The Interactions between Roughness Turbulence Generated by Block Arrays and Wake around Large Obstacle

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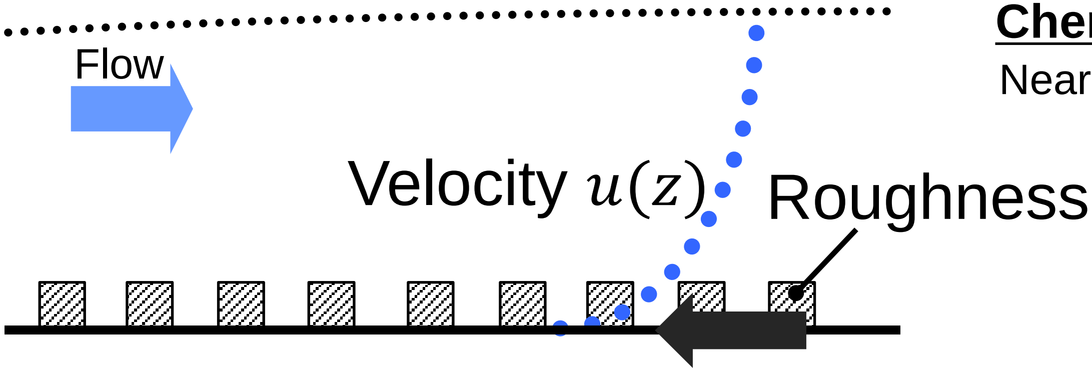
Outline

1. Background
2. Methodology
3. Experimental Details
4. Results and Discussions
5. Conclusions

Background

9th International Conference on Urban Climate (ICUC9), Toulouse

Urban Boundary Layer



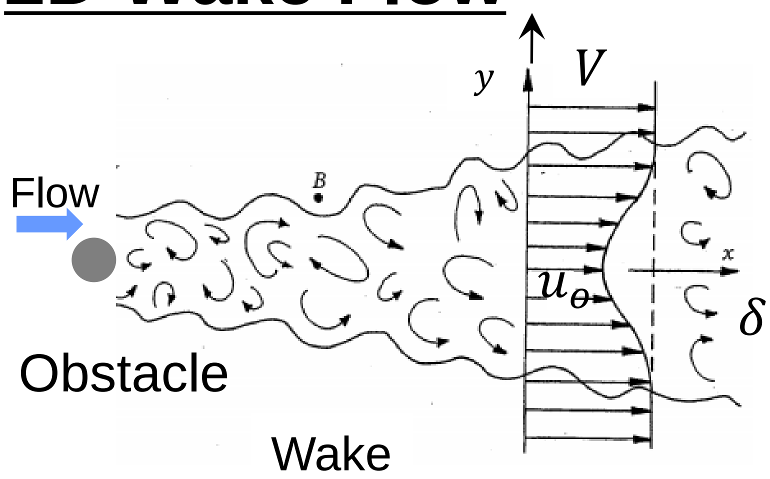
Hagishima et al., 2009
Aerodynamic effects of various array configurations of an urban array

Cheng and Castro, 2002
Near wall flow over urban like roughness

$$U = \frac{u_*}{k} ln\left(\frac{z-d}{z_0}\right)$$

The interaction between roughness turbulence generated by block arrays and wake flow behind large obstacle

2D Wake Flow

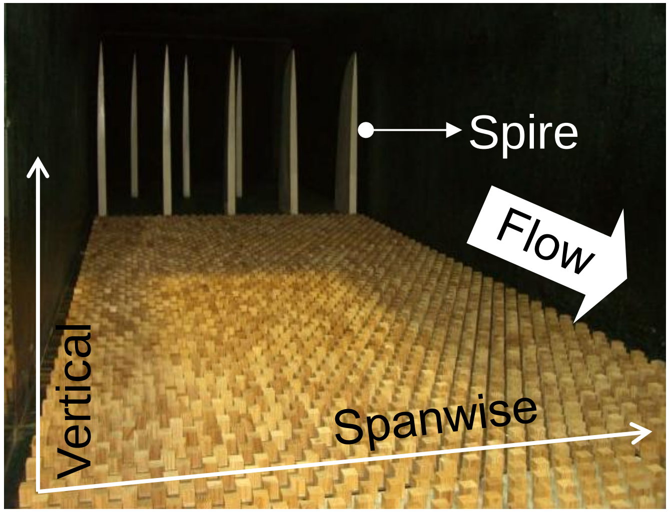


Self-similar Vel. Profile: $g(y/\delta(x)) = exp\left(-\left(\frac{y}{\delta}\right)^2\right)$

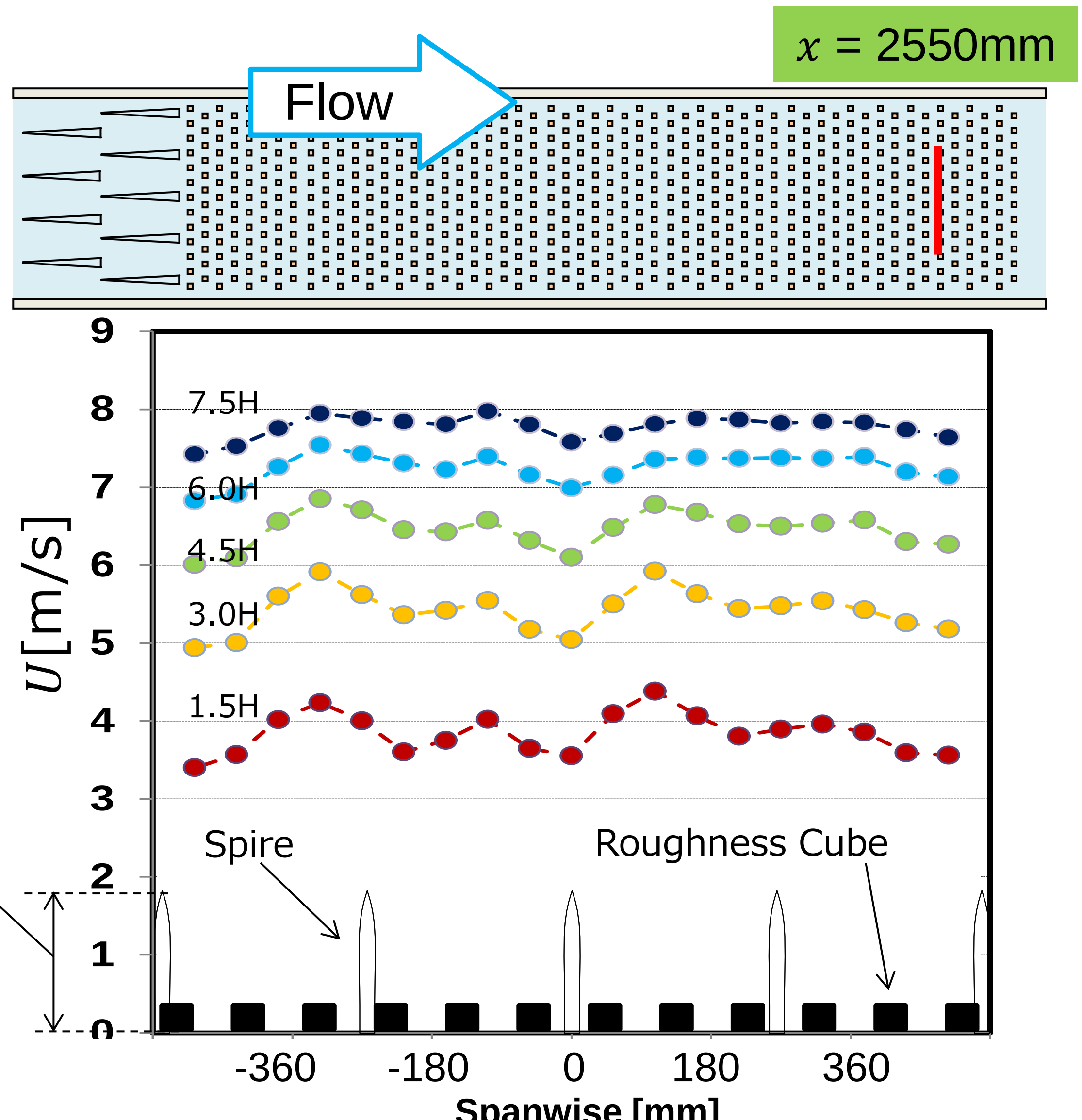
Max. Vel. Deficit: $\Delta U_n(y) = \propto x^{-0.5}$

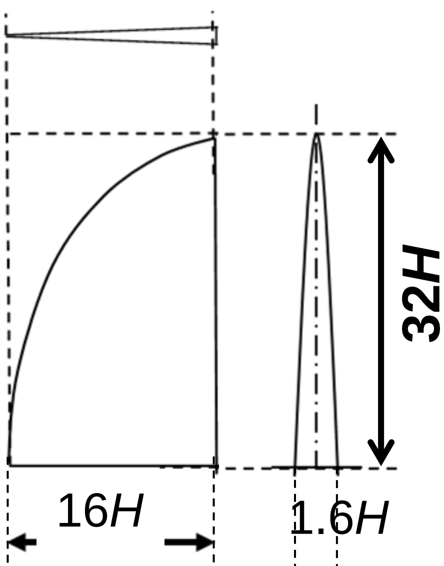
Half Wake Width: $\delta(x) \propto x^{0.5}$

