY

In the practice, firstly, we simplified pedestrian networks into cell spaces. Secondly, each cell space was divided into multiple layers in terms of connection patterns. Thirdly, the computation was carried out, and then, after determining the time step, connectivity scores were exhibited. Finally, the distribution maps were created according to the distribution of the value of Q in the cell spaces.

4.1 Research Areas

The research is considering the urbanized areas of Chinese direct-controlled municipality of Chongqing as the main object. Chongqing, which is located in the southwest, is the biggest mountainous city in China. The area is 82 thousand square kilometers where the population is more than 28 million. It includes 648 km^2 central urbanized areas and 7 million people in urbanized regions. Mountainous region takes up to 80% of urban territory. Carrying out outdoor activity is the main routine for the inhabitants of Chongqing as a result of blazing heat in summer and lack of sunshine in winter. At the same time, walking is the main traffic mode for 60% inhabitants in urban clusters of Chongqing. Pedestrian networks present the unique characteristics, for instance, public squares with sufficient spaces, free extensions of

Table 1 Fundamental Quantities and Connectivity Scores of the Four Mountainous Pedestrian Networks

Area	Q-L	S-L (m)	A-D (m)	P-Q-R		P-A-R		R-P-R	R-P-R		C-S	S-V	D-C-S	D-R
				D-R	S-W	D-R	S-W		D-R	S-W				
JFB	457	29733	18	91.3%	8.7%	93.0%	7.0%	15.3%	14.2%	1.1%	47.95	3.13	44.48	7.2%
SPB	508	31455	24	87.6%	12.4%	93.2%	6.8%	16.5%	15.4%	1.1%	53.28	3.23	47.53	10.8%
GYQ	873	46513	50	80.6%	19.4%	86.7%	13.3%	19.6%	17.0%	2.6%	54.17	2.76	46.32	14.5%
SBT	1188	52120	90	78.8%	21.2%	84.2%	15.8%	16.0%	13.5%	2.5%	30.39	1.90	26.52	12.7%

Note: Q-L=Quantity of Road; S-L= Sum of Length of Road; A-D= Altitude Differences; P-Q-R=Percentage of Quantity of Road; D-R=Direct-connected Road; S-W= Stairway; P-A-R= Percentage of Area for Road; R-P-R= Rate of Pedestrian Road; C-S= Connectivity Score (t=8); S-V= Standard Value (t=8); D-C-S= Direct-connected Connectivity Score (t=8); D-R= Decreasing Rate (t=8)

