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Academic Article

Study on the Evaluation Method of Wind Environment in the Street Canyon for the Preparation of Urban Climate Map

Hideki Takebayashi*[1] Keisuke Oku*[2]

*[1] Department of Architecture, Graduate School of Engineering, Kobe University
*[2] Kintetsu Corporation

Corresponding author: Hideki TAKEBAYASHI, thideki@kobe-u.ac.jp

ABSTRACT

Ventilation in street canyons contributes to mitigation of extremes in the thermal environment in urban areas. In previous studies, a strong relationship between the gross building coverage ratio and the mean wind velocity at pedestrian level has been confirmed. In this study, the relationship between wind environment and street canyon characteristics was analyzed using CFD and a GIS tool. Mean wind velocity is explained better by the open space ratio rather than the gross building coverage ratio in grids more than 250 m square grid. Mean wind velocity averaged in the area of about 250 to 1,250 m square grid is meaningful. Because two or more peaks of wind velocities occur in more larger scale. When the evaluation scale is less than 100 m square, the wind environment in street canyons is best evaluated by more specific indicators (e.g., road width) rather than spatially averaged indicators (e.g., gross building coverage ratio). Ventilation in street canyons improves on wider roads parallel to the main wind direction. If the perpendicular or staggered arrangement of building heights varied in the areas of interest, ventilation in the street canyon would be expected to improve, even if the mean building height were low.

Key Words : Wind environment, Urban climate map, Street canyon

1. Introduction

The urban climate map is an information and evaluation tool used to integrate urban climate factors and town planning considerations by presenting maps of climate analysis(1). Ren et al.(2) recently reviewed studies on urban climate map. In previous studies, Climatopes, which are closely related to the thermal environment near the ground surface, were mainly defined by land use. A spatial classification for ventilation near the ground surface has not been established. A number of features (e.g., air path, building ground coverage and building bulks, building height/street width ratio, street orientation, layout of building disposition, open spaces and greenery areas) have been linked to ventilation. Some study results were also used in an air ventilation assessment of Hong Kong(3).

Ventilation in street canyons contributes to mitigation of extremes in the thermal environment in urban areas, in terms of the dispersion of heat and pollutants, and the improvement of effective temperature. The importance of the relationship between urban morphology and ventilation has been pointed out by a number of researchers(4–7). Kubota et al. carried out a wind tunnel experiment in 22 residential Japanese neighborhoods and concluded that there is a strong relationship between the gross building coverage ratio and the mean wind velocity at pedestrian level(8). Ng has also confirmed a similar tendency in Hong Kong(3).

In this study, the wind environment in a street canyon in Osaka City was calculated using CFD. The relationship between the wind environment and street canyon characteristics was analyzed using CFD calculation results and a GIS tool, in order to identify the predominant indicators of the wind environment.

2. Calculation method and results

The standard k-ε turbulence model (one of the RANS models) was selected for use in the simulation. A general purpose computational fluid dynamics software (STREAM, version 8, Software Cradle Co., Ltd.) was used for calculation. The Navier-Stokes equations were discretized using a finite volume method and the SIMPLE algorithm was used to handle pressure-velocity coupling. The calculation conditions are shown in Table 1, referring to Tominaga et al.(9). The applicability of this CFD software for an urban area such as Osaka City has been verified using a verification database provided by Tominaga et al.[9].

The area of interest was all of Osaka City (223 km^2), which was divided into 50 target areas 2,500 m square, as shown in Figure 1. Appropriate adjustments were made near the boundary of Osaka City. Data about individual building shapes handled using a GIS tool, was provided by Osaka City Office. The height of each building was calculated by multiplying the floor height from each building use by the number of stories specified in the data of each building. Smaller objects (e.g., trees, signs, cars, human bodies) could not be reproduced. Building shape information of the adjacent city was added based on map data and aerial photographs.

As an example, the setting method of the calculation domain and the calculation mesh in Target area 5-4 is explained. The plan and cross section of the calculation domain are shown in Figures 2 and 3. Field 1 is the whole calculation area, each building is reproduced in Field 2, and Field 3 is the objective area 2,500 m square. The extra buildings have been reproduced 500 m to each side of the objective area in Field 2, based on the preliminary consideration of the horizontal smooth connection method of mutually adjacent wind fields. So that it was not affected by the setting of the calculation domain, a sufficiently large calculation domain was set in Field 1. The area of the leeward side was wider (5,000 m) than the windward side (2,500 m), to avoid having the flow disturbed by leeward obstacles, according to Tominaga et al[9]. The vertical height was also set sufficiently large. The size of the calculation domain was 11,000 m x 8,500 m x 550 m.

