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TURBULENT REDUCTION IN THE WAKE OF TALL BUILDING CLUSTERS

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ABSTRACT

This paper aims to investigate the response of the turbulence in the wake of a 4×4 tall building (square cylinder) cluster arranged in a regular array in the direction of the wind flow, where the spacing between the buildings (W_S) is equal to their width (W_B). Three different clusters of relative height (H_B/δ) = 0.125,0.240,0.500 were studied. Velocity fields were measured in a wind tunnel using 3D laser Doppler anemometry. Results show that there is a delay in the response of the recovery of u_{rms}, v_{rms} and w_{rms} when compared to that of the mean flow. In the transition-wake region, as defined by Mishra *et al.* (2023), the turbulent intensities within the wake flow drop below those of the freestream; this can be associated with the 'uniform' nature of the wake with negligible velocity gradients (dU/dy and dU/dz) throughout the wake's core width. With an increase in the cluster height, the wake was observed to show a slower recovery. The vertical mean profiles show that vertical shear plays a dominant role in the recovery of the wake behind tall building clusters.

INTRODUCTION

The number of tall buildings is increasing globally to accommodate the growing population in urban areas. These high-rise buildings affect the local atmospheric flow dynamics, leading to changes in local temperature, street level ventilation and pollutant dispersion (Fuka *et al.*, 2018; Makedonas *et al.*, 2021). Studies of finite-sized buildings immersed in a boundary layer have shown the formation of rooftop vortices on the building top and horseshoe vortices from the base; these enhance the vertical mixing of the flow in the wake region (Wang & Zhou, 2009). Additionally, in urban areas, there are several groups (or clusters) of tall buildings and the interaction of multiple wakes downstream of a cluster can make the flow more complex to understand. Two-dimensional wake studies of flow around multiple square cylinders have shown different wake structures depending on the spacing between them (Kumar *et al.*, 2008; Sewatkar *et al.*, 2012). Liu *et al.* (2015) experimentally studied the effect of wind incidence (α) and the spacing between the square cylinders at $Re = 4.06 \times 10^3$ and 4.58×10^4 and observed maximum lift force experienced by the downstream cylinders for $\alpha = 15^o$.

In most engineering applications pertinent to the study of the wake of high-rise buildings, such as those focusing on wind loading and transport of pollutants, two-dimensional wake theory is not exactly applicable. This is primarily because of two reasons: (a) the finite height of the buildings, and (b) the fact that the buildings are immersed in deep boundary layers. Some progress has been made in understanding the flow around patches of circular cylinders, essentially mimicking river vegetation, atmospheric flows over the forest, and wind farms (Chang & Constantinescu, 2015; Nicolai *et al.*, 2020; Wangsawijaya *et al.*, 2022). To understand the effect of tall building clusters on the wake flow in a deep boundary layer, Mishra *et al.* (2023) studied the 4×4 cluster of square cylinders arranged in a regular array with different spacing between them. They identified three different wake regimes based on mean flow characteristics, whose extent was found to scale depending on the cluster width alone. In recent years, there have been many studies on flow obstruction by considering porous circular patches of circular cylinders. These configurations are chosen to mimic river vegetation, atmospheric flow over forests, and wind farms. Wangsawijaya *et al.* (2023) conducted a simultaneous Particle Image Velocimetry and Laser-Induced Fluorescence to understand the scalar transport through and around the circular patches of tall circular cylinders. They observed that the flow was forced to bleed vertically with an increase in the canopy density, elevating the free shear layer. The mixing in the shear layer was also observed to increase with an increase in the density of the canopy. Sützl *et al.* (2021) used large-eddy simulation to understand the effect of morphological heterogeneity on urban airflow. They found that the variation in the total surface drag was correlated particularly with the maximum building height. Cheng & Yang (2023) numerically investigated the flow characteristics of realistic urban geometries with different building heights, observing that tall building canopies induced greater drag compared to shorter buildings. They also proposed a criterion to predict the urban canopy height based on the plan area fraction of the urban geometries. Lim *et al.* (2022) conducted a numerical study for the dispersion of pollutants by a tall cluster in the neighbourhood of low-rise buildings and concluded

