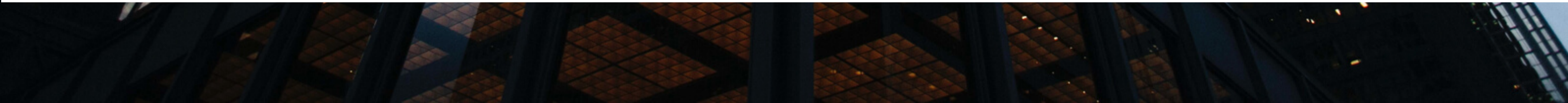
Institution of MECHANICAL ENGINEERS

UNIVERSITY OF SURREY

# URBAN BOUNDARY LAYERS

## OVER TALL AND VARIABLE HEIGHT BUILDINGS

AUTHORS: MARCO PLACIDI, ALEXANDROS MAKEDONAS, MATTEO CARPENTIERI



# INTRODUCTION

- By 2050, cities will host 68% of the world population (DESA 2019).
- Tall buildings are rapidly increasing.
- Dense cities are constantly being built.

DESA U (2019) World population prospects 2019: Highlights. New York (US): United Nations Department for Economic and Social Affairs

# INTRODUCTION

- By 2050, cities will host 68% of the world population (DESA 2019).
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- Dense cities are constantly being built.

How does the new urban environment affect:

- Pollution
- Air circulation and mixing
- Meteorological phenomena

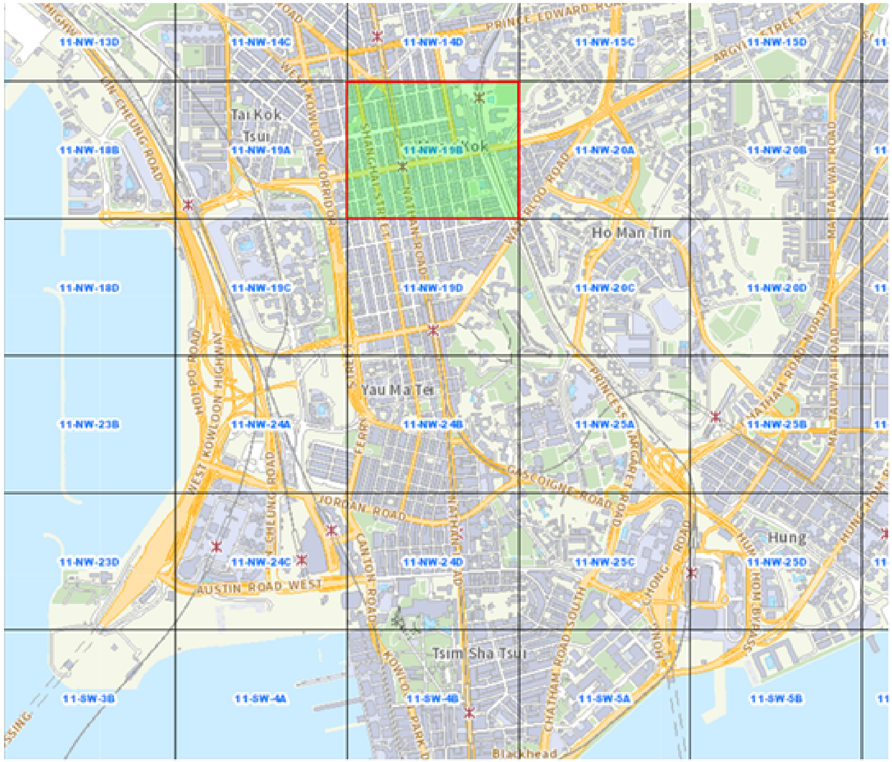
DESA U (2019) World population prospects 2019: Highlights. New York (US): United Nations Department for Economic and Social Affairs

# EXPERIMENTAL SET-UP

## Case study: Hong Kong

Hong Kong is one such city

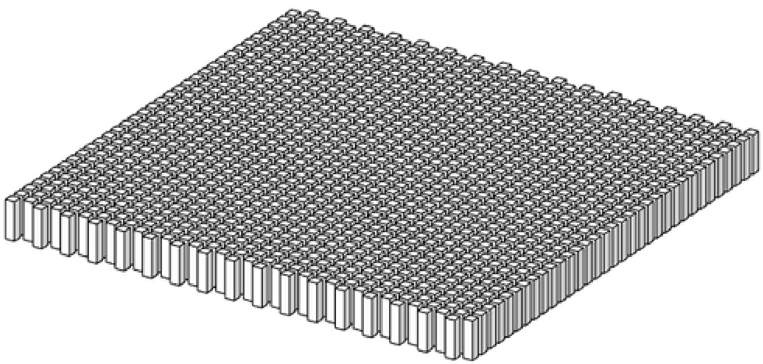
- Large density of buildings ( $\lambda_p$ )
- Many tall and 'super-tall' buildings.
- Standard deviation of height $\sigma_h$
- Average height $h_{avg}$
- Maximum height $h_{max}$



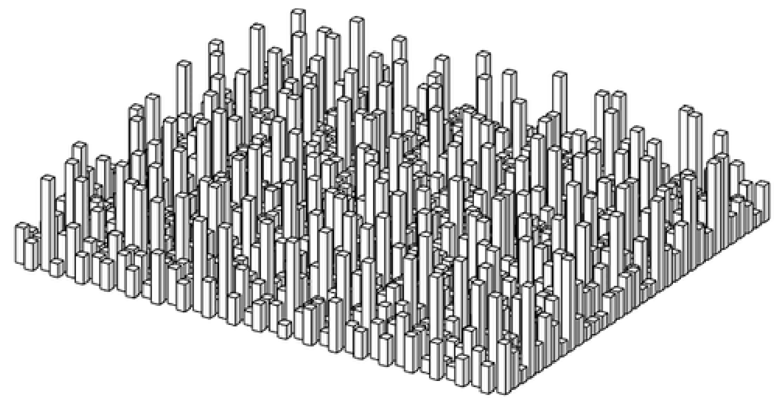
# EXPERIMENTAL SET-UP

## Models

Two idealized models were constructed that resembled some of Hong Kong's important geometrical parameters.