Spanwise velocity distribution



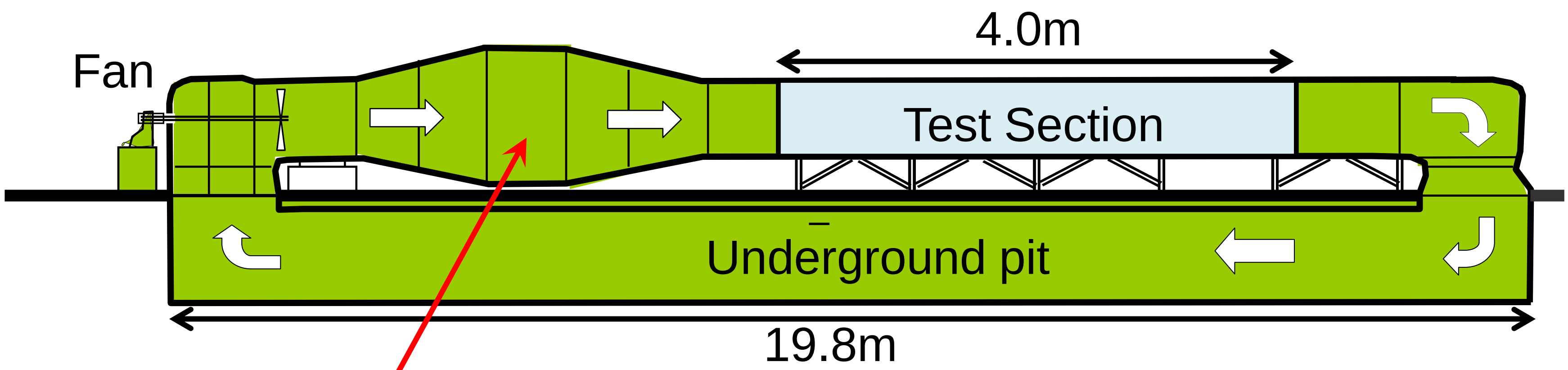
Rough Surface With Spire

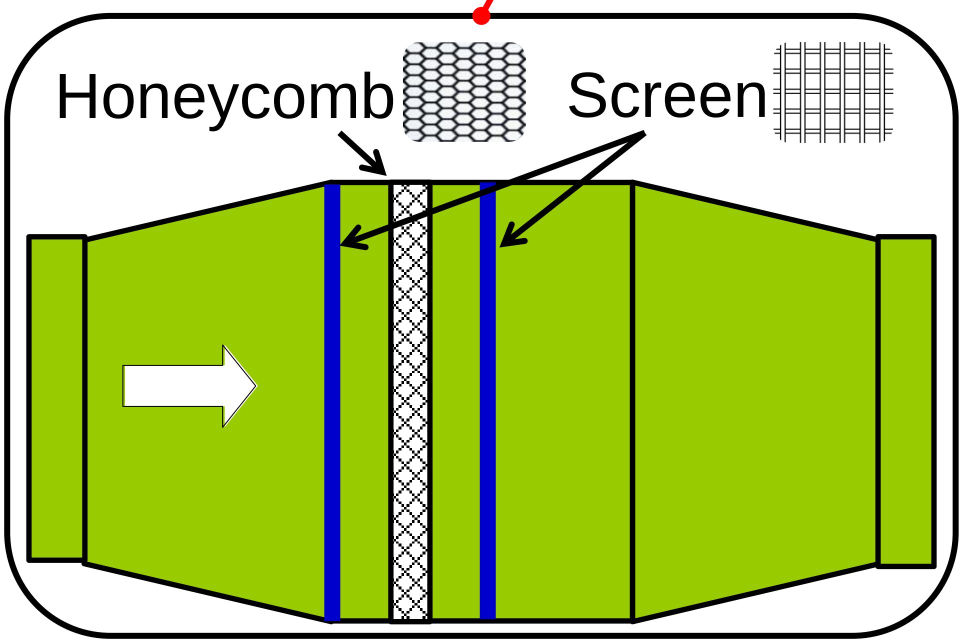




Outline

Methodology & Exp. Details

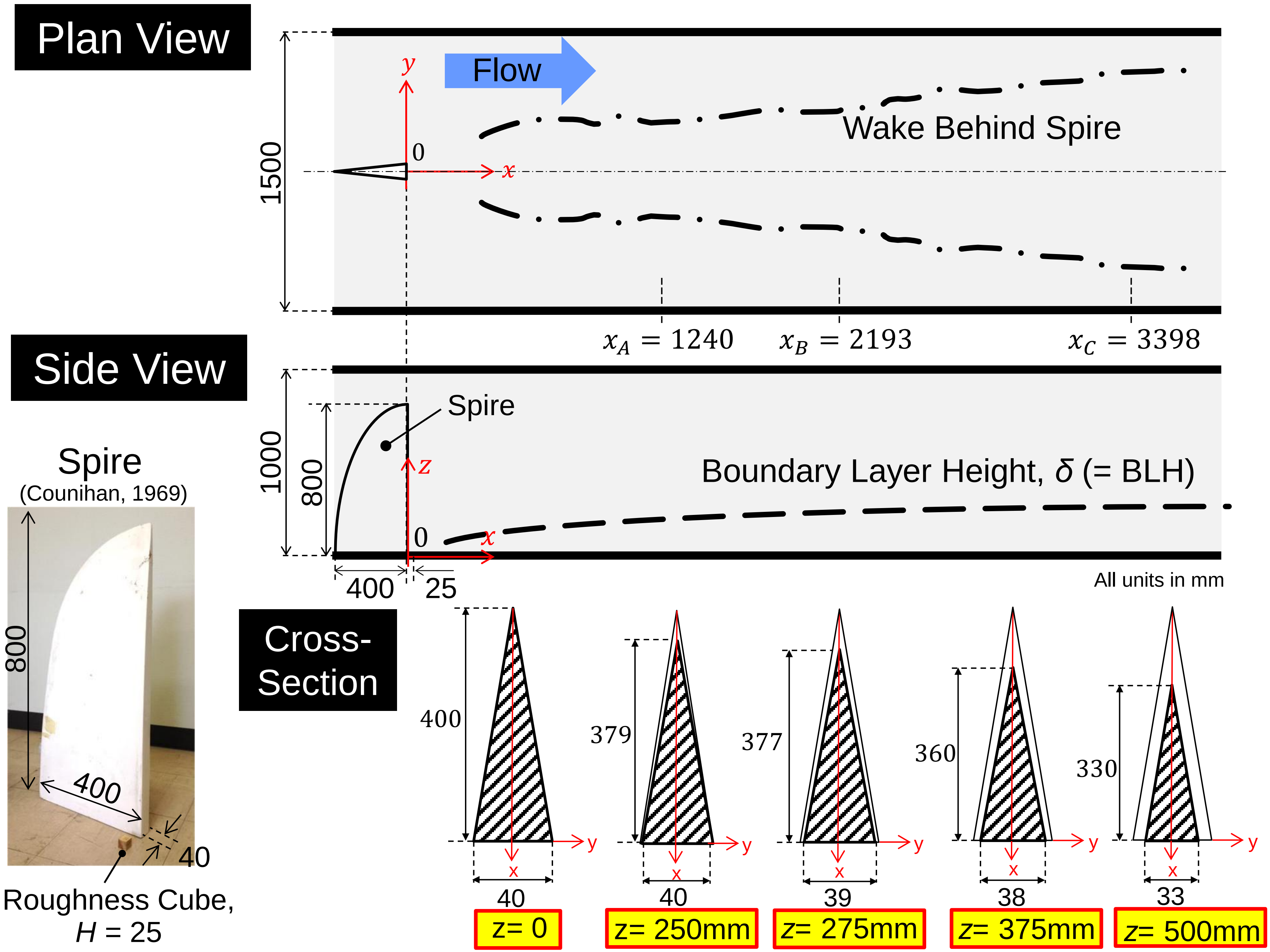




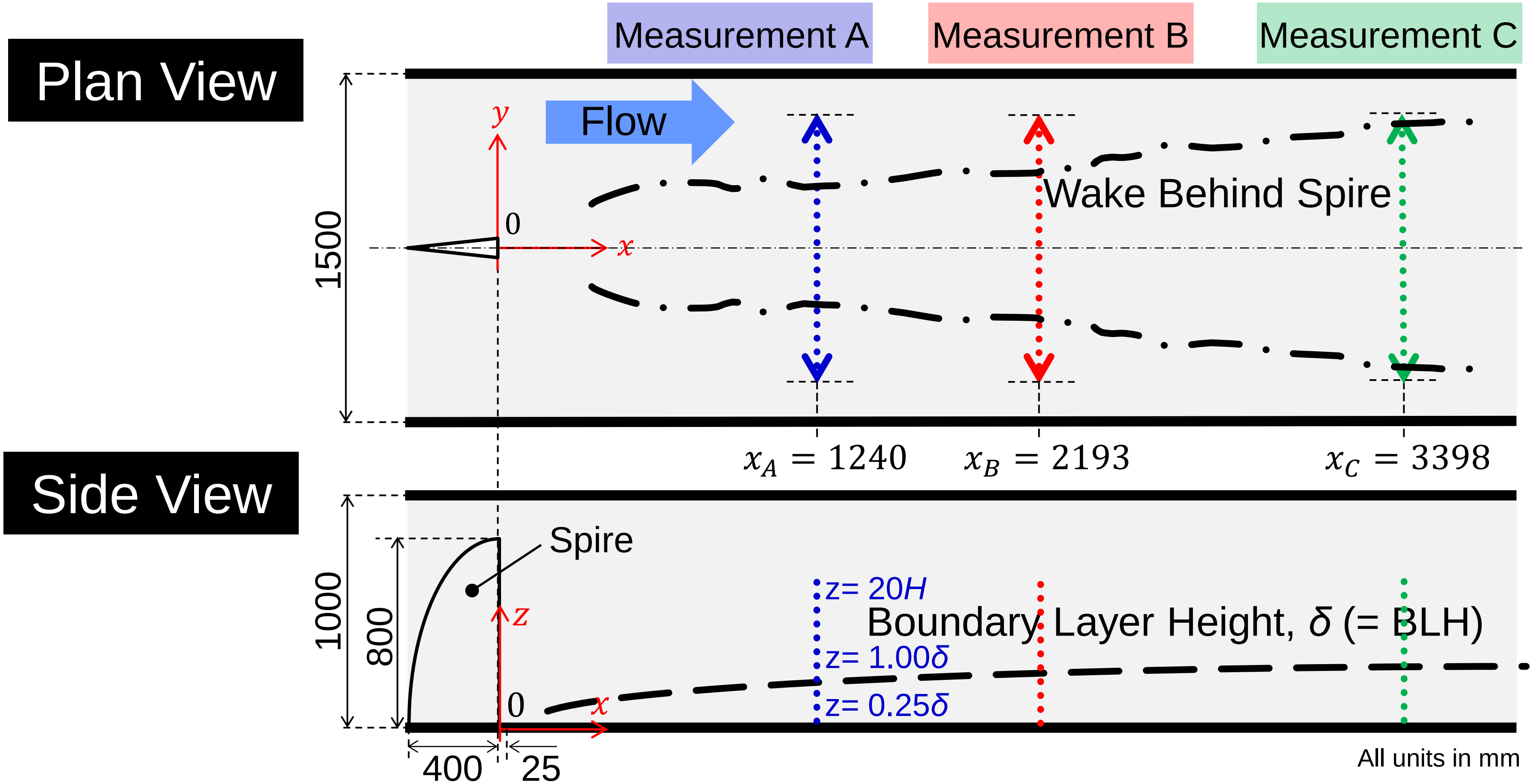
<u>Spatial uniformity of inflow condition</u>

Meshes, β > 0.57 to alter the inflow conditions.

(Mehta 1985 and Scheiman et al., 1980)



Plan View
Flow
y
0
x
1500
Wake Behind Spire
$x_A = 1240$
$x_B = 2193$