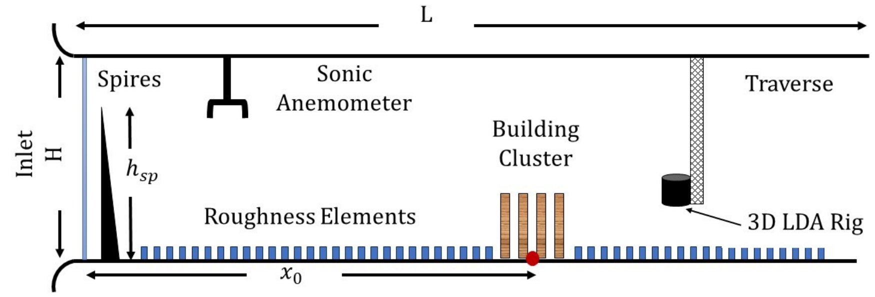

Figure 1. Schematic of the Enflo Wind Tunnel with building cluster.

that the depth of the urban canopy layer increases due to the tall buildings. It also results in a strong disturbance in the flow in the roughness sublayer. They, furthermore, observed that the vertical momentum and scalar fluxes were dominated by the rooftop shear layer. Makedonas *et al.* (2021) studied the flow over tall urban canopies with uniform as well as varying building heights. They observed that despite the same average canopy height, (h_{avg}), the boundary layer depth almost doubles in the case of a non-uniform height canopy when compared to a uniform height canopy. Hertwig *et al.* (2019) performed wind tunnel experiments to study the flow over urban canopies with and without tall buildings, and also tall buildings surrounded by buildings of varying heights at two different wind angles. A reduction in the streamwise velocity (U) was noted in the roughness sublayer due to the sheltering effect produced by the low-level buildings.

In the present paper, we discuss the existence of a uniform momentum zone in the transition-wake region of tall building clusters, extending almost up to the cluster height. This region of uniform flow results in a significant reduction in the mean shear and turbulent intensity. The switching of vortex shedding between the building scale and the cluster scale is also an interesting phenomenon occurring in this region. The reduction of turbulence in this region can have implications on the drag and accumulation of pollutants released within the cluster. Additionally, the effect of the cluster height on the development and recovery of the wake behind the building cluster is also presented.

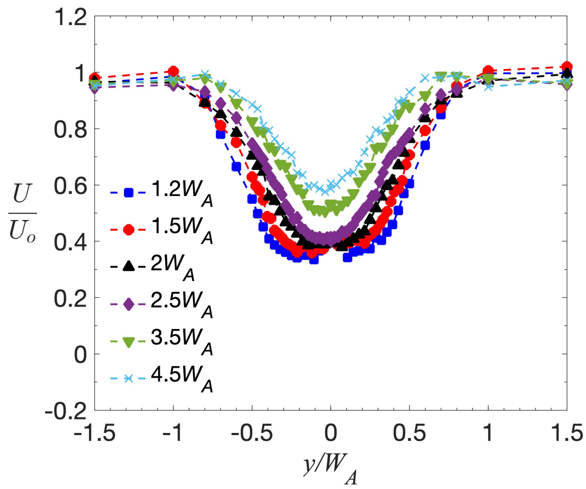

Figure 2. Lateral variation of U/U_0 for Case 1.

EXPERIMENTAL SETUP

The work was conducted in the EnFlo wind tunnel at the University of Surrey, which is an open circuit tunnel with a test section 20 m long, 3.5 m wide, and 1.5 m high. A set of 7 Irwin spires of height 986 mm were placed at the $x = 0.5$ m from the tunnel inlet to obtain an artificial boundary layer of thickness $\delta \approx 1$ m. A circular turntable of 1.5 m in diameter was located at $x_0 = 14$ m from the inlet, where the cluster model was placed for this study. The schematic of the relative arrangement of the Irwin spires, roughness elements and the building models is shown in Figure 1. A three-dimensional laser Doppler anemometry was employed to measure all components of velocity in the wake of building clusters. With a target acquisition frequency set to 100 Hz, the sampling duration for each measurement was set to 60 s. An aerosol solution of sugar particles with a mean diameter of 1 μm was used as tracer particles and was generated using an in-house ultrasonic mist generator. To obtain the reference velocity of the flow (U_{ref}), an ultrasonic anemometer was installed (5 m from the inlet, 0.75 m from the nearest side wall, and 1 m from the floor), as shown in figure 1. U_{ref} for the present experiment was set to be 2 m/s, providing a Reynolds number based on δ and U_{ref} of 1.3×10^5 for all cases presented here.