- $h_{avg}$ = 80 mm
- $\lambda_p$ = 0.44
- Uniform height
- $h_{max}$ = 80 mm
- $h_{max}$ = $h_{avg}$



- $h_{avg}$ = 80 mm
- $\lambda_p$ = 0.44
- $\sigma_h$ = 49 mm
- $h_{max}$ = 200 mm
- $h_{max}$ = 2.5 $h_{avg}$

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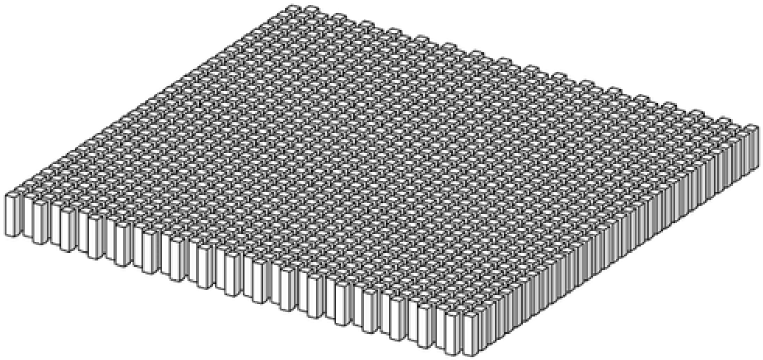

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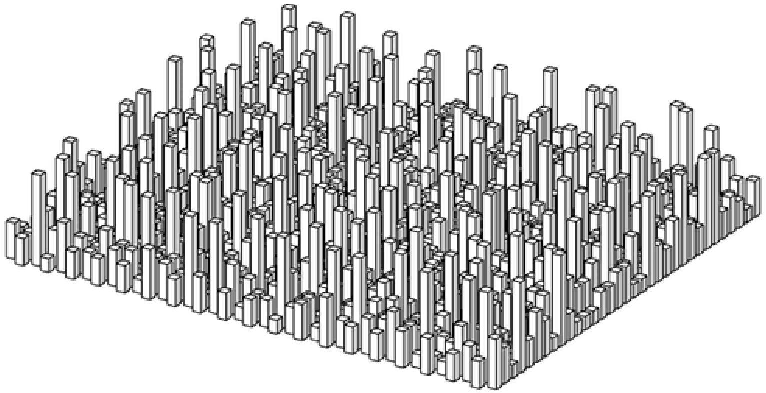

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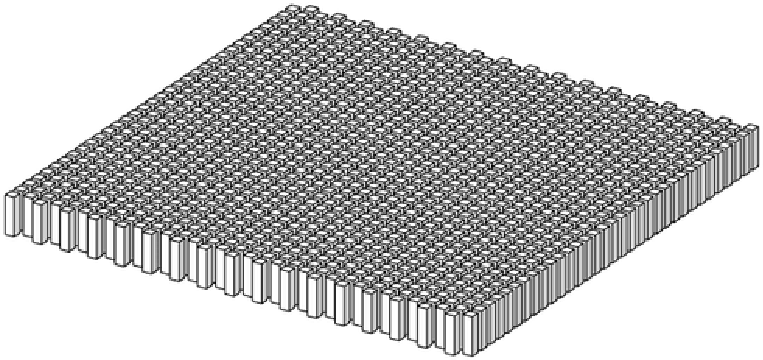

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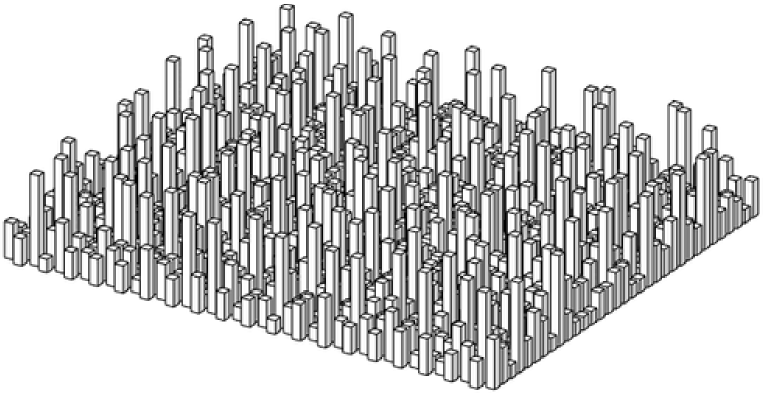

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# EXPERIMENTAL SET-UP

- All canopies have average height 80 mm.
- Similar process to Cheng and Castro (2002). Regular array of cubes.
- Closed-circuit wind tunnel testing at the University of Surrey EnFlo Lab.

Cheng, H. and Castro, I. P. (2002). Near wall flow over urban-like roughness. Boundary-Layer Meteorology, 104(2):229–259.