$x_C = 3398$
Side View
Spire
1000
800
z
0
x
Boundary Layer Height, δ (= BLH)
400
25
All units in mm
Spire
(Counihan, 1969)
800
400
40
Roughness Cube,
H = 25
Cross-Section
400
379
377
360
330
y
x
40
40
39
38
33
z= 0
z= 250mm
z= 275mm
z= 375mm
z= 500mm

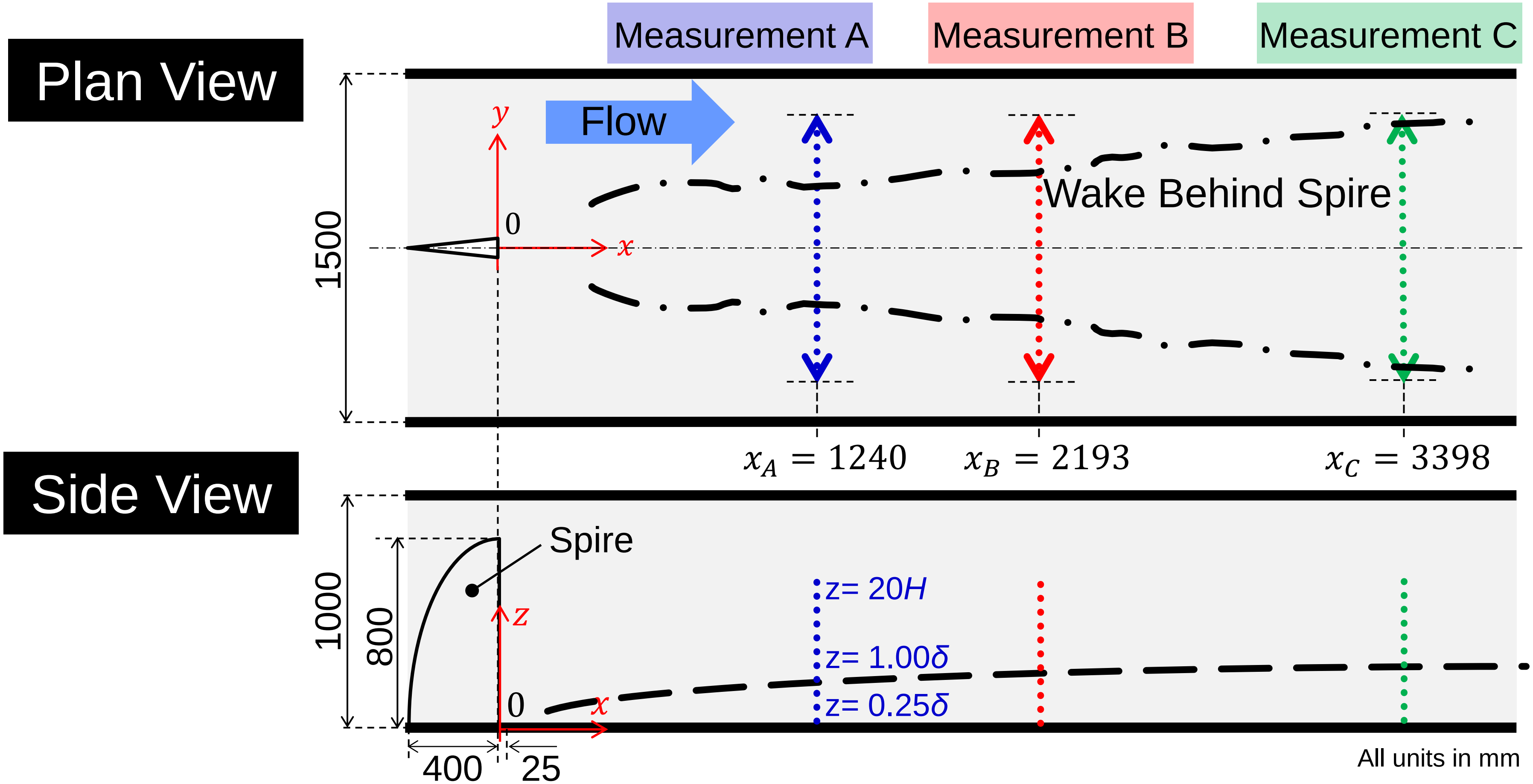


Spanwise (= total 162 points)

- Δy = 5mm for -14*H* ~ 14*H*
- Δy = 10mm for -18*H* ~ -14*H* and 14*H* ~ 18*H*)

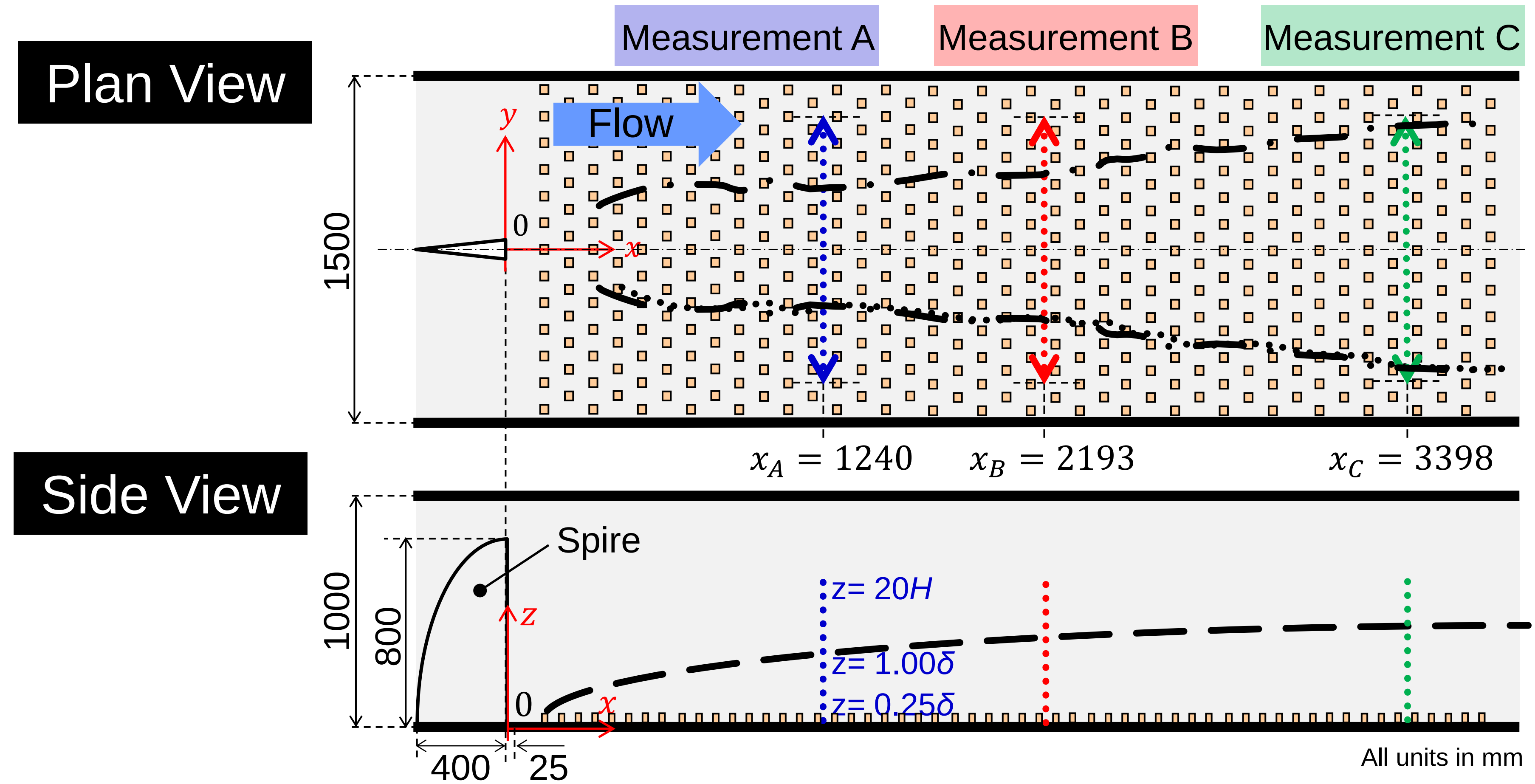
Vertical (= total 7 heights)