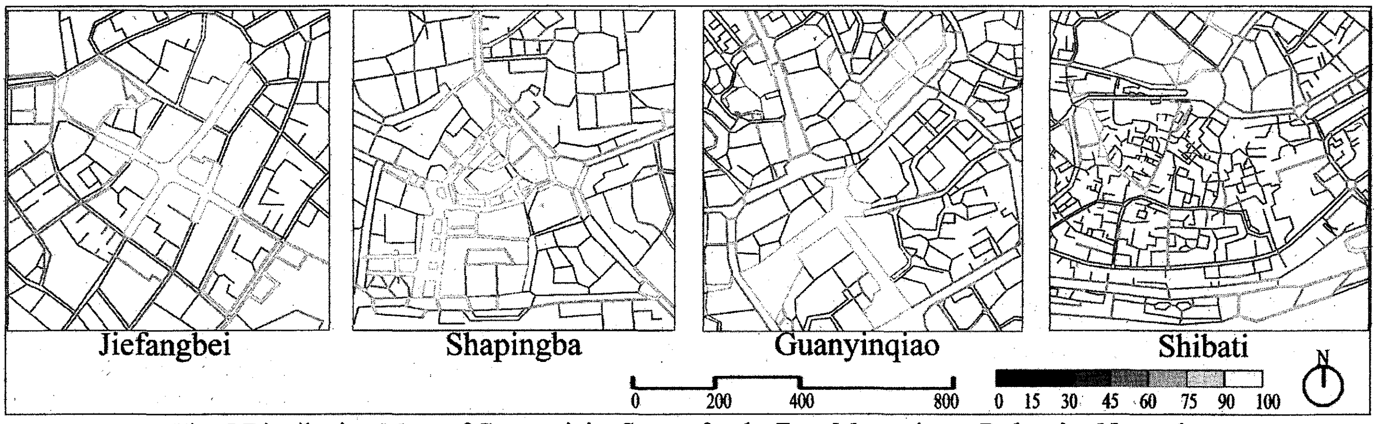

Fig. 5 Distribution Maps of Connectivity Scores for the Four Mountainous Pedestrian Networks

transportation and slant spaces connected to the different altitudes. We study on four pedestrian areas in the center of city clusters, which are the Jiefangbei pedestrian area (JFB), the Shapingba pedestrian area (SPB), the Guanyinqiao pedestrian area (GYQ) and the Shibati pedestrian area (SBT), following the period of constructions (Fig.4).

The scope of research areas in this study is considered to be as follows. The scope of pedestrian area in researches is usually a square area with side length of 400m as 5 minutes' walk or 800m as 10 minutes' walk[31]. The 400m walk is considered as an easy walking scope. On the other hand, the 800m walk is the limited scope of comfortable walking. Therefore, we should think of a choice of square area with sides of 800m in the center of urban clusters as research area. Meanwhile, the pedestrian areas are centered on landmarks, squares and commercial pedestrian streets. The Jiefangbei area and the Shapingba area are centered on landmarks, at the same time, the Guanyinqiao area is centered on a square combined with commercial areas. The center of the Shibati area is a commercial pedestrian street. In addition, the pedestrian areas are considered to be exclusive of large-scale blanks; for instance, large transportation terminals and undeveloped lands.

4.2 Characteristics of Connectivity though the Comparison of the Results

In this study, we consider two phases to analyze the characteristics of connectivity. As the first phase, in order to discuss the connectivity of mountainous pedestrian networks (referred to as mountainous network), the computation procedure proceeds by way of transforming multi-layer

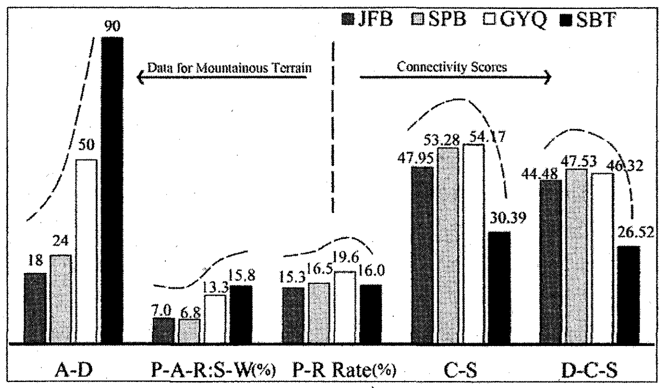

Fig. 7 Characteristics of Connectivity with the Aspect of Mountainous Terrain

to a compound layer by means of vertical transportation. As the second phase, to investigate the impacts of vertical transportation, the computation for multiple layers (referred to as direct-connected network) is exhibited. As a result, the characteristics are identified though the comparison of the connectivity data (Table 1) and distribution maps (Fig.5).

1) There are some common characteristics which are shown off in all pedestrian networks (Fig.6). First, with an increasing in the proportion of pedestrian road, the connectivity score is increasing. Second, in the same situation of proportion, with regard to the form of pedestrian roads, the connectivity is greater in the network which includes greater width of roads than in the network which contains bigger quantity of roads. Moreover, where there is clustered pedestrian space, there is greater connectivity. Third, in the same situation of proportion, with respect to the distribution of

