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Analysis of wind turbulence in canopy layer at large urban area using HPC database

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1. Introduction

In order to accurately predict the wind flow in canopy layer of large urban area, we introduce LES (Large eddy simulation) based on BCM (Building Cube Method) which is formulated on the very fine Cartesian mesh system. Houses and buildings were not aerodynamically modelled but directly reproduced their shapes in the numerical model, because the wind profile parameterization in cities requires the correct estimation of local flow field in the canopy layer close to the ground. Recent high-performance computing (HPC) technique has developed distinctly, so high-resolution computation becomes able to be applied to flows around a complicated configuration such as actual urban area. In this case we have to deal with buildings, vegetation and street etc. as a part of numerical model. Actually LES using the Cartesian coordinate encounters the non-correspondence of directions between the street lines and the discretized mesh lines. Very fine mesh system by BCM can solve this problem, supported by the external forcing technique at the boundary named IBM (Immersed Boundary Method). Also, in this numerical scheme, the computational process is so simple that the parallel algorithm and the memory access obtain the perfect efficiency. It is strongly expected that these advantages make it possible to efficiently simulate the flow around very complicated shapes with various scales consisting of a large amount of urban parts. In this study, we have applied LES by BCM to the wind flow estimation over the real complicated urban surface at straightforward and inclined wind directions to the main streets. Computational domain has the area of the order of 1×1 km^2 to 10×10 km^2 with resolution of 1m for numerical urban model. We also have exhibited the database of the wind turbulence in canopy layer among the buildings.

For the validity of numerical model with BCM, 3D contouring surfaces of Q values were examined. We pursued the behavior the 3D vortical structures in the wake of buildings. Conical vortex was also recognized to be reproduced on the roof clearly. These local flow structures determine appropriately turbulent characteristics in urban canopy layer. It can be found that, based on the present LES results using BCM, the turbulence structures at inflow and among a pack of tall buildings achieve statistical significance in comparison with the other data obtained by previous experiments. We can confirm that the BCM model estimates the wind flow above and within urban canopy with sufficient accuracy even at inclined wind direction to the main streets.

Using the HPC database for LES of turbulent boundary layer flow over urban-like roughened surface, analysis of turbulent wind in urban canopy can be performed. Actual buildings and houses, definitely larger effective height (height to boundary layer thickness) than those on conventional rough wall, are directly arrayed on the ground surface. Above- and within-region equilibrium profiles of mean velocity and turbulent statistics are investigated. Also, the turbulence structures in the urban canopy are elucidated and discussed for the canopy parameterization.

This research has another objective to establish the predictive method for the wind loading on the buildings in urban area and the resulting responses of the building in order to perform the wind resistant design of the actual buildings attached by the typhoon or the strong wind gust. The numerical simulation is carried out by using LES models which are made by representing directly each building shape and the aspect of the surrounding buildings in cities. Furthermore, under the conditions that the superficial parts of the building such as the double-skinned façade and the balcony are reproduced in the model, even the comfort and the functionality for buildings have been discussed based on the present LES results.

2. Importance of the present over-set numerical model of buildings in city

This research gives the numerical model which consists of three different domains according to the area and the resolution. The widest area has 25km x 25km domain and the smallest one has 1.5km x 1.5km domain. The reason of various sizes for the numerical model is that it becomes possible to set up the inflow condition on the intermediate and small computational domains by producing the database of temporal-spatial unsteady velocities with appropriate turbulence structures on the vertical section in wide area of a city. Also, it is expected that we can obtain arbitrarily the inflow conditions for the LES of the flow around the specified building in the small domain by the numerical simulation on the intermediate area based on the database. In the case of the LES on the small local area it is confirmed that the shape of not only the building itself, but also the structures and the building parts outside and around the building can be included to the numerical model by using the CAD data.
By the LES of the flow in the larger area with 7km by 2km from the sea to the center of Tokyo, the effects of the ground surface roughness and terrain undulation on the development of the turbulent boundary layers can be grasped. Successively, by the LES in the domain with 3km by 1.5km of city we clarify the pressure distribution on the wall of the tall buildings in comparison with the data of wind tunnel experiment, and the relation of the pressure with these flow patterns.