Within BL	0.25***δ***, 0.50***δ***, 0.75***δ***, 1.00***δ***, 1.25***δ***
Above BLH	15*H* and 20*H*



Instrumentation

- Split-film anemometer (Dantec Dynamics, 55R55)
- 1000 Hz and 30 seconds
- Reference stream velocity : 8m/s at $y = 0,\ z = 20\ H$



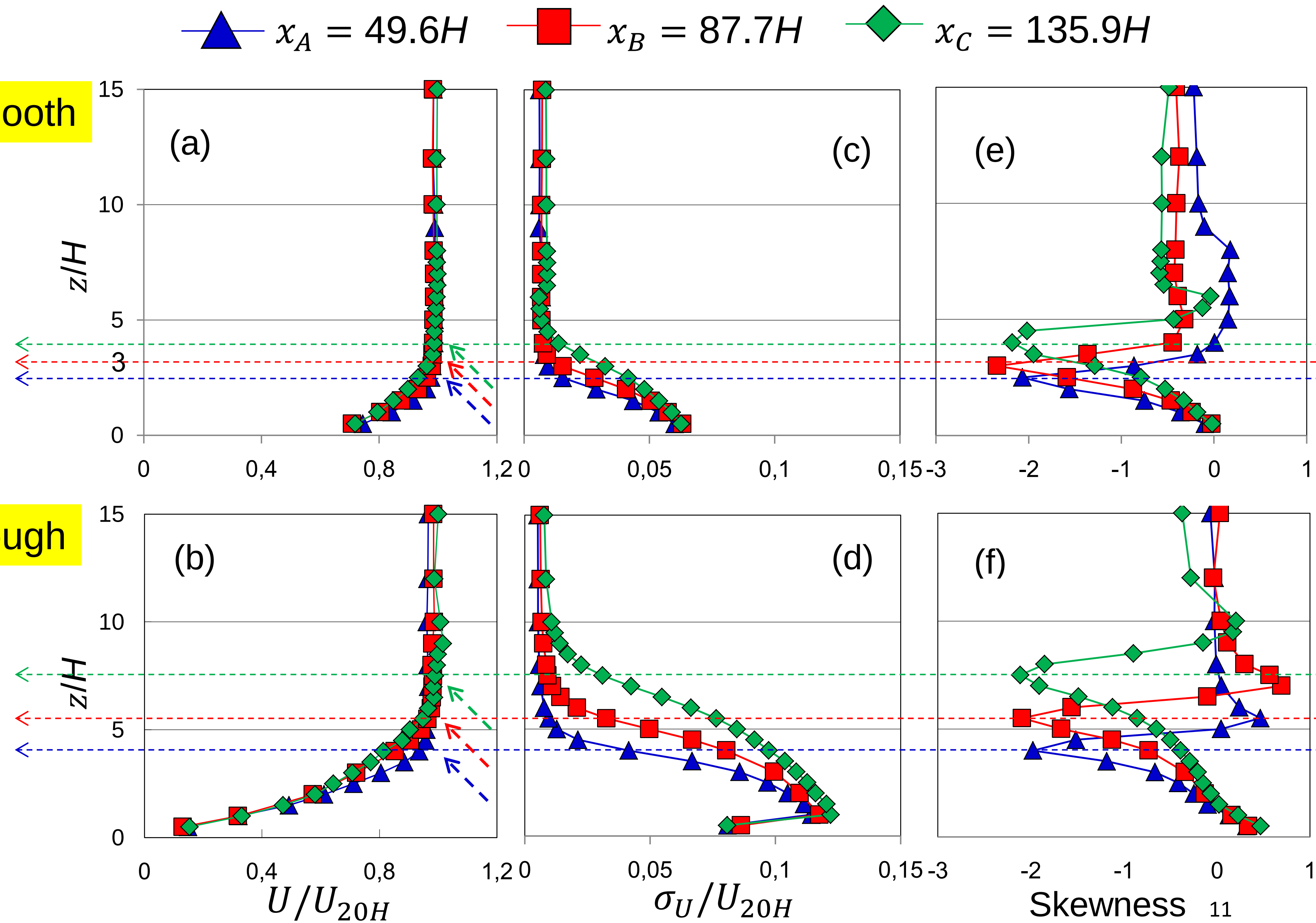
Wall Condition

- Smooth (Flat plate)
- Rough (Staggered Cubical Array, H = 25mm, λ_P =17.4%)

Spire Condition

- With Spire (=S)
- Without Spire (=NS)

Determination of the BLH, δ ($x = x_A, x_B, x_C$; $y = 0$)



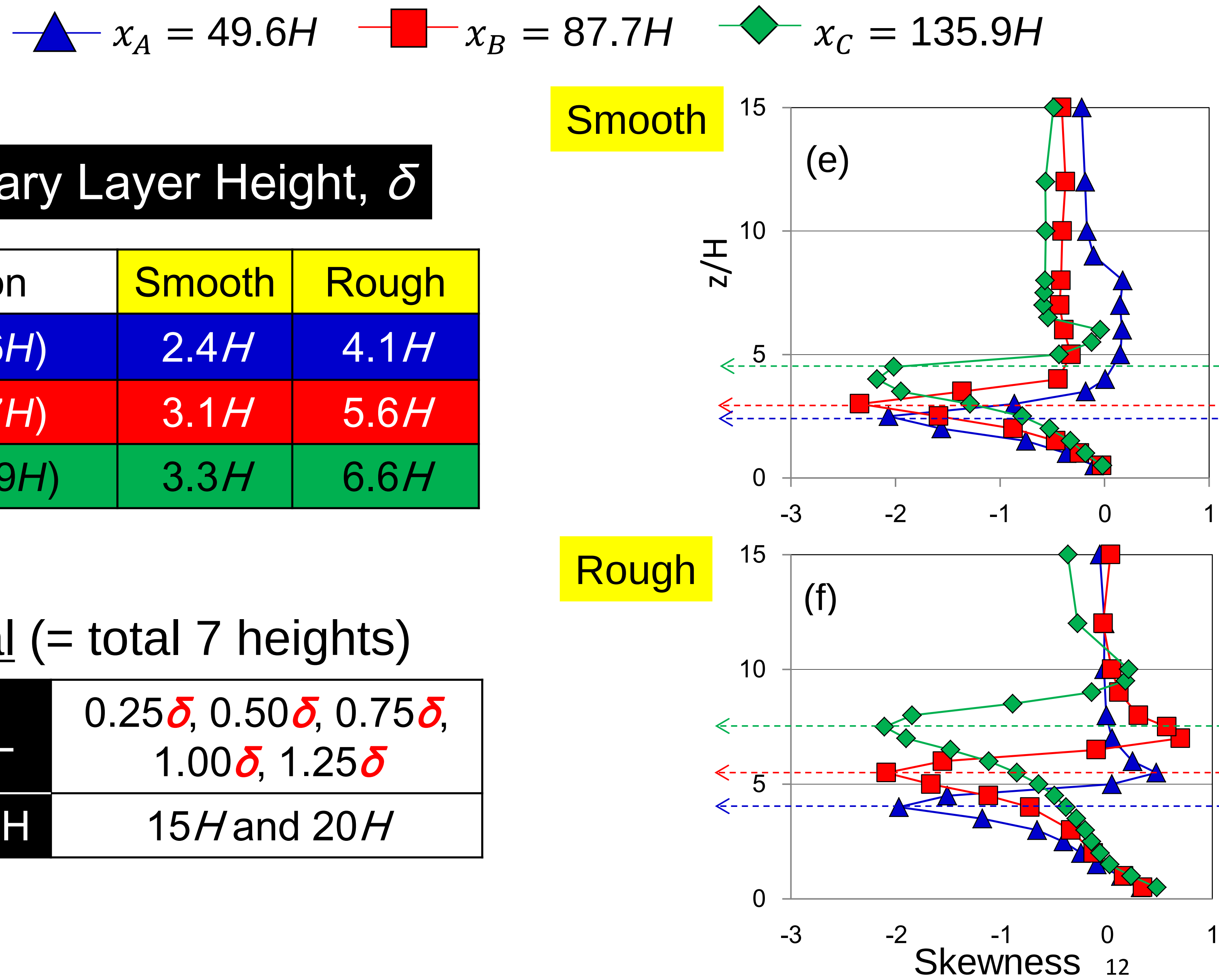
Determination of the BLH, δ $(x = x_A, x_B, x_C;\ y = 0)$