16 square cylinders each of width (W_B) 60*mm* were arranged in a regular array of size 4×4, with spacing between them (W_S) equal to W_B. Three different cases of the cluster were considered for the present study. For Case 1, the building height (H_B) was 240*mm*, while for Case 2 and 3, it was 500 mm, and 125 mm, respectively. This gives the ratio of the cluster height to the boundary layer thickness (H_B/δ) to be 0.24, 0.5 and 0.125. The origin of the reference system is taken at the cluster's centre and ground level (marked as a red dot in Figure 1). The mean velocities in x, y, and z directions are denoted by U, V, and W, respectively. The lateral wake profiles were measured at the building mid-height ($z = 0.5H_B$), while the vertical profiles were taken at the cluster centreline ($y = 0$). Both are measured at several streamwise stations.

RESULTS

Briefly recalling the results of Mishra *et al.* (2023), the wake of tall building clusters can be categorised into three different regimes: near-, transition-, and far-wake regime. In the near-wake regime, individual wakes are formed behind each building downstream of the cluster, having a local momentum deficit behind the individual buildings and a momentum ex-

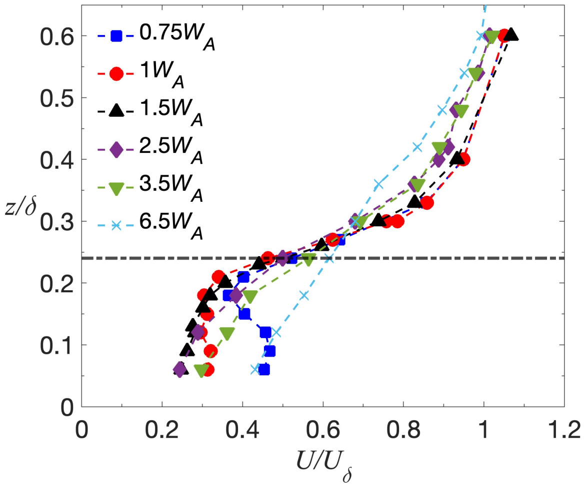

Figure 3. Vertical variation of U/U_δ for Case 1.

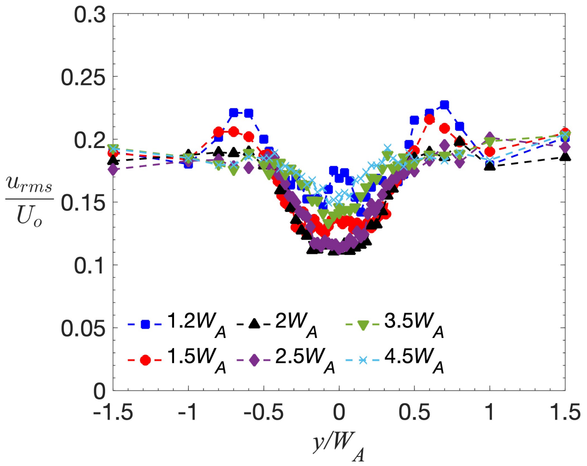

Figure 4. Lateral variation of u_{rms}/U_0 for Case 1.

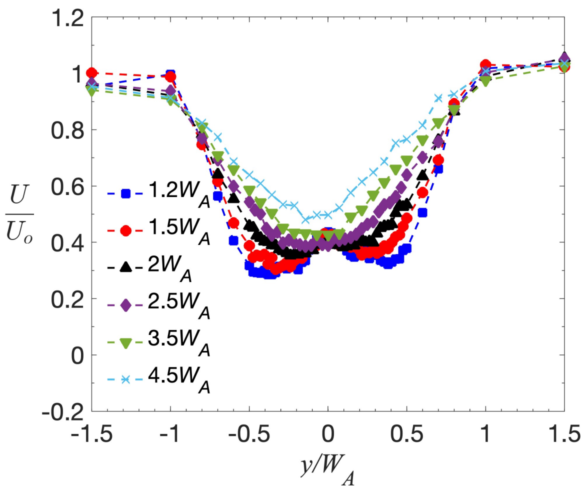

Figure 5. Lateral variation of U/U_0 for Case 2.

cess in the channel between them. Due to the energy exchange between buildings, the flow in the channel loses momentum downwind as the wakes behind the buildings gain it.