This research demonstrated that the LES can capture the flow field accurately for the detailed numerical space where the very complicated piloti is reproduced. Also, we show that the LES is efficient numerical method to predict the wind loading on the cladding such as eave or its ceiling which is very difficult to be measured by wind tunnel test.

3. Numerical method for high-performance computing

For the estimation of the comfort, functionality and safety of the buildings in the center of Tokyo city, the BCM (Building Cube method) is applied to the numerical simulation of wind turbulence over the urban area. BCM uses the mesh system consisting of cubes and cells in the Cartesian grid. Each cube has 16 by 16 by 16 cells, and then the algorithm of computation is quite simple. As a result, the efficient solver on high performance computing is realized for parallel algorithm where the load balance is appropriately obtained at each core. For the wall inside the cell, the approach of direct forcing of the immersed boundary method (IBM) is incorporated in BCM. This method allows the appropriate mesh to be generated even for the dirty CAD data such as zero-thickness walls or three-dimensional complicated geometries without any manual repair of the geometry.

4. HPC results by LES of wind turbulence in the center of Tokyo

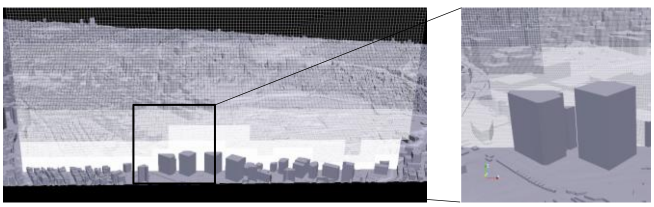


Fig. 1 BCM mesh system representing building aspects in Tokyo by GIS data (25 billion meshes for 25 kmx25km domain

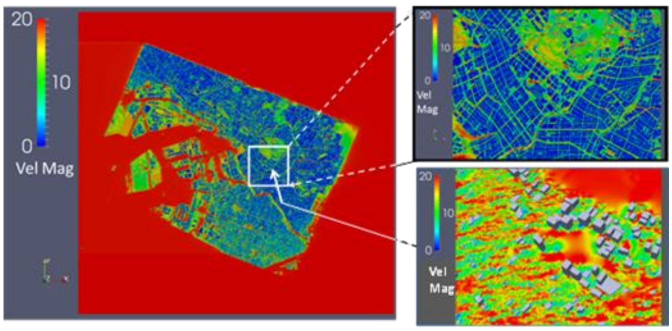


Fig. 2 LES results of wind flow field at wide area in the center of Tokyo

Tokyo, which is now gradually changing the aspect of urban surface due to reconstruction of new buildings at various locations, for example near the central station of Tokyo, has been targeted for the high-performance computing of wind turbulence in city. In order to establish the comfort, the functionality and the safety in the urban environment, the wind flow characteristics are elucidated for the wide and intermediate areas, also and for the local small area around the buildings. Figure 1 shows the mesh system representing building aspects in Tokyo by GIS data. The computed domain on area with 25 km x25km is divided using the cubes and cells in the hierarchical manner, and discretized with 0.8m resolution by totally 25 billion meshes. For the representation of the buildings in city, the GIS data for buildings and the terrain data for the ground surface are employed. Figure 2 depicts the contours of absolute instantaneous wind velocity for wide, intermediate and local areas in Tokyo. High speed wind flows can be recognized inside the main street. In the figure with highest resolution the coherent streak structures in the streamwise direction can be seen by the high speed velocity contour surfaces. It is discussed that the construction of the database of the wind turbulence and the urban surface data in Tokyo is useful for the estimation the comfort, functionality and safety of buildings in city. In the process of aging change of the building array, this database can provide the update of wind flow data and wind-resistant data for the buildings in cities.