Boundary Layer Height, δ

Position	Smooth	Rough
A (49.6*H*)	2.4*H*	4.1*H*
B (87.7*H*)	3.1*H*	5.6*H*
C (135.9*H*)	3.3*H*	6.6*H*

<ins>Vertical</ins> (= total 7 heights)

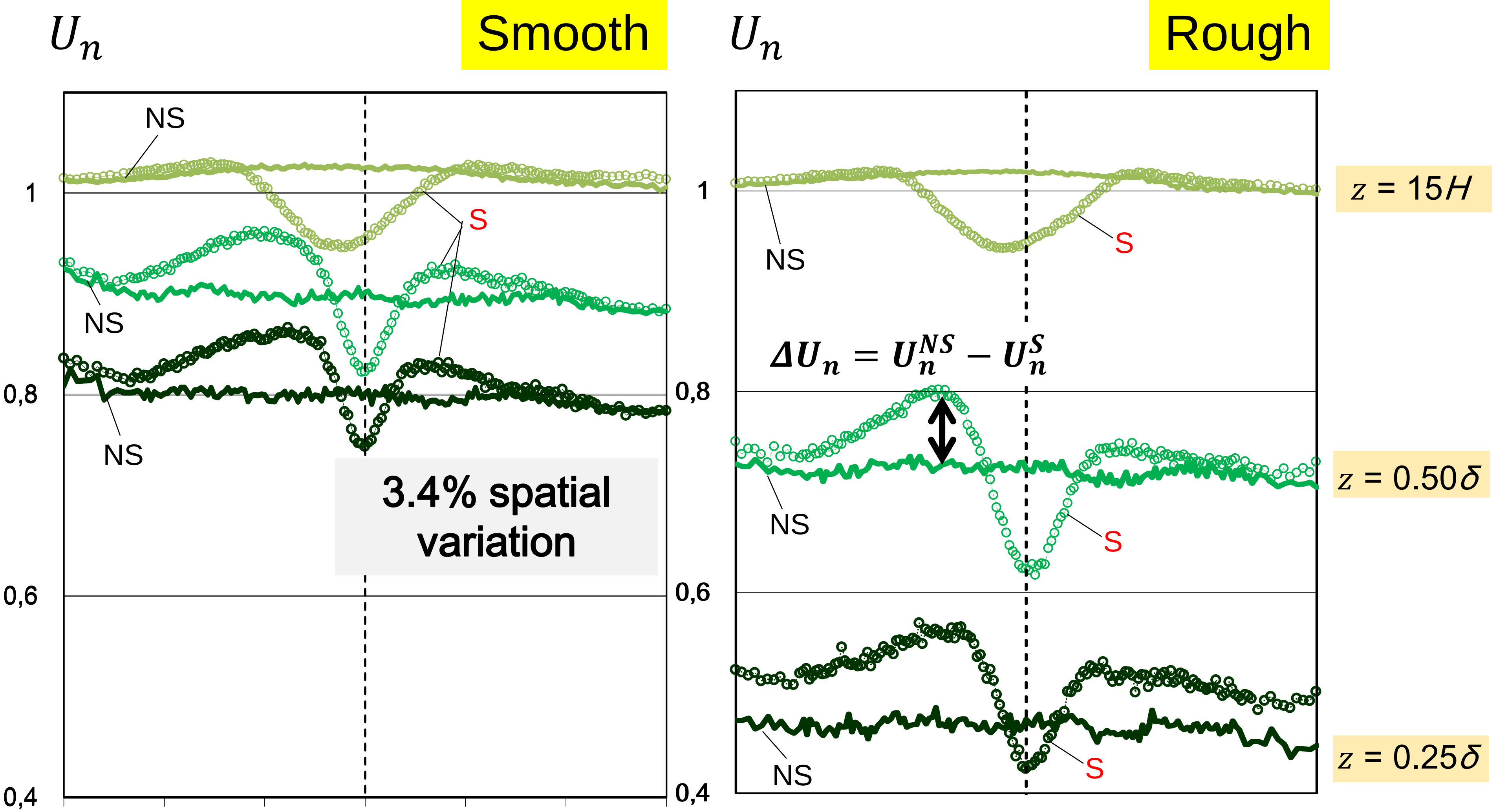
Within BL	0.25δ, 0.50δ, 0.75δ, 1.00δ, 1.25δ
Above BLH	15*H* and 20*H*



Outline

Spanwise distributions of velocity at C (x= 135.9H)

$$U_n = U/U_{ref}(y = -18\,H, z = 20H)$$



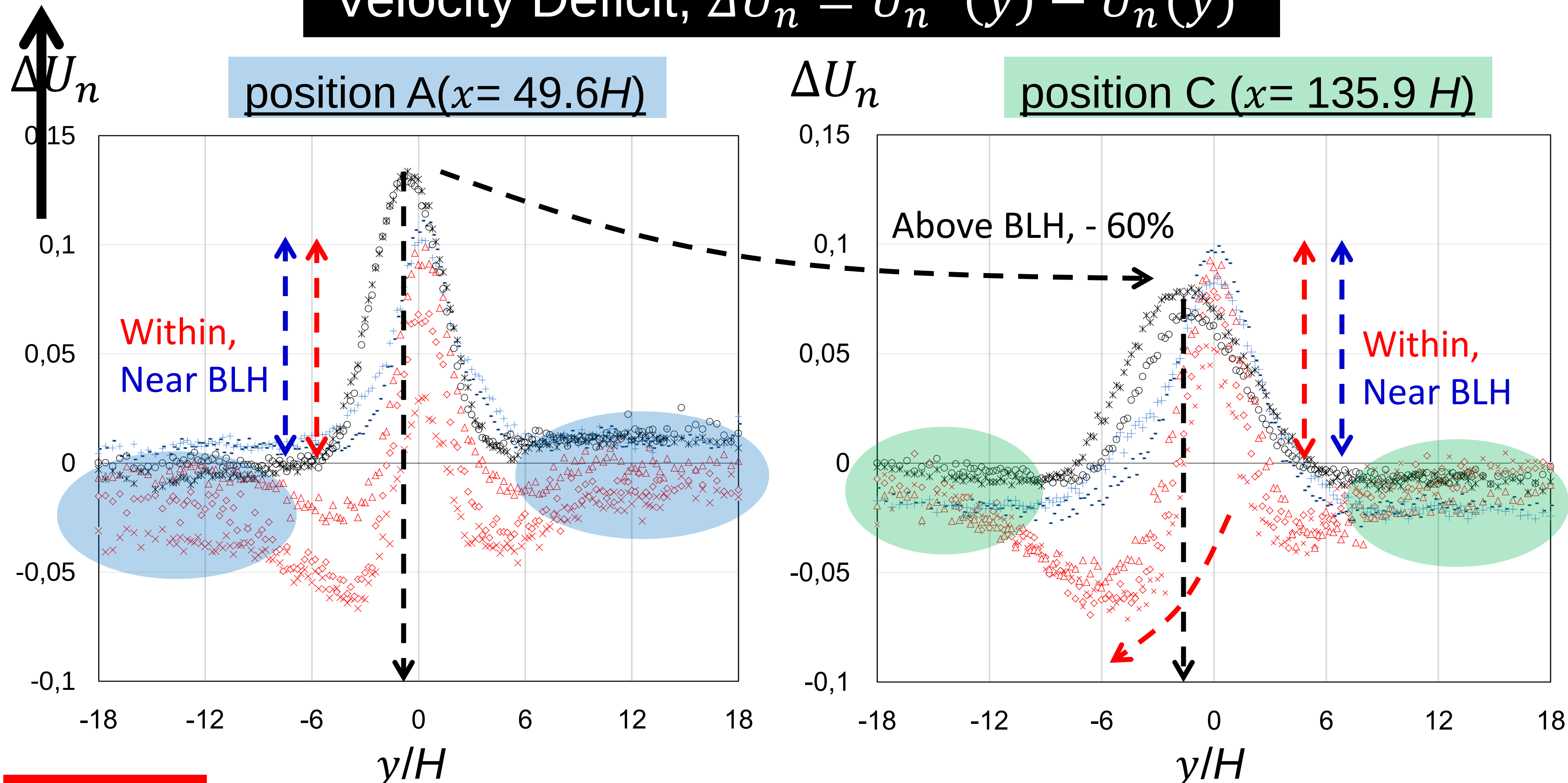
Velocity Deficit, $\Delta U_n(y) = U_n^{NS}(y) - U_n^{S}(y)$