The lateral profile of streamwise velocity plotted in Figure 2 for Case 1 ($H_B\delta = 0.24$) shows that the transition-wake regime extends between $W_A \leq x \leq 2W_A$ from the cluster centre. In this regime, the non-dimensional streamwise velocities (U/U_0) in the wake are observed to be almost uniform in the x direction. The wake velocity starts to recover similarly to the single building case in the far-wake region ($x \geq 2.5W_A$). The vertical profile of mean streamwise velocity plotted in Figure 3 shows the reduction of U/U_δ in the transition-wake regime ($W_A \leq x \leq 2W_A$) as compared to the near-wake regime ($x = 0.75W_A$). The cluster height (H_B) is also marked with a black horizontal line. It is interesting to note that U/U_δ is largely uniform in the wall-normal direction as well up to $z = 0.75H_B$ (0.18δ). This uniformity in the streamwise velocity significantly reduces the shear strength both in the lateral (dU/dy), and vertical (dU/dz) directions in the central core of the transition-wake regime. This results in a significant reduction in turbulent intensity within the wake in this regime. At $x = 0.75W_A$, accelerated flow is observed at the cluster centreline. It is typical for flow to accelerate in the channel between buildings, as recirculation regions are formed behind each building in the near-wake region. As we move downstream, the momentum exchange between the jet-like flow and the building individual wakes results in the uniform flow zone characterising the transition region. Figure 4 shows the lateral variation of the normalised streamwise turbulent intensity (u_{rms}/U_0) for Case 1. Within the cluster ($-0.5W_A \leq y \leq 0.5W_A$), there is a significant reduction in the turbulence intensity ($\approx$ 11% at $y = 0$, compared to 18% in the freestream region). Similar trends were observed for v_{rms} and w_{rms} (though not shown). The u_{rms} profile shows that the building wake effect is still persistent at $x = 1.2W_A$ as evident from alternate maxima and minima within the cluster region. Interestingly, the mean profiles do not have this characteristic at the same locations (see Figure 2). This trend suggests that there is a delay in the response/adjustment of the turbulent intensities to the change in the mean flow characteristics. This phenomenon of a delayed response has been observed in transient flow conditions (He & Jackson, 2000; Guerrero *et al.*, 2021, 2023). Steep reductions in the u_{rms}/U_0 along the cluster centreline ($y = 0$) in the region $1.5W_A \leq x \leq 2.5W_A$ suggests that the shear layer that grows along the edge of the cluster still has not penetrated the wake's core. The u_{rms} starts to recover from $x = 2.5W_A$ onwards.

For the taller cluster (Case 2 in Figure 5), the individual wakes have still not merged completely at $x = 1.2W_A$, suggesting that with an increase in H_B/W_A, the wakes necessitate a larger spatial range to merge. The transition wake is also observed to extend up to $x = 2.5W_A$ compared to $x = 2W_A$ for Case 1. The lateral profiles of u_{rms}/U_0 at different streamwise locations presented in Figure 6, show a further delay in response to changes in the mean flow field. The effect of the individual buildings wake for Case 2 is present for $x = 1.5W_A$, while its recovery in the far-wake region starts to occur for $x > 3.5W_A$. This behaviour exhibits the role of vertical shear on the wake recovery behind the cluster of tall buildings. The vertical velocity profiles for Case 2 are shown in Figure 7; these exhibit a uniform velocity throughout most of the cluster height, up to $z = 0.4\delta$ till $x = 2.5W_A$. The vertical gradient of streamwise velocity (dU/dz) is also observed to be smaller for taller building clusters (Case 2). With an increase in height, the vertical shear layer penetrates more slowly into the cluster wake region, resulting in a greater extent of the uniform flow region. The vertical profile for Case 3 ($H_B/\delta = 0.125$) is reported in Figure 8. These show the fastest recovery of the wake, while the zone of the uniform vertical velocity is not observed for this case. These results suggest that the cluster height, unsurprisingly, has a large influence on the development and recovery of the wake flow. It is also interesting to note that the vertical shear is the dominant factor in the wake recovery behind the cluster of tall buildings rather than the lateral shear.