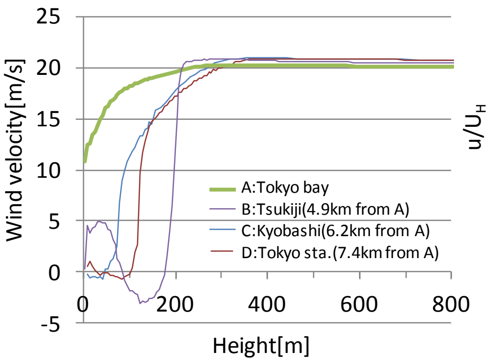


Fig. 3 Vertical profiles of mean wind velocity in the streamwise direction

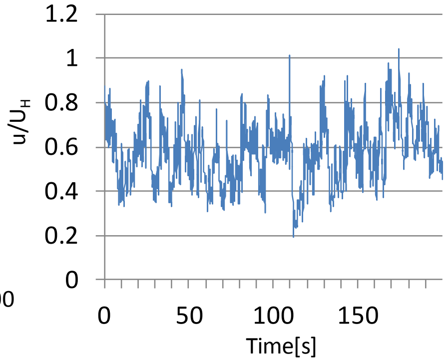


Fig. 4 Time history of wind velocity

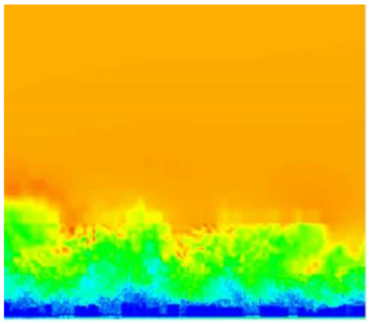


Fig. 5 Contours of instantaneous wind velocity in the vertical section at inflow for small area.

Figure 3 shows the vertical profiles of mean wind velocity at several locations in the streamwise direction. At the coastline of Tokyo bay, the urban boundary layer starts to develop and its depth of the boundary layer is thin. Then, the urban boundary layer develops gradually and constructs the urban canopy layer within dense buildings at center of Tokyo

Figure 4 shows the time history of wind velocity. It can be recognized that the wind velocity fluctuations have the high turbulence intensity with the broadband frequencies. Figure 5 illustrates the contours of instantaneous wind velocity in the vertical section at inflow location which is utilized for the LES on smaller area inside the wide area. Sufficient velocity fluctuations are shown and the urban boundary layer has fully developed.

5. Wide-area computation of flow field in urban area of Tokyo

Wide-area computation was carried out to investigate the characteristics of the boundary layer developed over the urban area from the coastal area to the center of Tokyo by using the K-computer. In this area, development of the boundary layer will be influenced by buildings and topographies. Figure 6 shows the aerial view of the computational domain of 7km×2km. Pink colored vertical lines show sampling points of vertical velocity profiles. For this computation, the mean wind velocity profile with a power law component of 0.1 was given at the inflow boundary and the turbulence of wind velocity was not considered. The minimum gird resolution was 1m around building surfaces and ground surfaces and the immersed boundary was utilized. The target wind direction SSE was the sea breeze of wind direction 157.5 degree. Figure 7 shows the development of the boundary layer with the mean wind velocity. It can be seen that the boundary layer gradually develops from the coastal area to the inland.

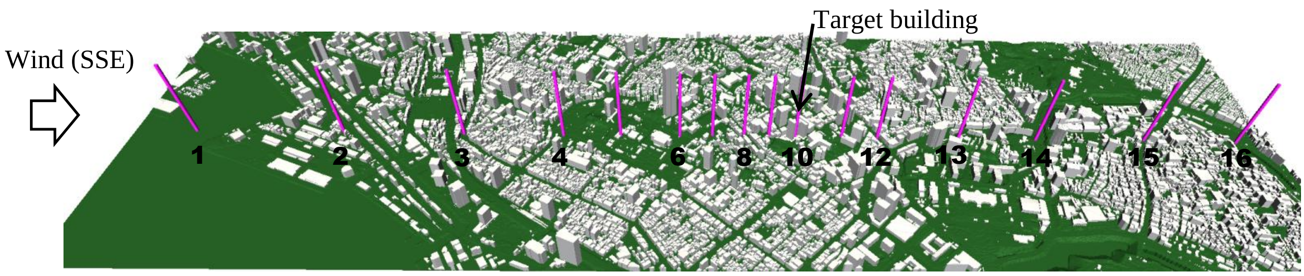


Figure 6 Aerial view of computational domain (7km×2km)