Velocity Deficit ΔU_n – Smooth Surface

Vel. largely reduced due to spire

$$U_n = U/U_{ref}$$

Velocity Deficit, $\Delta U_n = U_n^{NS}(y) - U_n^{S}(y)$



Within BL
- × z= 0.25δ
- △ z= 0.50δ
- ◇ z= 0.75δ

Near BLH
- – z= 1.00δ
- + z= 1.25δ

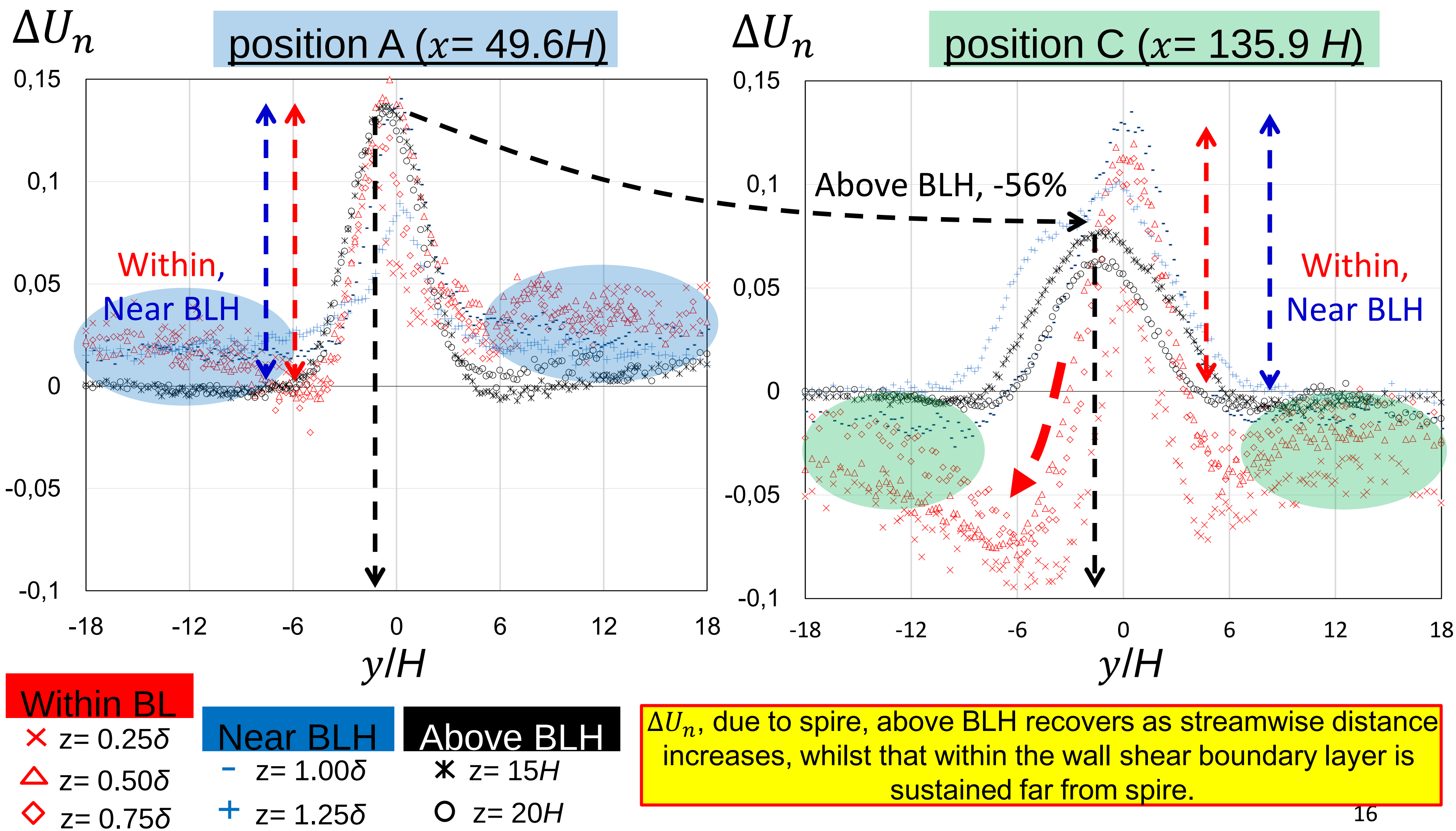
Above BLH
- ✱ z= 15H
- ○ z= 20H

ΔU_n, due to spire, above BLH recovers as streamwise distance increases, whilst that within the wall shear boundary layer is sustained far from spire.

Velocity Deficit ΔU_n – Rough Surface

$$U_n = U/U_{ref}$$

Velocity Deficit, $\Delta U_n = U_n^{NS}(y) - U_n^{S}(y)$



ΔU_n, due to spire, above BLH recovers as streamwise distance increases, whilst that within the wall shear boundary layer is sustained far from spire.

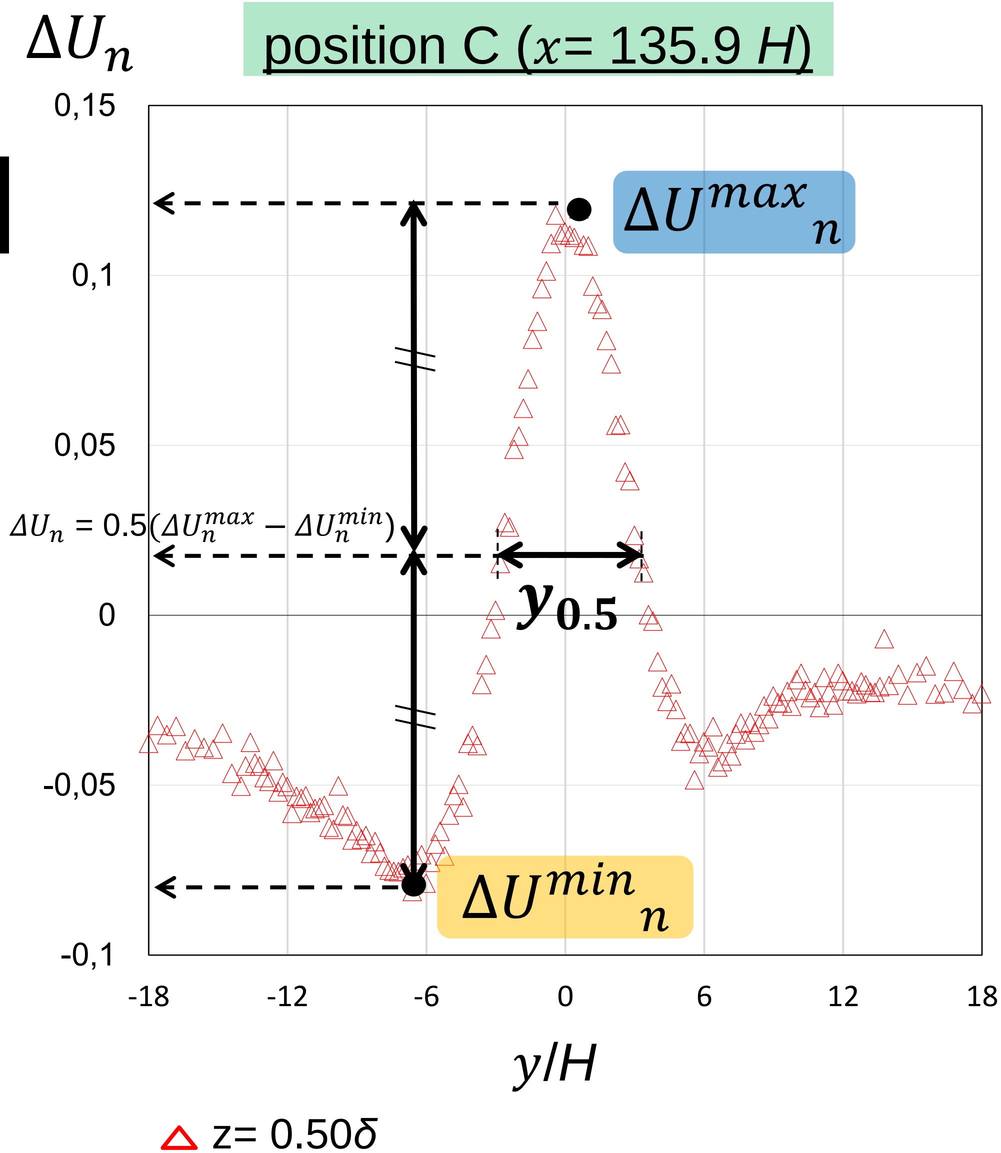
Half wake width $y_{0.5}$ determination

Normalized Max Vel. Deficit, $\varnothing_n$;

$$\varnothing_n = \frac{\Delta U_n - \Delta U^{min}{}_n}{\Delta U^{max}{}_n - \Delta U^{min}{}_n}$$

Half Wake Width, $y_{0.5}$;

Distance between two positions where $\Delta U_n = 0.5(\Delta U_n^{max} - \Delta U_n^{min})$



Normalized Max. Vel. Deficit at C(x= 135.9H)