Plan and cross sectional views of the calculation mesh are shown in Figures 4 and 5. Grid resolution is 10 m x 10 m x 1 m in Field 2 and 3. The grid intervals increase gradually horizontally (outside of Field 2) and vertically (above the maximum building height of 161 m).

Figures 6 and 7 show a wind rose and the frequency of wind velocity at Osaka Observatory when the sea breeze is blowing on summer days. Osaka Observatory is located in the center of Osaka City. The anemometer is set 54 m above the ground. The wind direction was most often from the west-southwest and west. The mean wind velocity was 3.2 m/s when the sea breeze was blowing on fair summer days. Wind speed (3.2 m/s) for westerly wind 54 m above the ground, with a power law vertical profile (power: 0.25), were the inflow boundary conditions set.

The calculated results of wind velocity 2 m above the ground are shown in Figure 8. All the wind velocities used for analysis in this study are the result of calculations for wind at the height of 2 m above the ground. Wind velocity is higher over open spaces, such as sea, rivers and large parks, and lower inside Osaka City where the density of buildings is great.

Table 1 Calculation conditions

Turbulence model	Standard k-ε model
Advection term	Up-wind difference scheme
Inflow boundary	Power-law, 3.2m/s at 54m high, power: 0.25
Outflow boundary	Zero gradient condition
Up, side boundary	Free-slip condition
Wall, ground surface	Generalized log-law
Grid resolution	10 m (x), 10 m (y), 1 m (z) in the target area