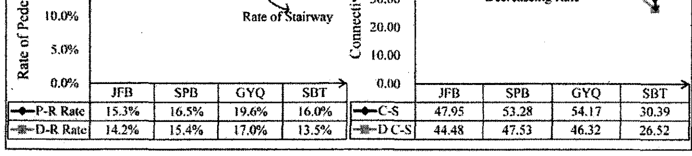

Fig. 6 Comparison of Connectivity between Mountainous Network and Direct-connnected Network

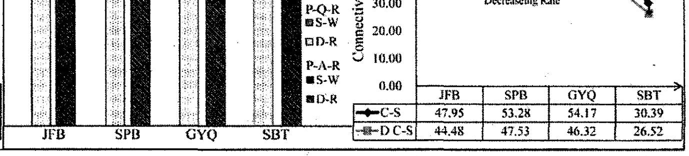

Fig. 8 The Relationship between Connectivity and Proportion of Stairway

pedestrian roads, the connectivity is greater in the network with partially compacted distribution than in the network with even distribution. Furthermore, the connectivity is greater in the network including less quantity of cul-de-sac roads and unconnected roads.

2) In the mountainous networks, basically the connectivity score becomes bigger as an increasing in the proportion of pedestrian roads. However, there is an exception which is SBT (Fig.7). Comparing to JFB, the percentage of pedestrian road is greater, but the connectivity score only takes up to 63.3% of JFB's connectivity score. The primary reason is 2 times percentage of stairway area in its network, and what's more, greater restriction of terrain due to more than five times altitude differences.

3) In the direct-connected networks, with a decreasing in the proportion of stairway area, the connectivity score is increasing. It shows that the vertical transportation has considerable influence on the connectivity of networks .

4) Comparing to mountainous networks, we get the results for direct-connected networks as follows. The decreasing of connectivity scores is impressive with 11.3% decline on average and 14.5% decline at most, while the proportion of stairway area makes up to 10.7% on average from the total. It is proved again that vertical transportation has distinct influence on the connectivity of pedestrian networks in mountainous cities (Fig.8).

5) With regard to the fundamental quantities, the characteristics of network structure are exhibited. Firstly, the fact that the percentage of quantity of stairway is greater than the percentage of area of stairway shows the influence on the vertical transportation by the restriction of mountainous terrain. Secondly, with an increasing in the differences of altitude, the quantity of road, the sum of length, the proportion of quantity of stairway and the percentage of its area are all becoming greater. However, the pedestrian rate and the connectivity score are decreasing.

5. CONCLUSIONS

This study focusing on understanding on the connectivity in mountainous pedestrian networks from simulation with analysis methods and application on the pedestrian areas can get the following conclusions.

Firstly, the analysis method which is applied to analyze the connectivity of pedestrian networks is proved to be reasonable. Comparing to previous researches, road scale which is one of the most important factors in pedestrian networks is discussed. After considering the vertical transportation, it becomes practical to analyze the pedestrian networks in mountainous cities as well.

Secondly, it is demonstrated that the vertical transportation has considerable influence on the connectivity of mountainous pedestrian networks in the practice. With an increasing in the differences of altitude, the proportion of stairway quantity and the percentage of its area are becoming greater at the same time. However, the pedestrian rate and the connectivity score are decreasing considerably. In addition, both the structure of pedestrian networks and the form of roads are irregular as a result of adapting to the complex mountainous terrain.

Finally, the results gathered in the practice could provide the information to reform and design mountainous pedestrian networks. In the further planning, on the one hand, the distribution map of connectivity is able to intuitively illustrate the important paths in the pedestrian network which should be preserved, also is able to point out the inferior connection paths which could be reformed; on the other hand, the study is able to support planners to predict the influences of the vertical transportation on mountainous pedestrian networks in order to exert an effect on network connectivity design.

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NOTE

note1) The source 'pedestrian space network data development specification (2010)' is from the home page of Ministry of Land, Infrastructure, Transport and Tourism of Japan. http://www.mlit.go.jp/sogoseisaku/soukou/seisakutokatsu_soukou_tk_000026.html

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