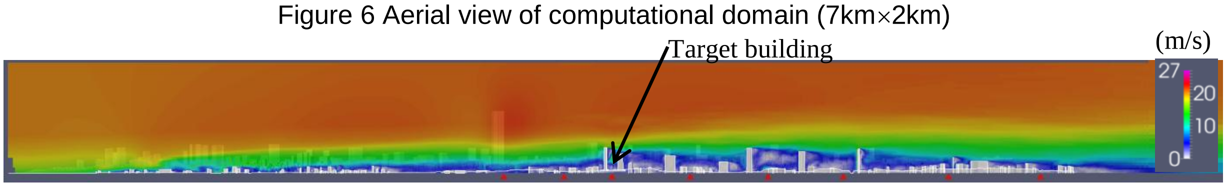
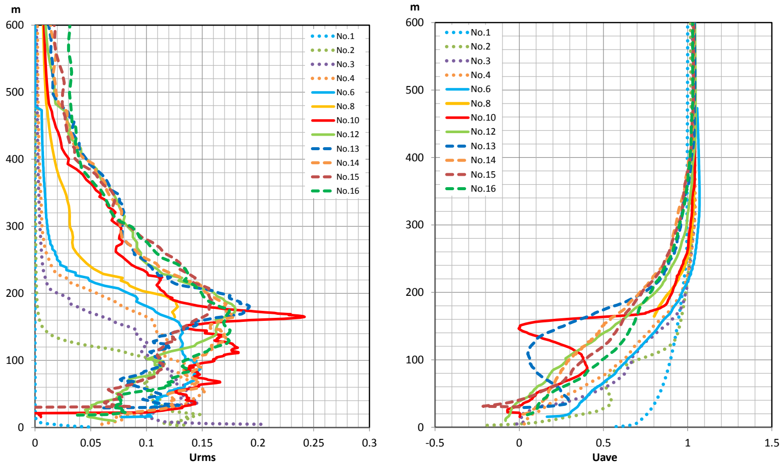


Figure 7 Development of boundary layer (mean wind velocity, 7km×2km domain)

Figure 8 shows the vertical profiles of the mean wind velocity and the fluctuating wind velocity. Figure 9 shows the power spectral densities of the u-component wind velocities at the height of 150m. The values of these figures are normalized by the mean wind velocity at the top of the inflow boundary layer. The mean wind velocity profile given at the inflow boundary is maintained at the point 1 on the sea area. Then the mean wind velocity profiles are decreased and the fluctuating wind velocity profiles increased immediately under the height of 120m at the point 2 located inland. This development of the internal boundary layer is caused by the blocking effect of buildings located at the coastal area. The internal boundary layer gradually develops for the inland and the decrease of the mean wind velocity and the increase of the fluctuating wind velocity advance. The gradients of the mean wind velocity profiles of the internal boundary layer are larger than that of the surface terrain category V of AIJ Standard with a power law component of 0.35. On the other hand, the mean wind velocity increases and the fluctuating wind velocity decreases near the ground surface among the points 4 and 6. Here are Shibakoen park and Zojo-ji temple. In this area, the ground surface is smoother than neighboring areas and the height of the ground increases gradually with the mean gradient of 1.8 degrees. Tendencies of the vertical profiles at points 10 and 13 are different from those at other points. These are because the point 10 is located between two high-rise buildings and the point 13 is located at the wake field of the high-rise building. However, the tendency of the development of the boundary layer does not change at the surrounding area.