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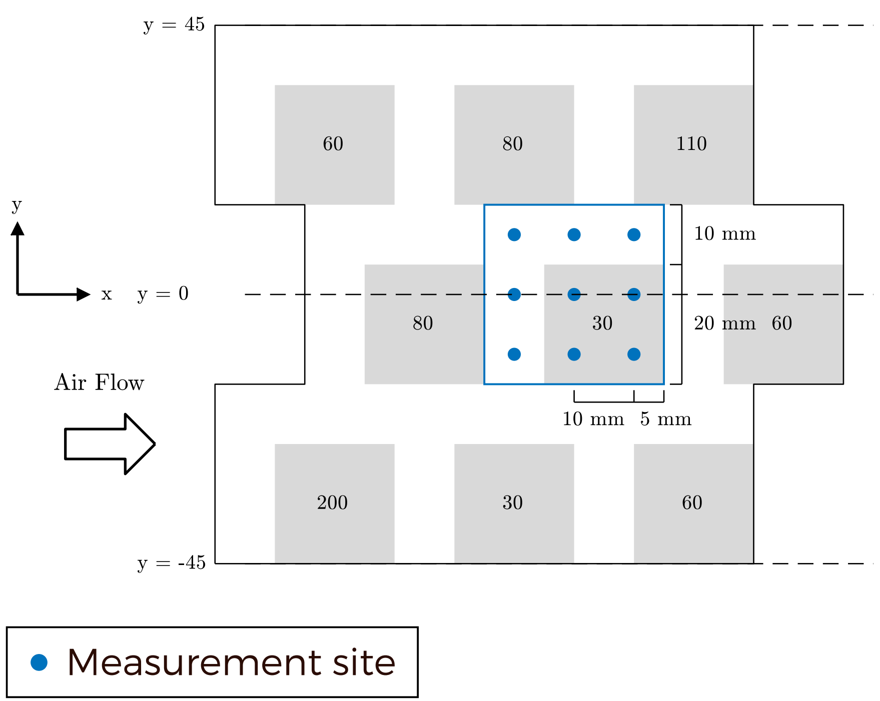
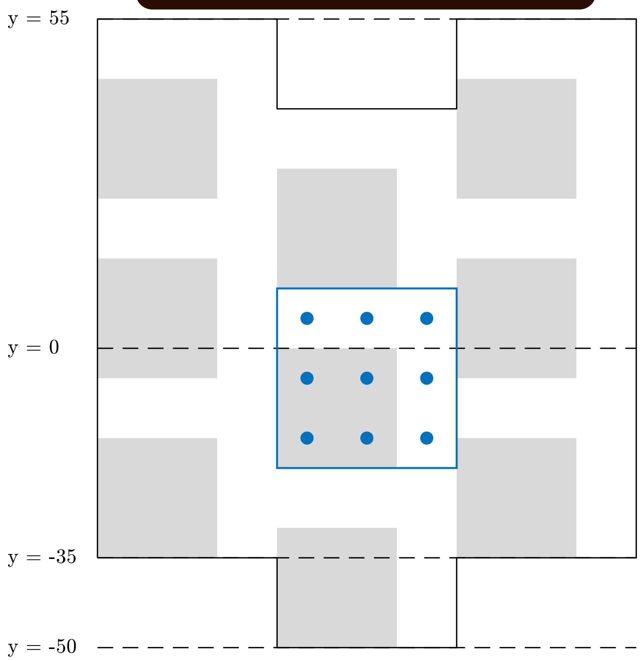
- All canopies have average height 80 mm.
- Similar process to Cheng and Castro (2002). Regular array of cubes.
- Closed-circuit wind tunnel testing at the University of Surrey EnFlo Lab.
- Rotate 90 degrees to go from aligned to staggered.

## UHA/VHA




## UHS/VHS

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# AIMS & INSTRUMENTATION

- Examine the effects of a tall canopy and compare with Cheng and Castro (2002) and Cheng et al. (2007).
- Examine effects of a large standard deviation in a tall canopy, and compare them with the uniform height tall canopy.

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## Instrumentation

- Two-component Laser Doppler Anemometry (LDA) used to create vertical velocity profiles and vertical shear stress profiles.
- Pressure tapped elements to measure drag (friction scaling).

Cheng, H., Hayden, P., Robins, A., and Castro, I., 2007. Flow over cube arrays of different packing densities. Journal of Wind Engineering and Industrial Aerodynamics 95, 715–740.

# OUTLINE OF RESULTS

## UH

- Depth of Boundary Layer (BL)
- Depth of Roughness Sublayer (RSL)
- Depth of Inertial Sublayer (ISL)

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- Depth of Boundary Layer (BL)
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- Depth of Inertial Sublayer (ISL)
- Comparison of aerodynamic parameters