As the vertical shear has a crucial effect on wake development, it is important to understand the vertical momentum exchange in the wake of tall building clusters. To understand the efficiency of the vertical momentum transfer through cluster height, the correlation coefficient $r_{uw}(=\overline{u'w'}/\sigma_u\sigma_w)$ against z/δ for Case 1, 2, and 3 are plotted in Figures 9, 10 and 11, respectively. For Case 1, we observe a positive r_{uw} at $x = 0.75W_A$ and $1W_A$ in a certain region ($0.05 < z/\delta < 0.2$) along the cluster height, which is because of the jet flow ($dU/dz < 0$)). The change in the sign of r_{uw} in the near-wake region is a response to the change in the sign of dU/dz between $0.25H_B \leq z \leq 0.75H_B$, as discussed in Hertwig *et al.* (2019). It is observed that r_{uw} is close to 0 up to $z = 0.75H_B$ in the near-wake region. According to Oke *et al.* (2017), this value of r_{uw} implies highly disorganised eddies. Similar behaviour is observed for Case 2 in the near-wake region. Here, the flow is still recovering till $x = 3.5W_A$, as inferred from the r_{uw} profiles. However, a strong correlation between streamwise (u') and wall-normal fluctuations (w') is observed at all the streamwise locations for Case 3. Here, the vertical shear penetrates the cluster region, facilitating the organization of coherent structures in the wake. With an increase in cluster heights, this phenomenon is delayed, resulting in a larger extent of the uniform flow region within the transition-wake regime.

This occurrence of the uniform flow region due to the reduction in turbulence in the transition-wake regime is expected to have some effect in terms of natural ventilation, pedestrian comfort, and pollutant dispersion in urban areas. Furthermore, due to this uniform velocity deficit region behind the cluster, the recovery of the wake is expected to be delayed further downstream. This could increase the overall drag force generated by the cluster. Moreover, the reduction in turbulence results in the suppression of the vertical and lateral mixing in the wake flow. This can lead to an accumulation of pollutants in this region when these are released within or upstream of the cluster. With an increase in the cluster height, the recovery of the wake is delayed further, emphasising the importance of the vertical momentum exchange in clusters' wakes.

CONCLUSION

The present paper aims to explore the turbulent characteristics in the wake of tall building clusters. Experiments were performed in the wake of 4 clusters with $W_S = W_B$ using a 3D laser Doppler anemometer. Three different cases with different relative clusters to boundary layer heights were considered ($H_B/\delta = 0.125, 0.240, 0.500$). Results show the existence of a uniform momentum zone in the transition-wake regime, which results in a significant reduction of turbulent intensity within the core of the wake behind the cluster. This inhibits the mixing of fluid in both the lateral and vertical directions. The cluster height has a dominant effect on the recovery of the wake; increasing it inhibits the vertical momentum transfer, thus extending the region of uniform momentum within the transition-wake regime.

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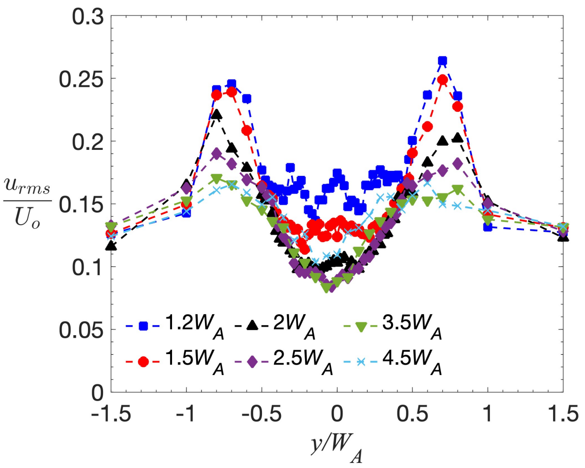

Figure 6. Lateral variation of u_{rms}/U_0 for Case 2.

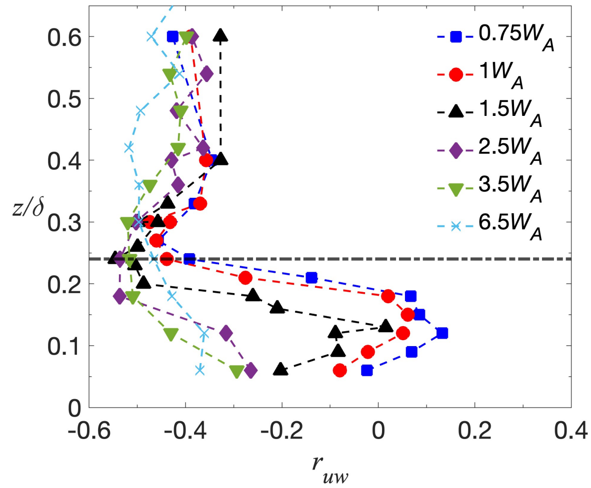

Figure 9. Vertical variation of correlation coefficient (r_{uw}) for Case 1.