(a) mean wind velocity (b) fluctuating wind velocity

Figure 8 Vertical wind velocity profiles

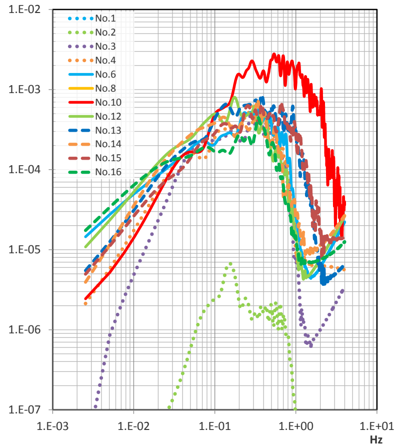
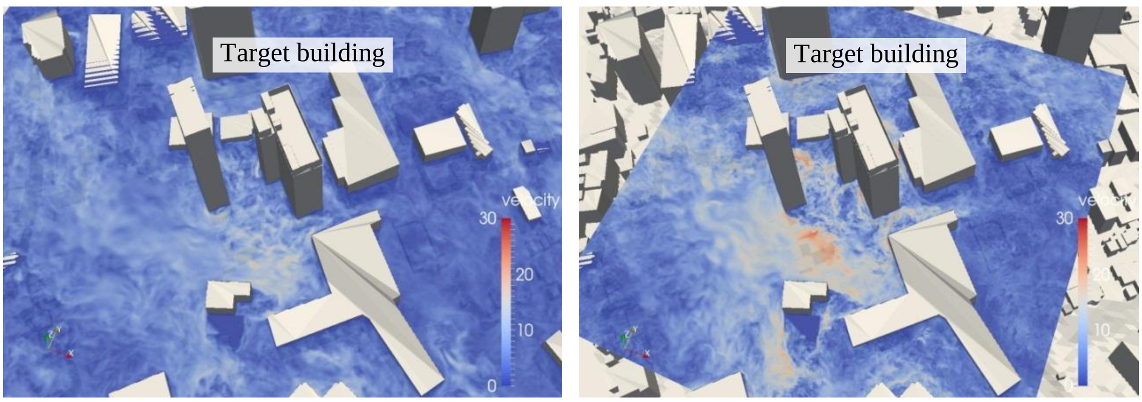


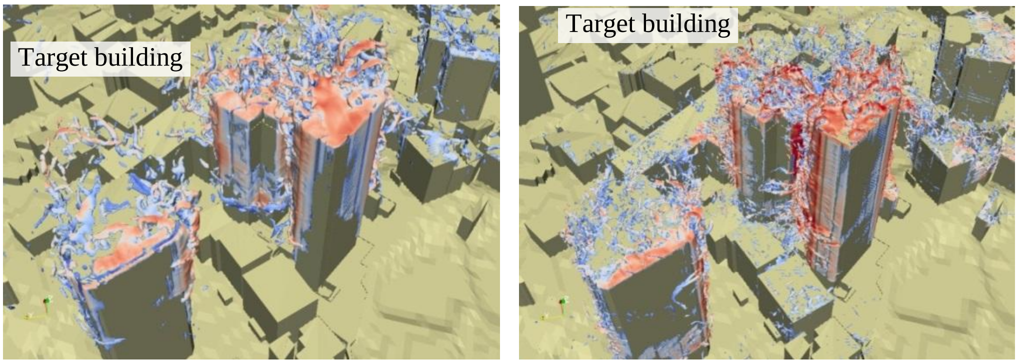
Figure 9 Power spectral densities (u-component, 150m high)

To compare the wind pressure distributions acting on the target building surfaces between wind tunnel results and computed results, the computation was carried out using the minimum grid resolution of 0.5m. In this computation, because the number of computational grids becomes enormous, the narrower computational domain of 3km×1.5km was used. The inflow boundary condition was same as that for 7km×2km domain. Figure 10 shows the comparison of the instantaneous wind velocity contours in the horizontal sections for different computational domains. Figure 11 shows the comparison of the instantaneous distributions of the root mean square values of vorticity. The development of the boundary layer in case of the 3km×1.5km domain delayed in comparison with the 7km×2km domain. Therefore, the wind velocities of the 3km×1.5km domain are larger than those of 7km×2km domain. Because we used the higher grid resolution for the computation of the 3km×1.5km domain, more complicated vortex structures such as conical vortices over the roof could be reproduced. Figure 12 shows the distributions of the mean wind pressure coefficients on the target building wall surfaces. The mean wind pressures coefficients were normalized by the velocity pressure at the building height of the windward 400m position. The reference static pressure of the wind tunnel test was the value on the wind tunnel wall surface at the target building position and that of the computation was the value on the outflow boundary. The mean wind pressure coefficients of the computed results are slightly smaller than those of the wind tunnel test results. This is because that the internal boundary layer was developed in the windward area of the target building and the mean wind velocity was decreased near the ground. However, the tendency of the distribution of the mean wind pressure coefficients of the wind tunnel test results could be reproduced by the computation.