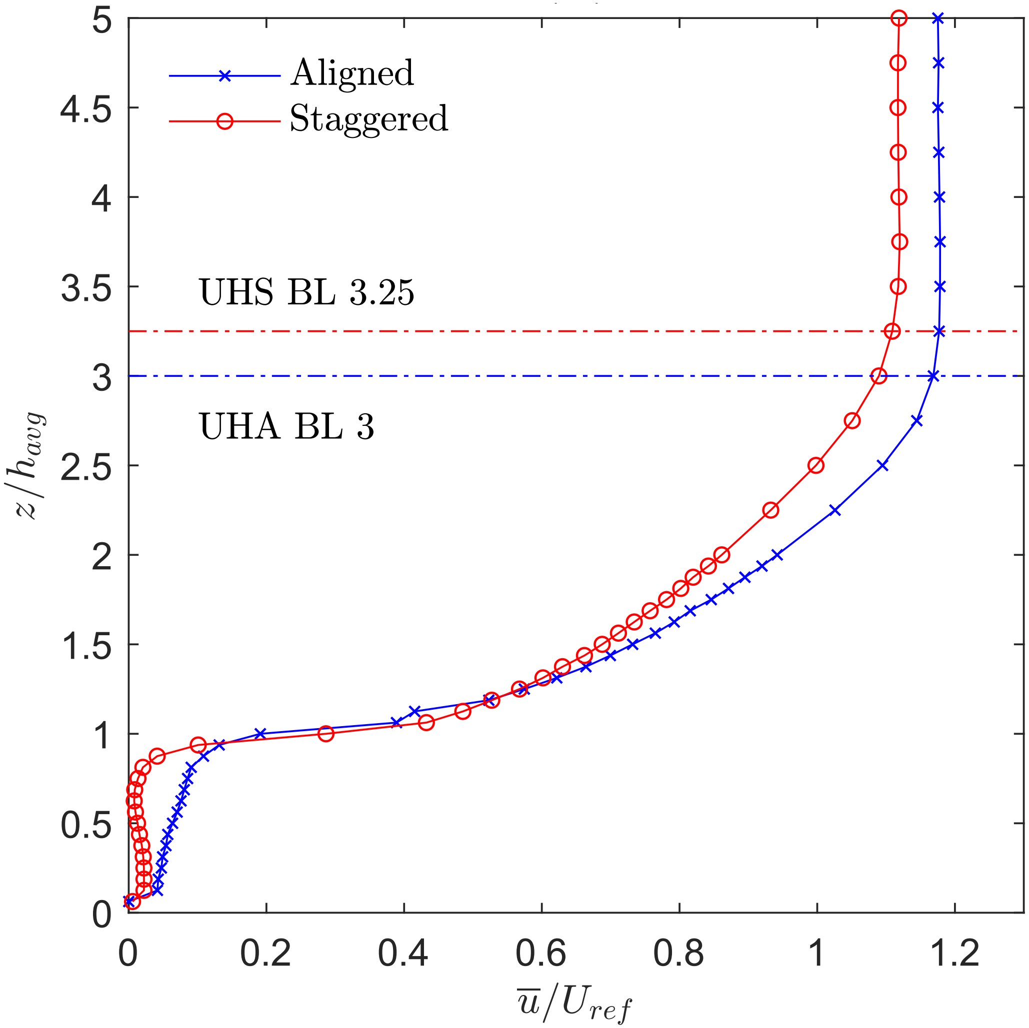
# RESULTS & DISCUSSION

## UNIFORM HEIGHT

### Boundary Layer Depth

| | C&C(2002) | Cheng(2007) | Mak(2019) |
|---|---|---|---|
| Block (mm) | 10 | 20 | 80 |
| BL $\delta$ (mm) | 121 | 130 | 250 |
| BL $\delta$ ($h$) | 12 | 7 | 3.25 |

- Increase in BL thickness in staggered likely due to increase in street canyon length behind elements, likely 'wake flow' regime occurs.



# RESULTS & DISCUSSION

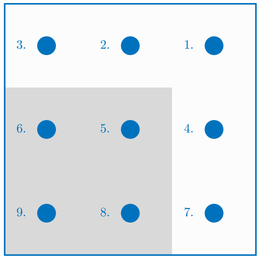
## UNIFORM HEIGHT

### Roughness Sublayer

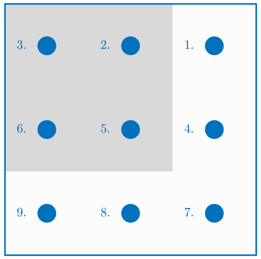
| | C&C(2002) | Cheng(2007) | Mak(2019) |
|---|---|---|---|
| Block (mm) | 10 | 20 | 80 |
| RSL ($h$) | 2 | 2 | 1.2 |
| Collapse | No | No | Yes |