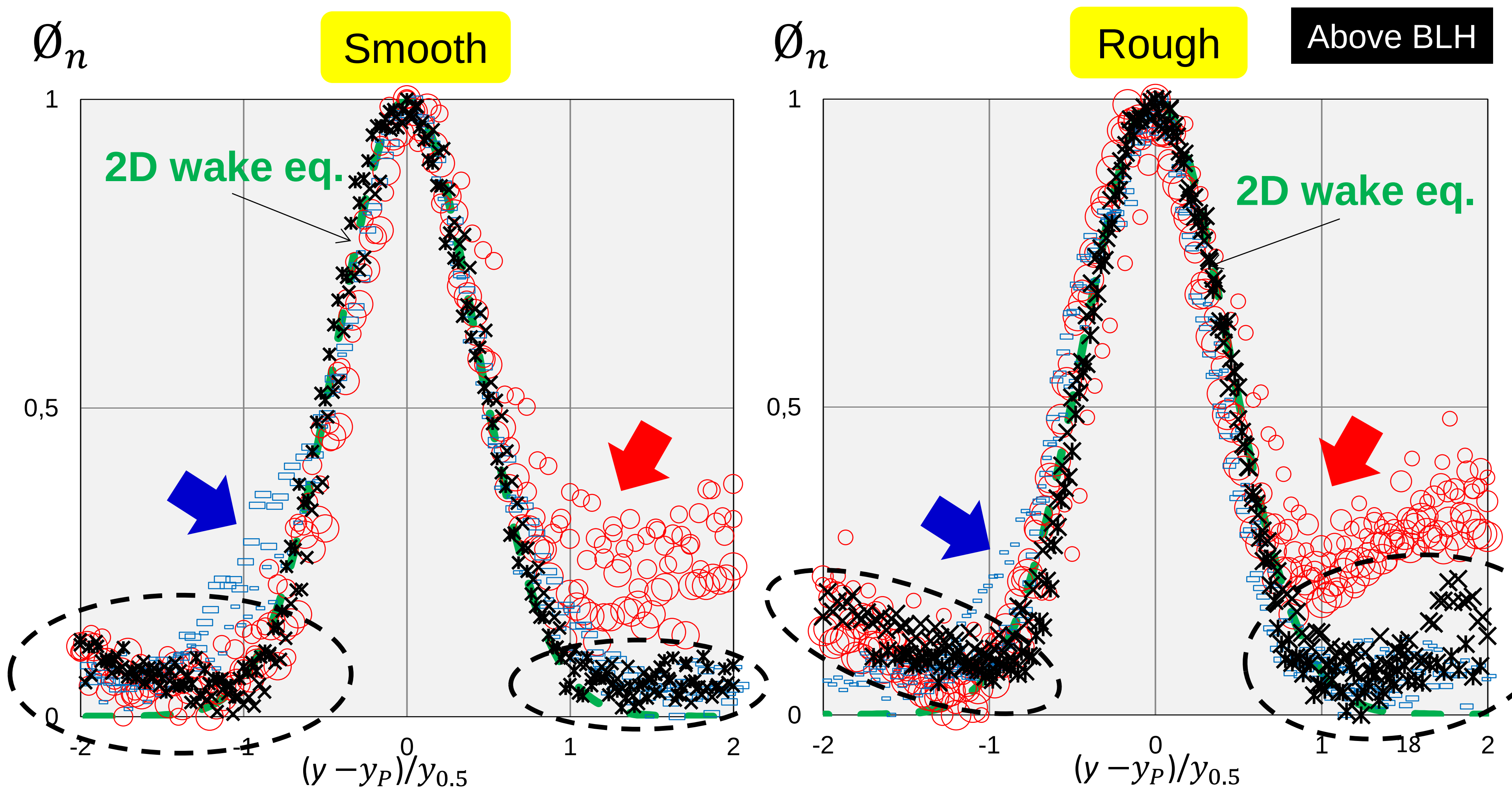
Normalized Maximum Vel. Deficit, $\varnothing_n = (\Delta U_n - \Delta U^{min}{}_n)/(\Delta U^{max}{}_n - \Delta U^{min}{}_n)$

General function 2D wake : $g\left(\frac{y}{y_{0.5}}\right) = \exp\left(-a\left(\frac{y}{y_{0.5}}\right)^2\right)$

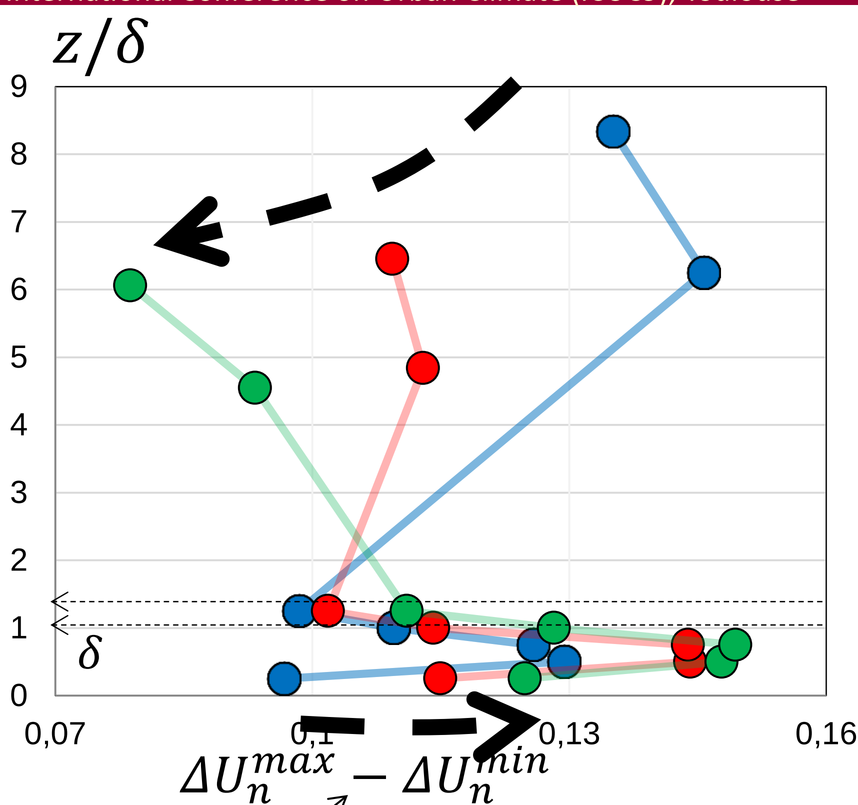
(a: empirical const ; $y_{0.5}$: half wake width)