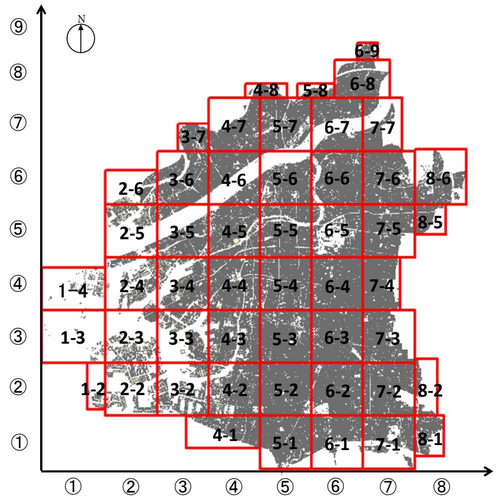

Fig. 1 Objective area

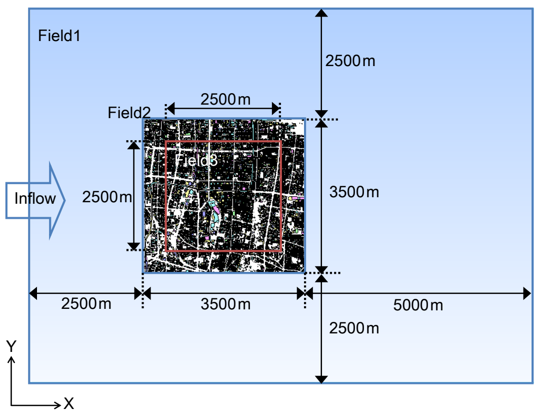

Fig. 2 Plan of calculation domain in the target area 5-4

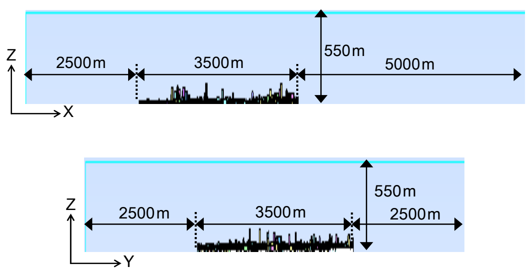

Fig. 3 Cross section of calculation domain in the target area 5-4

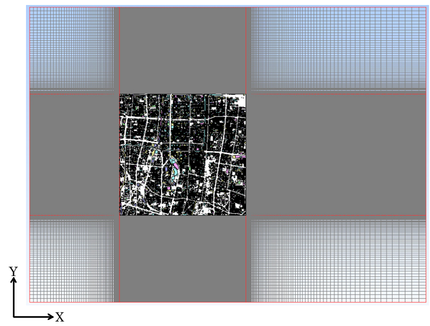

Fig. 4 Plan of calculation mesh in the target area 5-4

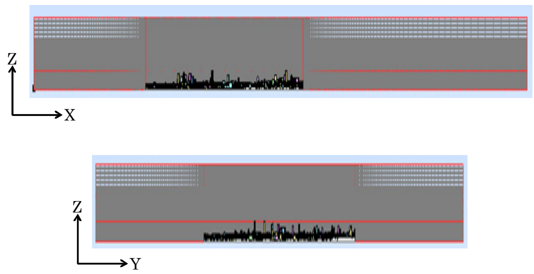

Fig. 5 Cross section of calculation mesh in the target area 5-4

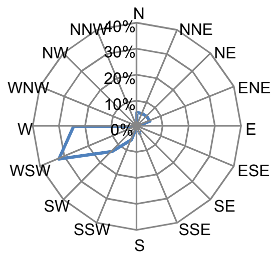

Fig. 6 Wind rose at Osaka observatory in summer fine days

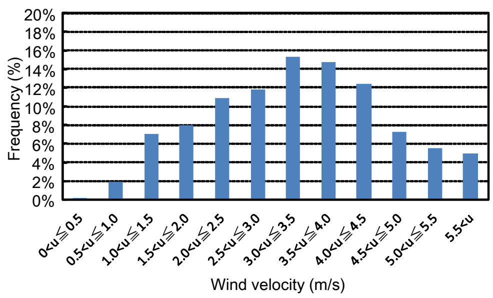

Fig. 7 Frequency of wind velocity at Osaka observatory when the sea breeze is blowing in summer fine days

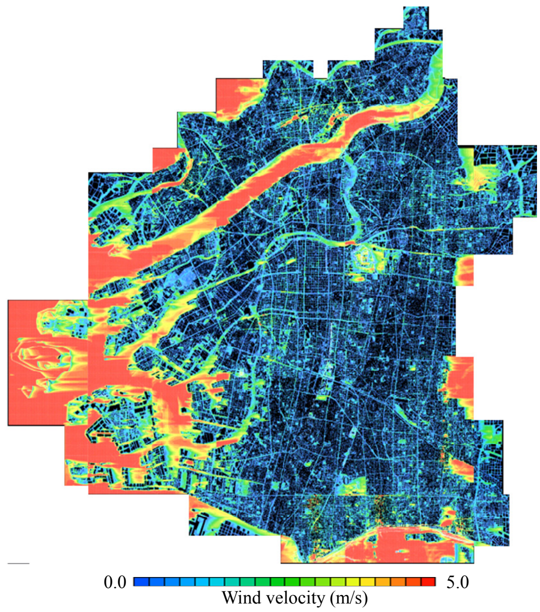

Fig. 8 Calculation results of wind velocity at the height of 2 m

3. Analysis method and results

3.1 Classification of urban block components

Urban block components are generally classified as either buildings or open space. In addition, open space is classified as road, space around buildings and independent open spaces (such as parks or rivers). In this study, independent open space is called 'open space'; therefore, the urban block components were classified as 'building', 'road', 'space around building' or 'open space'. The classification of urban block components is shown in Figure 9. 'Space around building' means the open space belonging to each building site, (e.g., approach, garage, plantings). The ratio of each urban component was calculated based on 10 m resolution data used for the CFD calculation.

3.2 Relationship between mean wind velocity and urban block component ratio at each evaluation scale

Calculated results for 10 m square grids were averaged for 100 m, 250 m, 500 m, 1,250 m and 2,500 m square grids. Grid partitioning at each scale is shown in Figure 10. Mean wind velocity was calculated from all calculated results of horizontal wind velocity, without the solid points (such as buildings) in each square grid. Therefore, in the case of a 100 m square grid, the mean wind velocity might be calculated from an extremely low number of wind velocity calculation results. The relationship between the urban block component ratio and the mean wind velocity averaged over grids 500 m square is shown in Figure 11. Mean wind velocity is better explained by the open space ratio rather than the gross building coverage ratio. Here, 'building ratio' and 'gross building coverage ratio' are the same. Relationships between the gross building coverage ratio and mean wind velocity averaged in 500 m grid, and between gross building coverage ratio and the other urban block component ratios in 500 m square grids are shown in Figures 12 and 13. When the gross building coverage ratio was less than 30%, the mean wind velocity decreased with the increase of this ratio. In contrast, when the gross building coverage ratio was more than 30%, mean wind velocity was almost constant and the open space ratio was almost constant. Overall, the mean wind velocity averaged in 500 m square grids is influenced more by the open space ratio rather than by the gross building coverage ratio.