- Collapse likely due to tight packing and skimming-flow regime

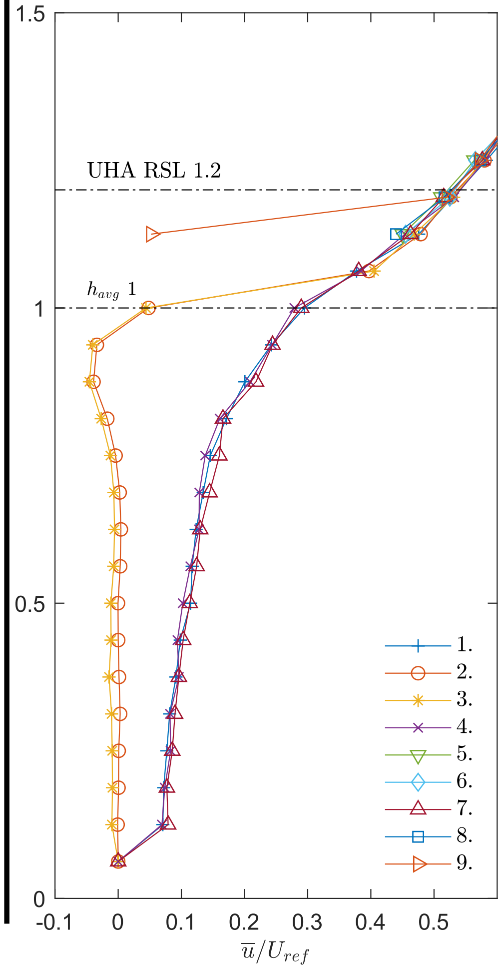
VHA



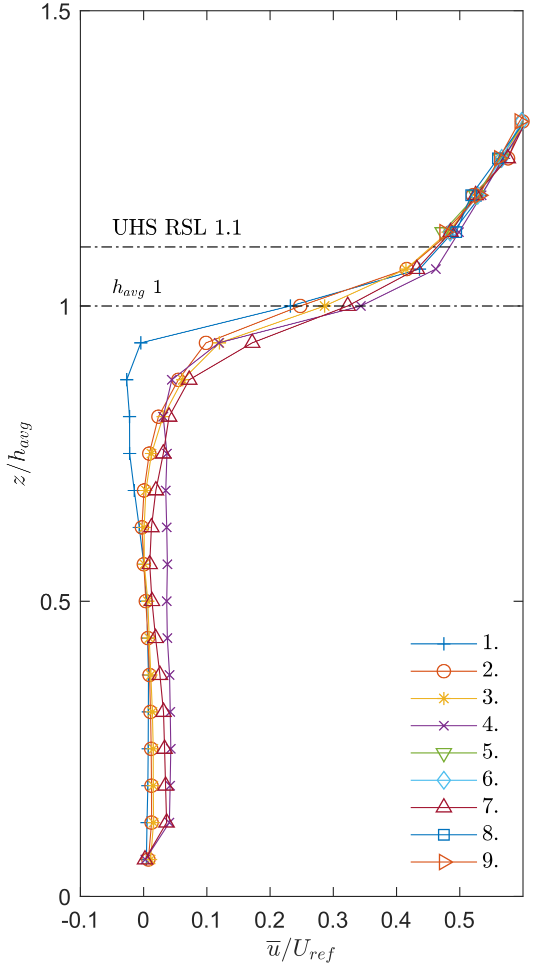

VHS




VHA




VHS

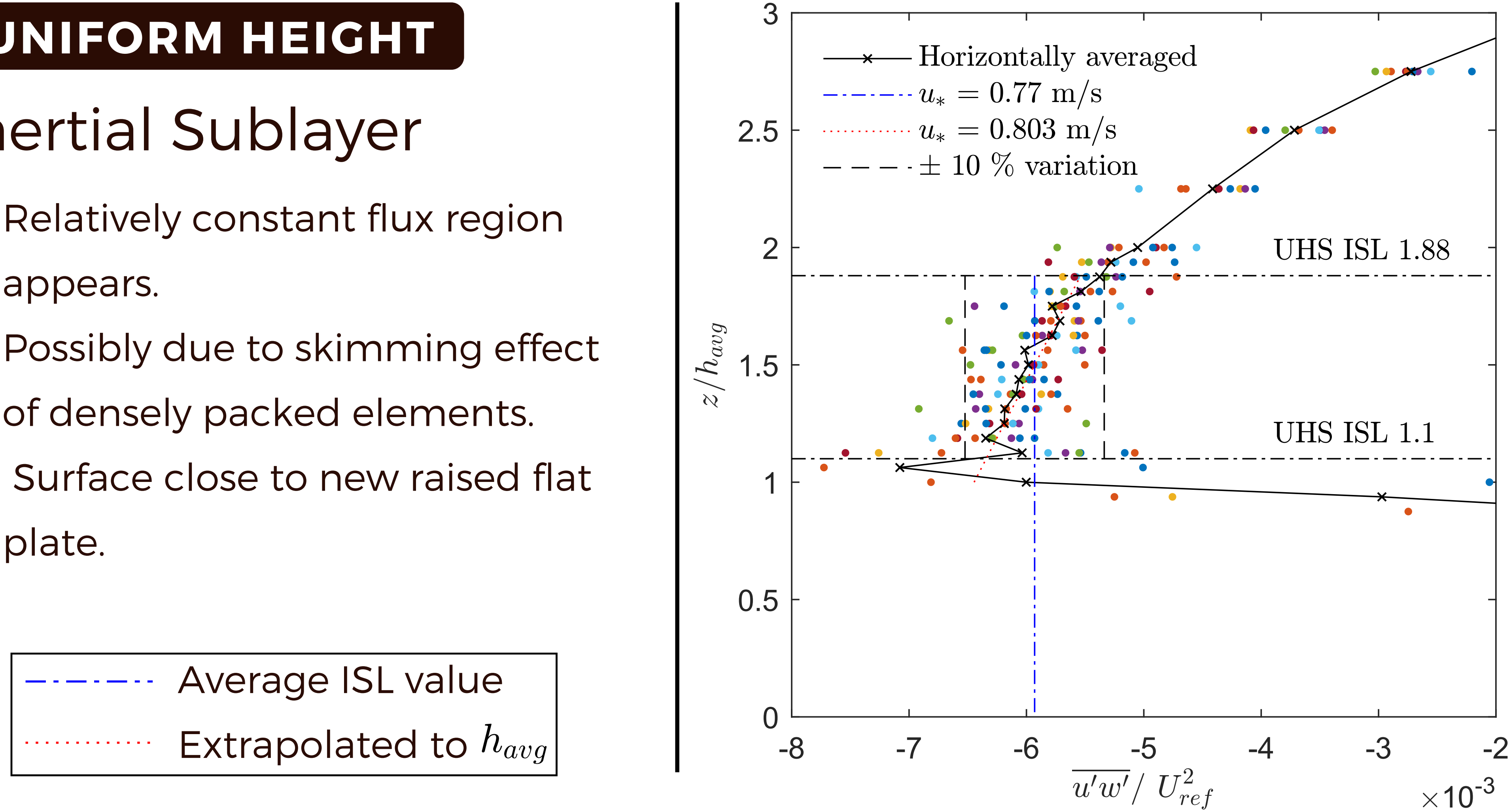


# RESULTS & DISCUSSION

## UNIFORM HEIGHT

### Inertial Sublayer

- Relatively constant flux region appears.
- Possibly due to skimming effect of densely packed elements.
- Surface close to new raised flat plate.



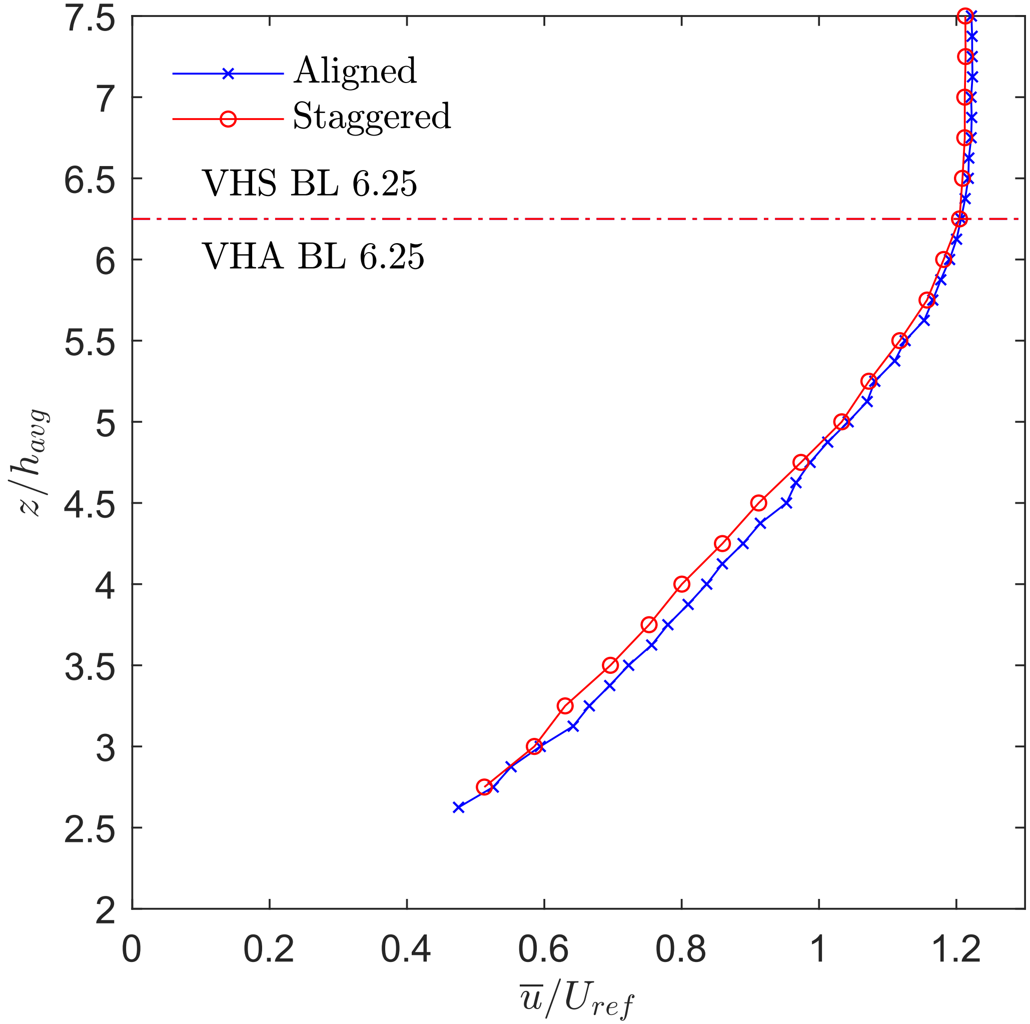
# RESULTS & DISCUSSION

## VARYING HEIGHT

### Boundary Layer

- BL doubles in depth from uniform height, despite average height of elements being the same.
- Standard deviation of height and height of maximum element increase drag.