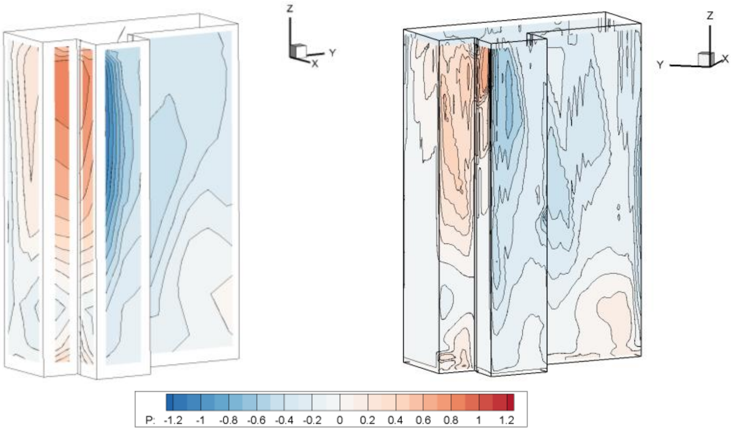
(a) 7km×2km domain (b) 3km×1.5km domain

Figure 10 Instantaneous wind velocity contours in horizontal section



(a) 7km×2km domain (b) 3km×1.5km domain

Figure 11 Instantaneous distributions of root mean square values of vorticity

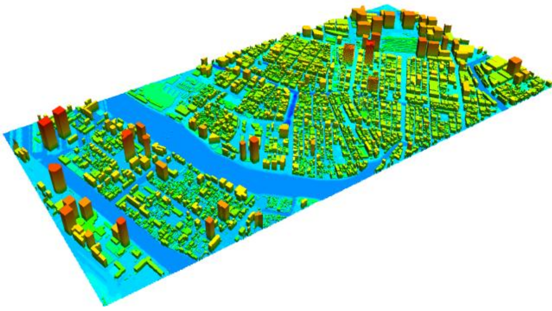


(a) Wind tunnel test (b) LES

Figure 12 Distributions of mean wind pressure coefficients on target building

6. Wind velocity field and wind pressure distribution around a high-rise building with complicated shape on the local small area

The calculation domain size in the small area is 3.0 km x 1.5 km (see Fig.13). The specified buildings have cladding fins attached to the outer wall and the complicated piloti in lower stories. We have reproduced these parts in the model (see Fig.15).



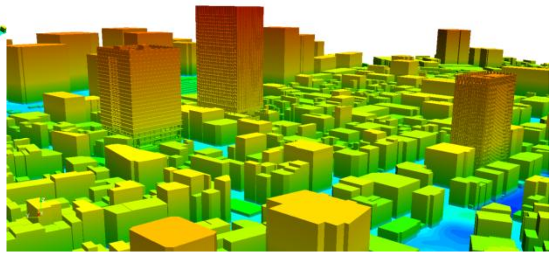


Fig.13 Calculation domain in the small area Fig.14 Building arrangement around specified buildings