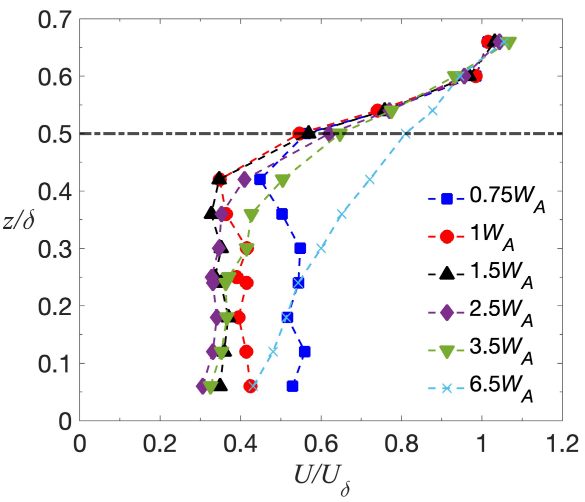

Figure 7. Vertical variation of U/U_δ for Case 2.

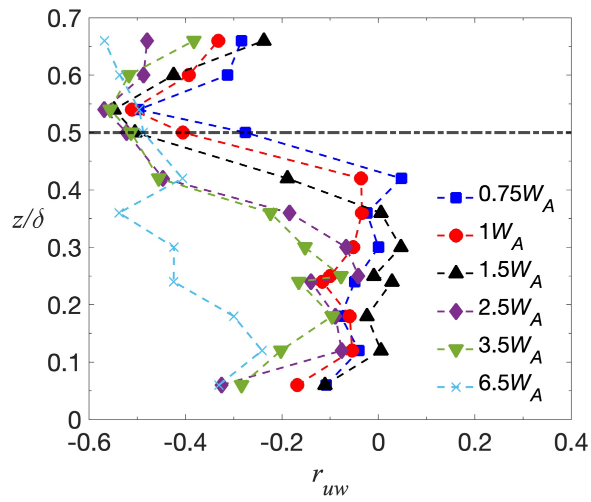

Figure 10. Vertical variation of correlation coefficient (r_{uw}) for Case 2.

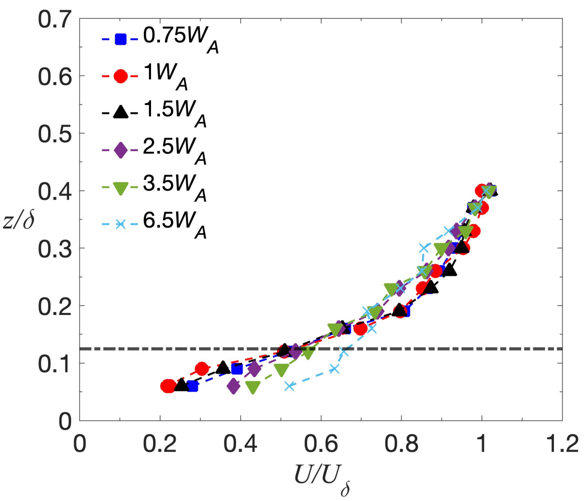

Figure 8. Vertical variation of U/U_δ for Case 3.

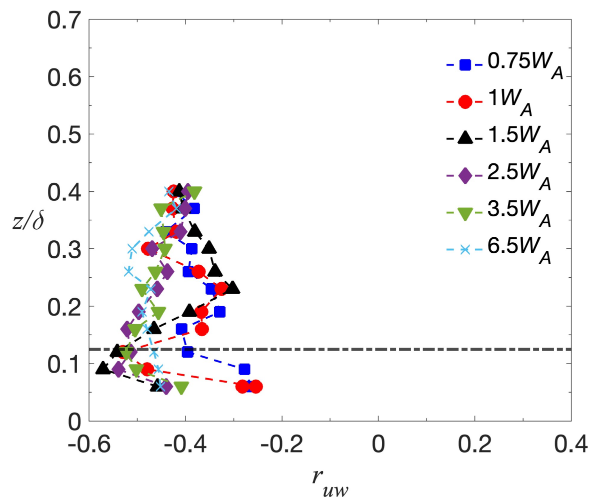

Figure 11. Vertical variation of correlation coefficient (r_{uw}) for Case 3.