| | UH | VH |
|---|---|---|
| $h_{avg}$ (mm) | 80 | 80 |
| BL $\delta$ (mm) | 250 | 500 |
| BL $\delta$ ($h_{avg}$) | 3.25 | 6.25 |
| BL $\delta$ ($h_{max}$) | 3.25 | 2.5 |



# RESULTS & DISCUSSION

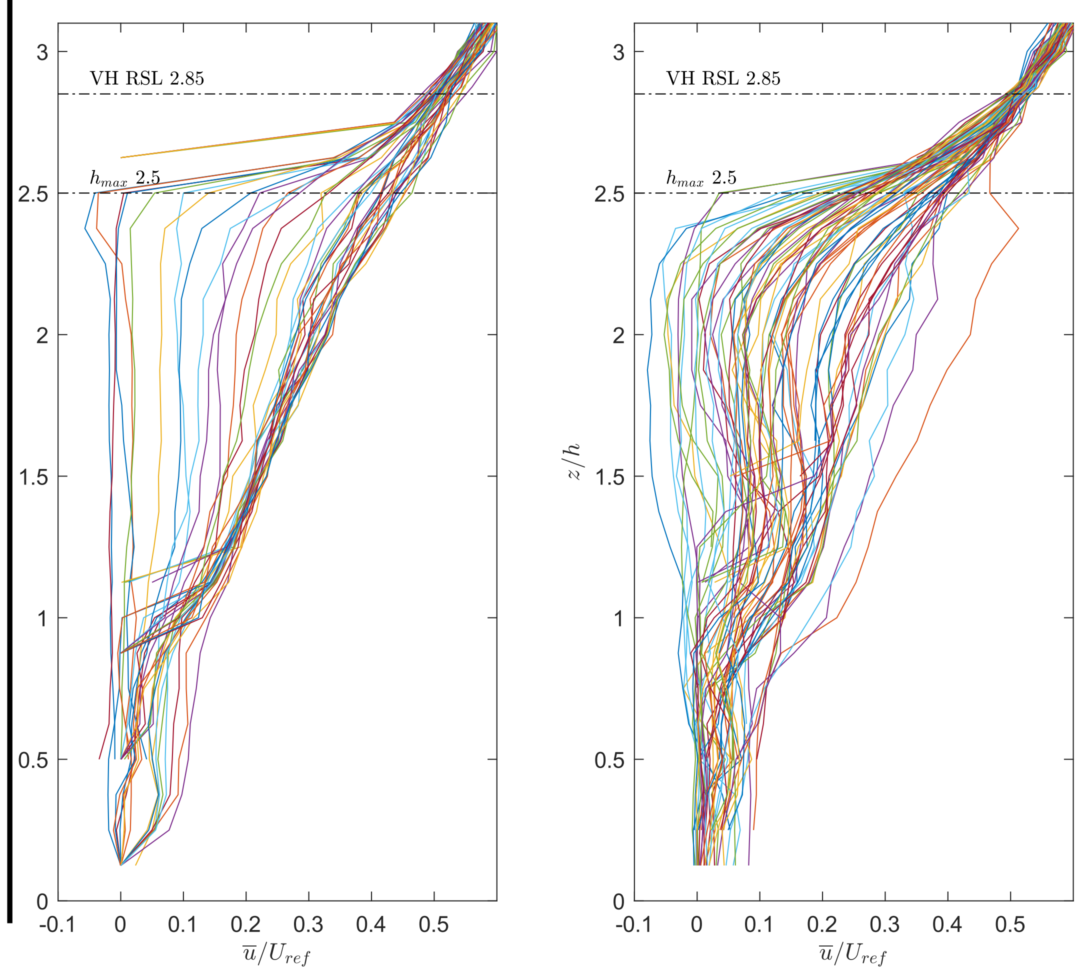
## VARYING HEIGHT

### Roughness Sublayer

- The velocity profiles clearly collapse just above the tallest element height ( $z/h_{max}$ = 2.5).
- Large range of velocities occur below $h_{avg}$.
- Large $\sigma_h$ increases mixing deep into canopy and skimming regime no longer occurs.