The determination coefficient for each urban block component ratio to the mean wind velocity averaged at each evaluation scale is shown in Table 2. Determination coefficients by gross building coverage ratio and open space ratio were as large as, and almost the same in 2,500 m and 1,250 m square grids; those by open space ratio were larger than those in 500 m and 250 m square grids. The relationship between any urban block component ratio and mean wind velocity was not confirmed in 100 m square grids. Overall, the mean wind velocity was explained by the open space ratio in grids more than 250 m square.

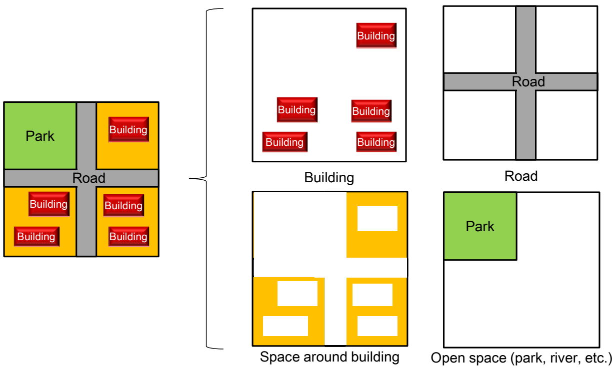

Fig. 9 Classification of urban block components

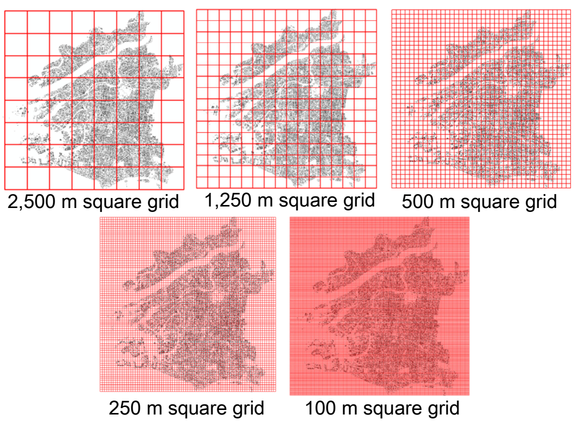

Fig. 10 Grid partitioning in each scale

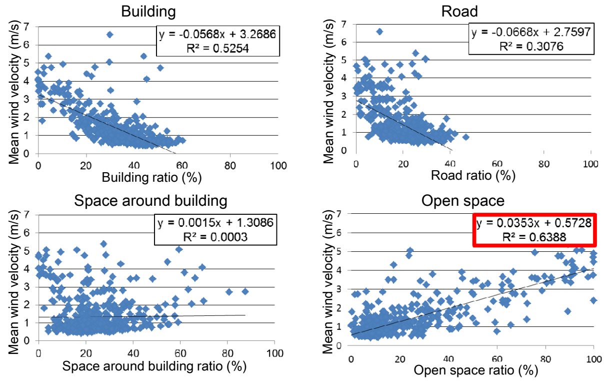

Fig. 11 Relationship between urban block component ratio and mean wind velocity at the height of 2 m, averaged over grids 500 m square

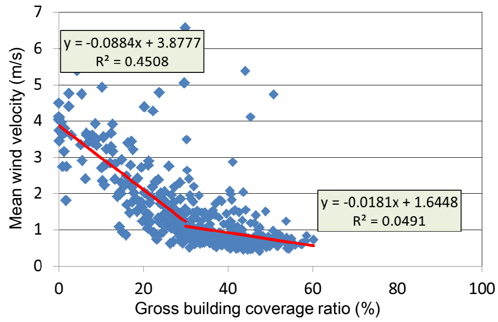

Fig. 12 Relationship between gross building coverage ratio and mean wind velocity at the height of 2 m, averaged over grids 500 m square