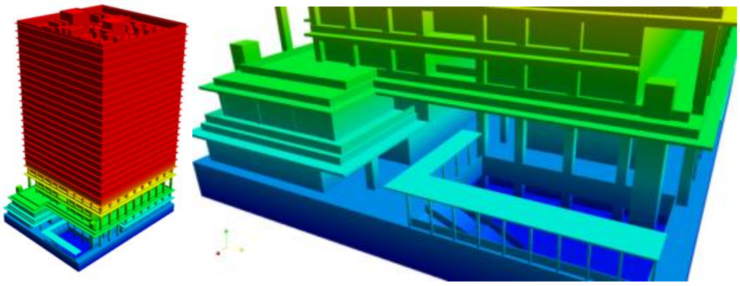
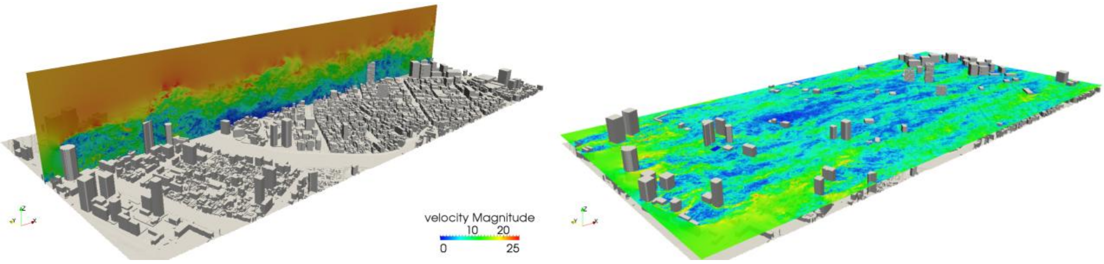


Fig.15 The specified building with cladding fins attached to the outer wall and the complicated piloti

Fig.16 shows time-averaged and instantaneous wind velocity field. There are many high-rise buildings in upstream side. Therefore, it can be recognized that the inner boundary layer was developed rapidly, and we could confirm that the specified buildings exist inside the inner boundary layer.



(1) Vertical instantaneous wind velocity (2) Horizontal instantaneous wind velocity
Fig.16 Time-averaged and instantaneous wind velocity field

Fig.17 illustrates time-averaged and instantaneous wind velocity field in the complicated piloti of the specified building. We can see the wake of the thin column and fast flows in the piloti.

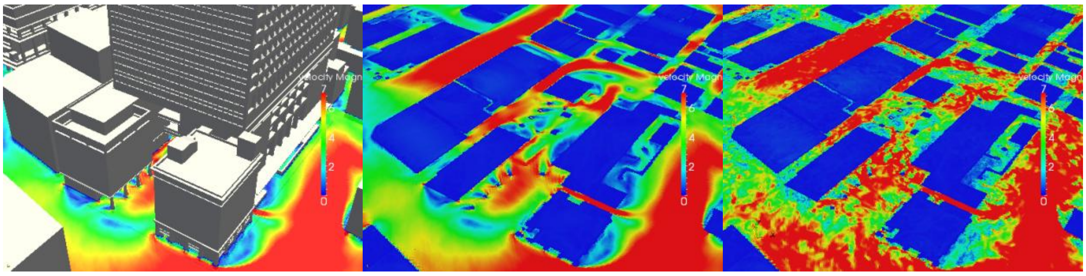


Fig.17 Wind velocity field in the complicated piloti of the specified building

7. Concluding remarks

The obtained results are displayed as follows:

1) The database for the for temporal and spatial unsteady wind velocity with the appropriate turbulence structures has been provided on the vertical section and makes it possible to give the inflow conditions for the intermediate and small local areas.
2) In the case that the specified building is planned to be built at any location in Tokyo, the unsteady inflow conditions for the local area can be set up using the simulated data of the intermediate area by the database.
3) With regard to simulation of the small local area, the CAD data can construct the numerical model which represents the building parts, the claddings and the small structures outside buildings as well as building shape itself.
4) In developing process of urban boundary layer, it is shown that turbulence statistics such as turbulent intensity and spectra can be classified according to various types of surface shape such as the commercial, residential and business areas.
5) BCM can predict accurately and reasonably the wind flows and the pressure distributions around the each building with realistic complicated shape, including the small structures connecting to underground mall.

Acknowledgments

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