VHA

VHS



# RESULTS & DISCUSSION

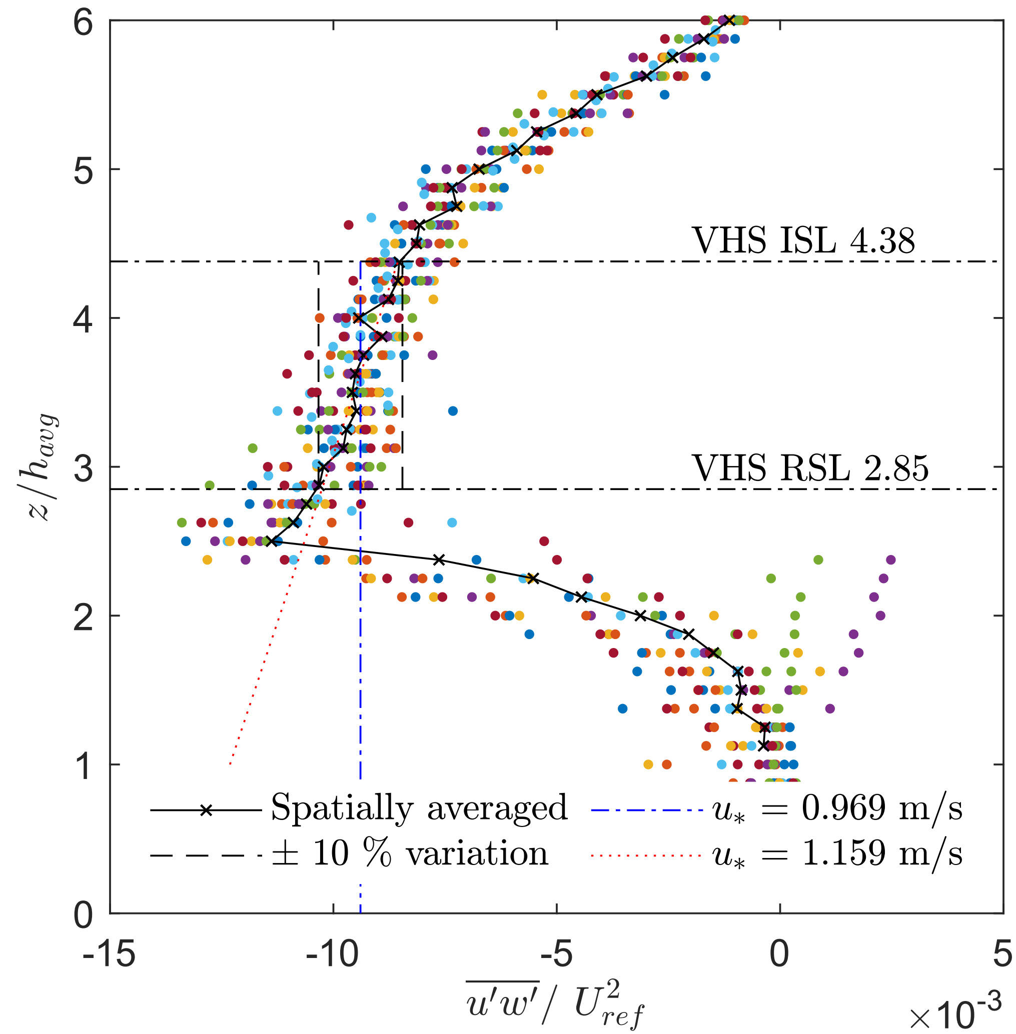
## VARYING HEIGHT

### Inertial Sublayer

- ISL formation still present.
- Large pressure gradient in wind tunnel due to BL thickness increase may cause the ISL to slope.
- Definition based on ±10 % variation perhaps inaccurate

Average ISL value

Extrapolated to $h_{avg}$



# RESULTS & DISCUSSION

## Aerodynamic parameters

### UH

- Our results from uniform height experiments and literature showed decent agreement.

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### VH

- The varied height results could not be compared with previous literature.
- Morphometric methods were used to compare VH results, but no resemblance was found.

# CONCLUSION

## Highlights

- From UH to VH the BL almost doubles in thickness.
- The RSL in both UH and VH converges just above the $h_{max}$.
- An ISL forms in the UH experiments.
- There is indication that a ISL can form over surfaces with large standard deviation, but more research is necessary.
- Much research in VH canopies still necessary.

# CONCLUSION

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Matteo Carpentieri: m.carpentieri@surrey.ac.uk