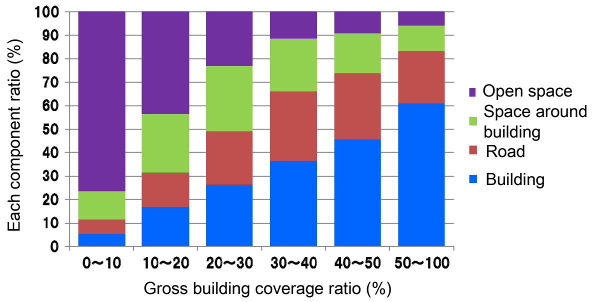

Fig. 13 Relationship between gross building coverage ratio and the other urban block component ratios in grids 500 m square

Table 2 Determination coefficient by each urban block component ratio to mean wind velocity averaged in each scale

	2,500 m	1,250 m	500 m	250 m	100 m
Gross building coverage ratio	0.83	0.79	0.53	0.40	0.16
Road ratio	0.56	0.54	0.31	0.17	0.01
Space around building ratio	0.12	0.01	0.00	0.00	0.01
Open space ratio	0.76	0.74	0.64	0.46	0.16

4. Validity of spatial mean wind velocity

The frequency distribution of the calculated results and their approximation in 500 m and 2,500 m square grids, are shown in Figure 14. The accuracy of the approximation by normal distribution in 2,500 m square grids was reduced in regions where wind velocity was greater, such as rivers and parks. The ratio of the number of areas where the determination coefficient was approximated by the Normal and Weibull distribution was more than 0.7 (Table 3). This ratio was approximated more appropriately by the Weibull distribution. Both methods are inappropriate in 100 m square grids. The ratio of inappropriate areas is a little larger in 2,500 m square grids, because there is a possibility that there were two or more wind velocity peaks in the area. Approximation may be worse in the case of larger evaluation areas. After all, the mean wind velocity averaged over an area of about 250 to 1,250 square meters is meaningful.

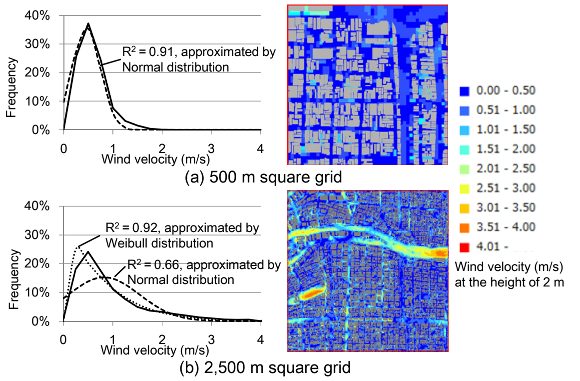

Fig. 14 Frequency distribution of wind velocity at the height of 2 m, and its approximation in grids 500 m and 2,500 m square

Table 3 The ratio of areas where the determination coefficient approximated by Normal, Weibull distribution is more than 0.7

	2,500 m	1,250 m	500 m	250 m	100 m
approximated by Normal distribution	25%	50%	55%	51%	29%
approximated by Weibull distribution	75%	81%	83%	78%	37%

5. Analysis of wind velocity by more specific indicators in grids less than 100 m square

5.1 Influence of road width on wind velocity in street canyons

CFD calculation is carried out as intended for the city center of Osaka. The region enclosed by the bold line in Figure 15, was subjected to analysis. The research area was 3,600 m (east to west) by 2,700 m (north to south), and the horizontal grid interval was 2.5 m. The other calculation conditions are the same as described in Section 2. The relationship between road width and wind velocity ratio of upper level wind, is shown in Figure 16. The left side indicates a road parallel, and right side a road perpendicular, to the main wind direction. Since these figures were made from the calculations for the city center of Osaka, there are road widths with no calculation results. Ventilation in street canyons improved on wider roads parallel to the main wind direction.