# INTRODUCTION

## Atmospheric Boundary Layer

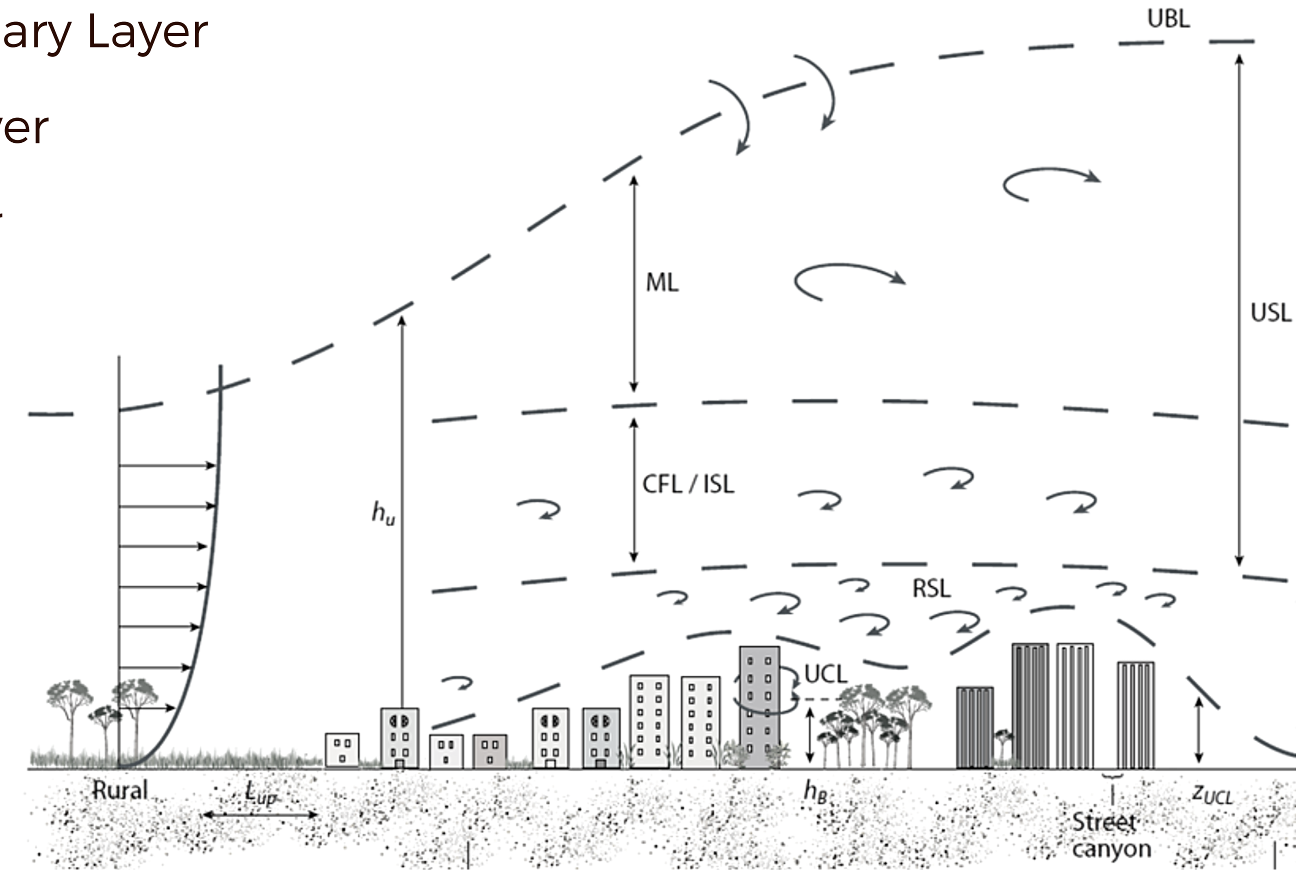
ABL - Atmospheric Boundary Layer

UBL - Urban Boundary Layer

RSL - Roughness Sublayer

ISL - Inertial Sublayer

UCL - Urban Canopy Layer




Fernando, H. (2010). Fluid dynamics of urban atmospheres in complex terrain. Annual review of fluid mechanics, 42:365–389.

# INTRODUCTION

## Parameters

$z_0$ - Zero-plane displacement

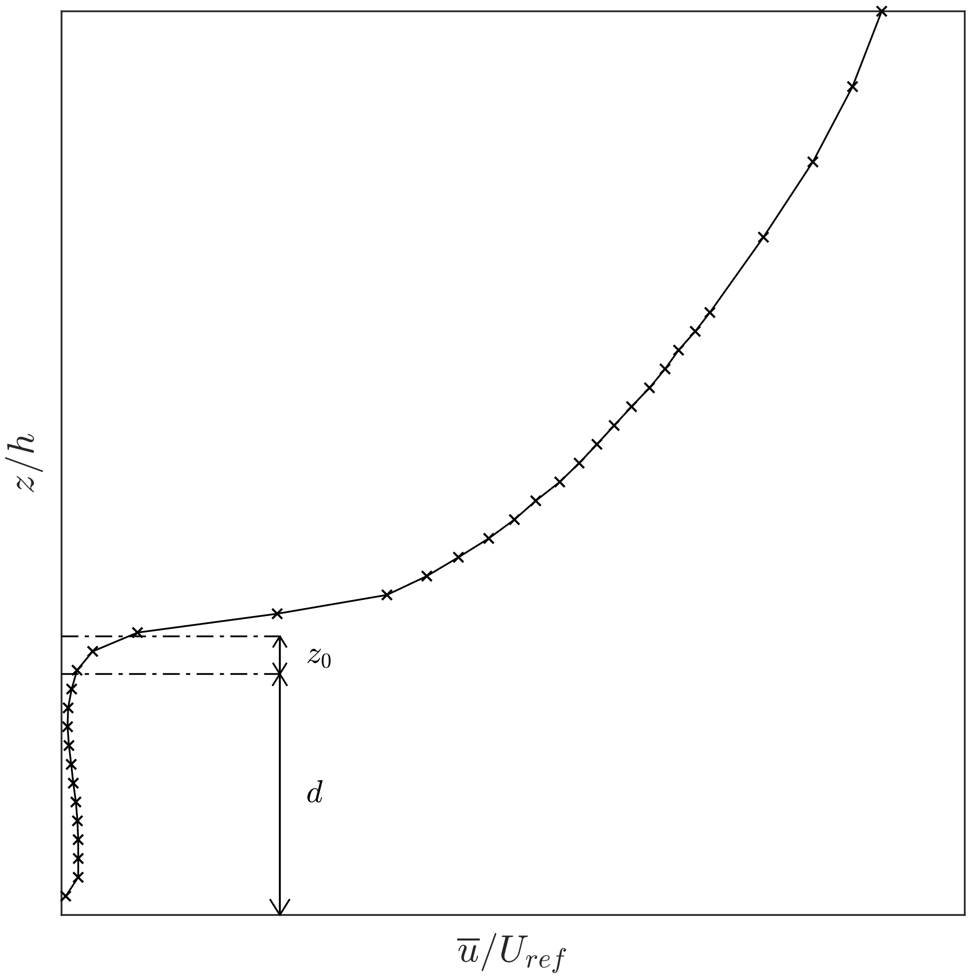
$d$ - Roughness length

$u_*$ - Friction velocity

$h_{max}$ - Maximum height

$\sigma_h$ - Standard deviation

$\lambda_p$ - Packing density

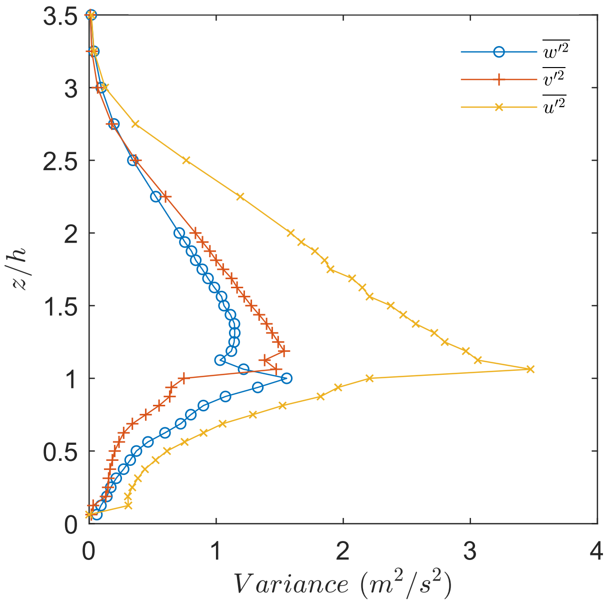


# RESULTS & DISCUSSION

## Turbulent Kinetic Energy

- In UH $\overline{w'^2}$ and $\overline{v'^2}$ are 2.3 times smaller than $\overline{u'^2}$
- $\overline{w'^2}$, $\overline{v'^2}$ not proportional
- In VH $\overline{w'^2}$ is 1.9 times smaller than $\overline{u'^2}$
- Cannot assume $\overline{w'^2} = \overline{v'^2}$

UH




VH