Fig. 15 Analysis area
(East-west: 3,600 m, North-south: 2,700 m)

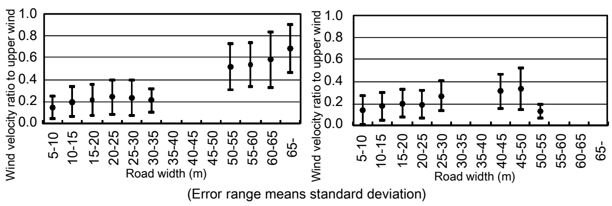

Fig. 16 Relationship between road width and wind velocity ratio at 2 m, to upper level wind at 54 m (Left: parallel to main wind direction, Right: perpendicular to main wind direction)

5.2 Influence of building height on wind velocity in street canyons

A supplemental calculation was carried out using the Aligned Urban Block Model with uniform heights of the windward and objective areas. Here, the urban block was 80 m square, road width was 15 m, building height was changed from 20 to 80 m, in every 10 m, in reference to the city center of Osaka. The settings of the research area and the windward area are shown in Figure 17.

The relationship between the difference of building heights (between research and windward areas) and the mean wind velocity ratio for upper level wind in the research area is shown in Figure 18. When the difference in building heights was large, the mean wind velocity ratio was large. The mean wind velocity was much higher due to downdrafts when the building height in the research area was higher than that in the windward area. The relationship between the mean building height and mean wind velocity (upper level) ratios is shown in Figure 19. The left side shows results when building height in the research objective area changes, right side is in the case that building height in windward area changes. Buildings arrangement is shown in figure 20. If there is a variation in perpendicular or staggered arrangement of building heights in objective area, ventilation in the street canyon is improved even if mean building height is low. Influence of building height in windward area on wind velocity in street canyons was not large.

6. Conclusions

The relationship between wind environment and street canyon characteristics was analyzed using CFD and a GIS tool. Mean wind velocity is explained better by the open space ratio rather than the gross building coverage ratio in grids more than 250 m square grid.

Mean wind velocity averaged in the area of about 250 to 1,250 m square grid is meaningful. Because two or more peaks of wind velocities occur in more larger scale.

When the evaluation scale is less than 100 m square, the wind environment in street canyons is best evaluated by more specific indicators (e.g., building height and road width) rather than spatially averaged indicators (e.g., gross building coverage ratio).

Ventilation in street canyons improves on wider roads parallel to the main wind direction. If the perpendicular or staggered arrangement of building heights varied in the areas of interest, ventilation in the street canyon would be expected to improve, even if the mean building height were low.

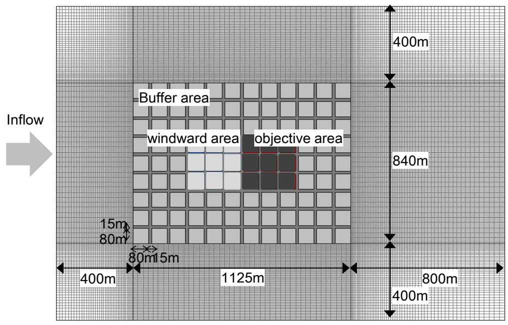

Fig. 17 Setting of the research (objective) and windward areas

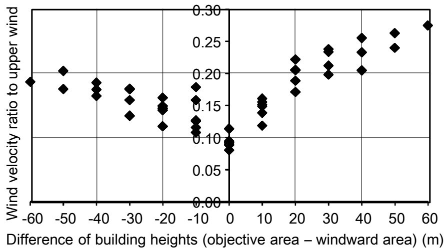

Fig. 18 Relationship between the difference in building heights and mean wind velocity ratio at 2 m, to upper level wind at 54 m

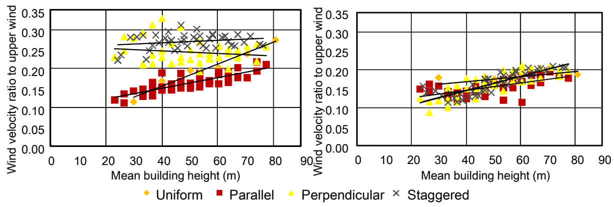

Fig. 19 Relationship between mean building height and mean wind velocity ratio at 2 m, to upper level wind at 54 m (Left: building height varies in research area, Right: in windward area)

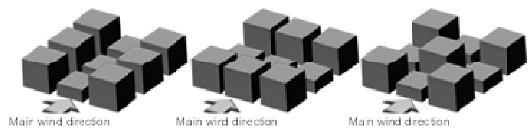

Fig. 20 Building arrangement (Left: parallel, Center: perpendicular, Right: staggered)

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