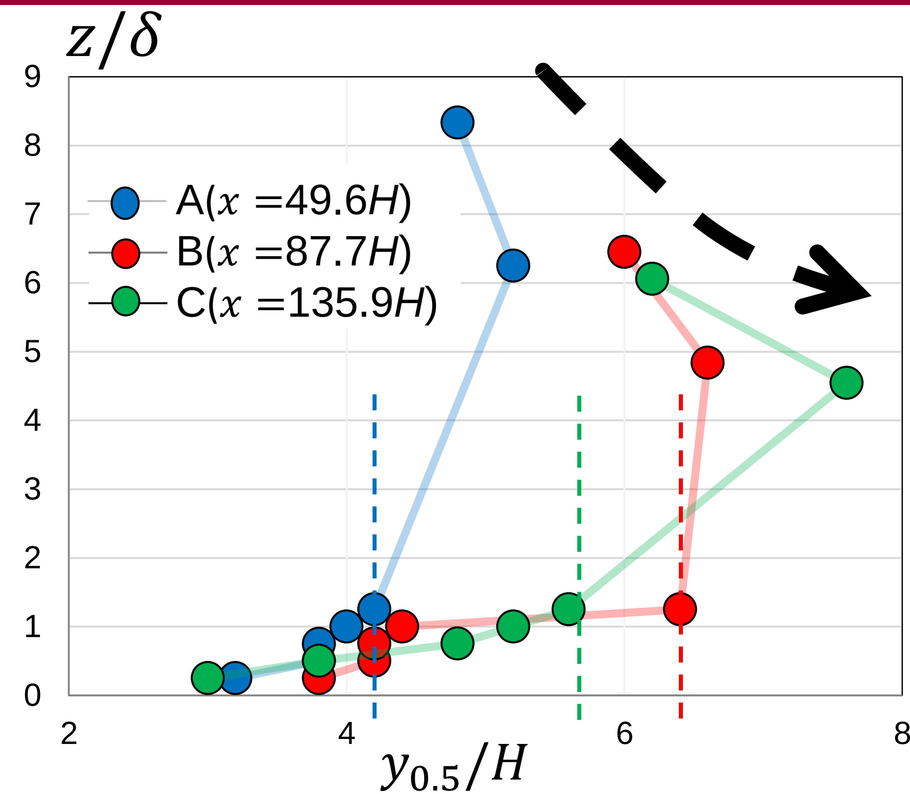
Within BL

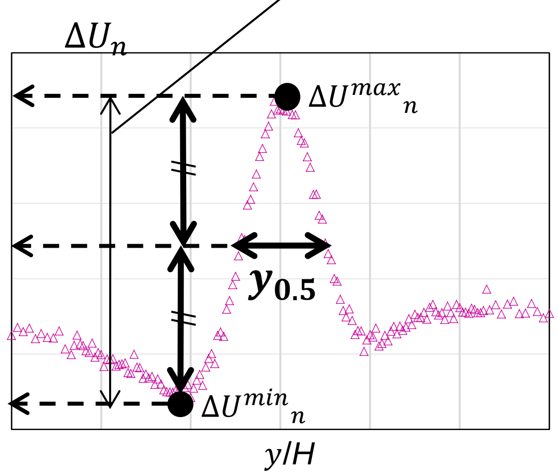
Near BLH

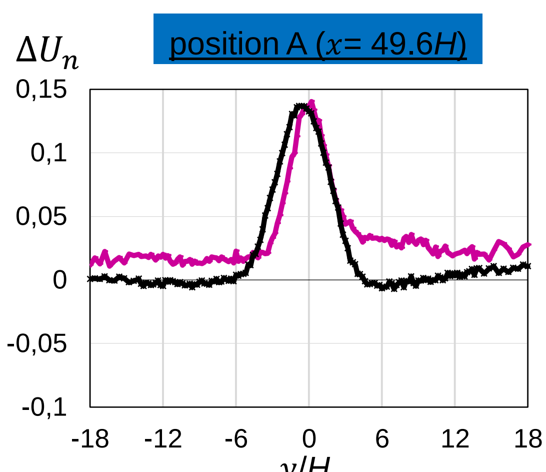


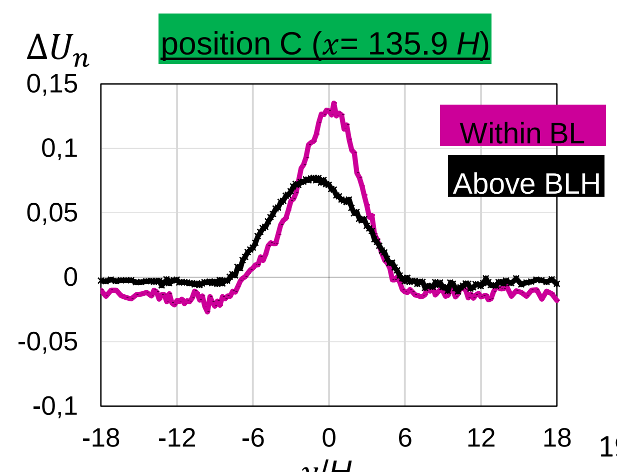
Change of ΔU_n and $y_{0.5}$ with heights – Smooth



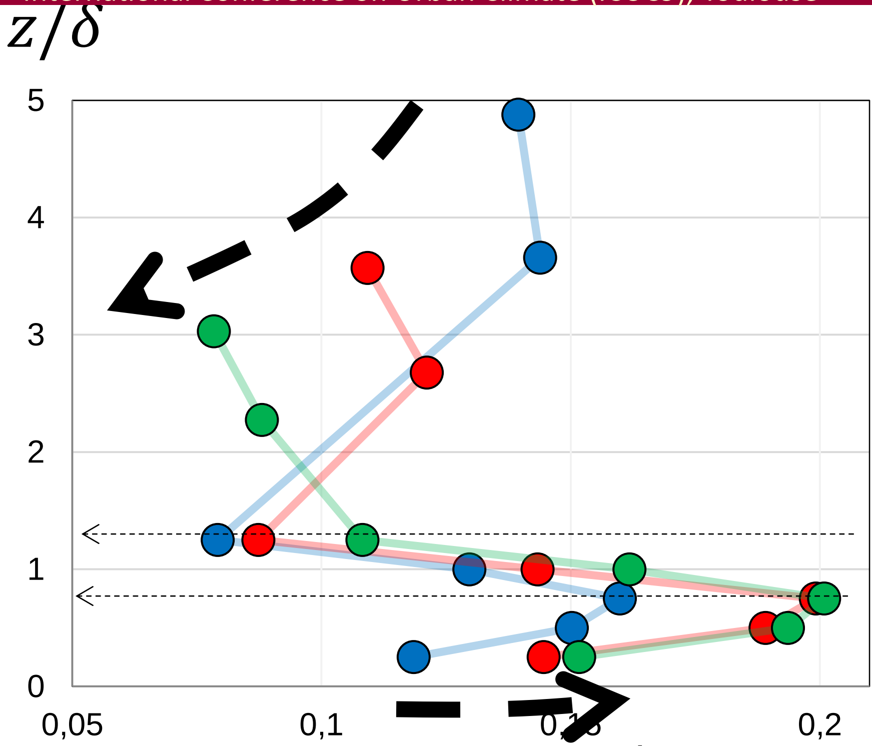


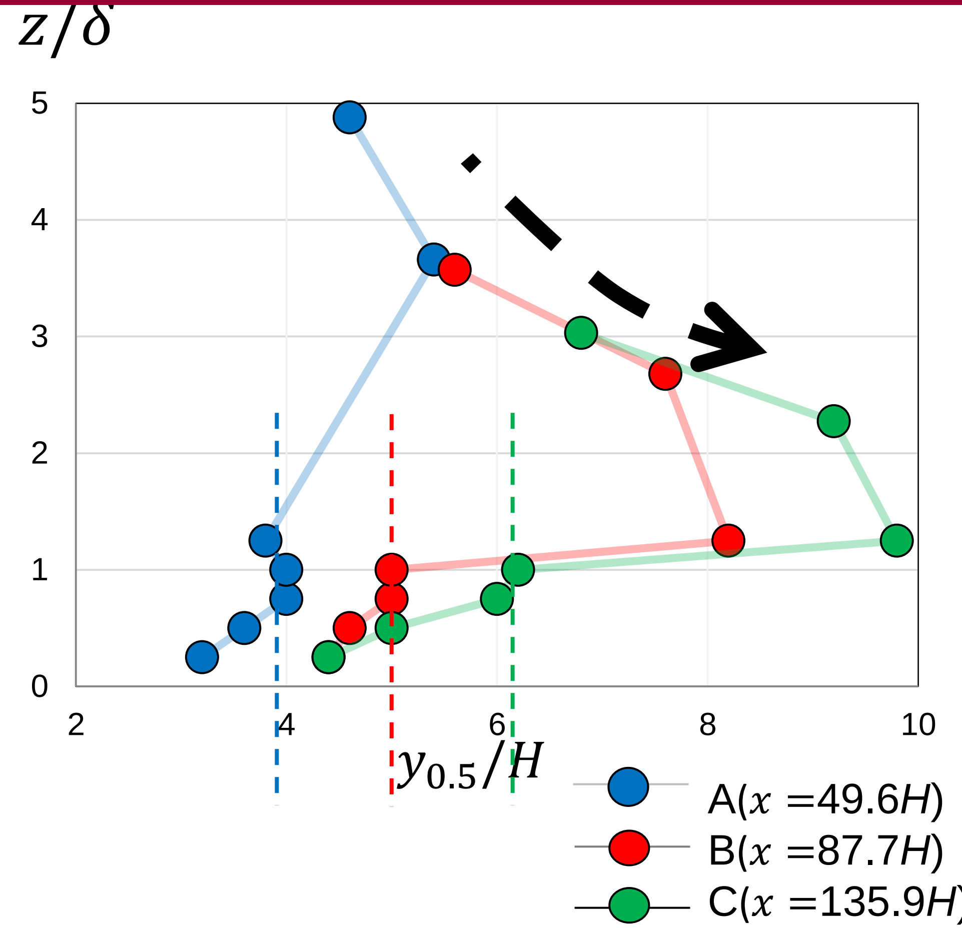




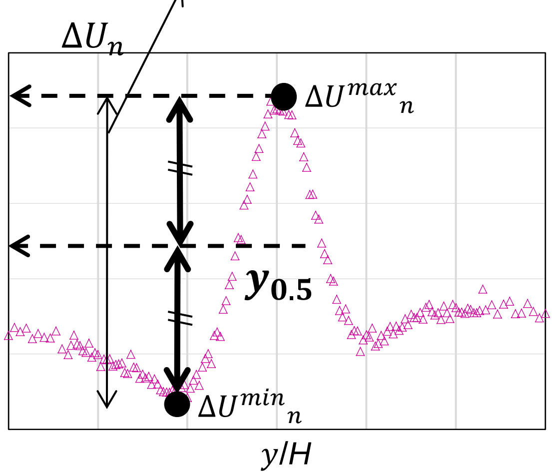


Change of ΔU_n and $y_{0.5}$ with heights – Rough





$$\Delta U_n = \Delta U_n^{max} - \Delta U_n^{min}$$



Expansion of wake behind a slender obstacle is compressed in lateral direction by the turbulence of the wall boundary layer, and alternatively ΔU_n of the wake becomes steep compared to the ordinary 2D wake flow in a free shear flow

Outline

Conclusions

Wind tunnel exp. on aerodynamic interaction between the wall shear boundary layer and wake flow behind isolated slender obstacle

1) Spanwise variations of Ø_n behind a spire above the wall boundary layer show good agreement with the 2D self-similar profile for a 2D wake flow in a free shear flow, despite the weak asymmetrical inflow condition of the wind tunnel

2) The ΔU_n, due to the spire, far above the BLH with low turbulence gradually recovers as the streamwise distance increases, whilst that within the wall shear boundary layer with high turbulence is sustained far away from the spire.

3) The expansion of the $y_{0.5}$ is compressed in the lateral direction by the turbulence of the wall boundary layer

Thank You

Although the present experimental data indicate an obvious difference in the profiles of the wake flow within and above the wall boundary layer, a detailed understanding of the features of these differences has not been completely attained due to certain limitations mainly caused by the non-uniform inflow condition of the wind tunnel. In addition, the turbulent statistical information of not only the streamwise velocity component, but also the lateral component would be essential for elucidating the mechanism of the interference of the spanwise expansion of the wake due to the wall boundary turbulence, and will be one of our future tasks.

Background

Population

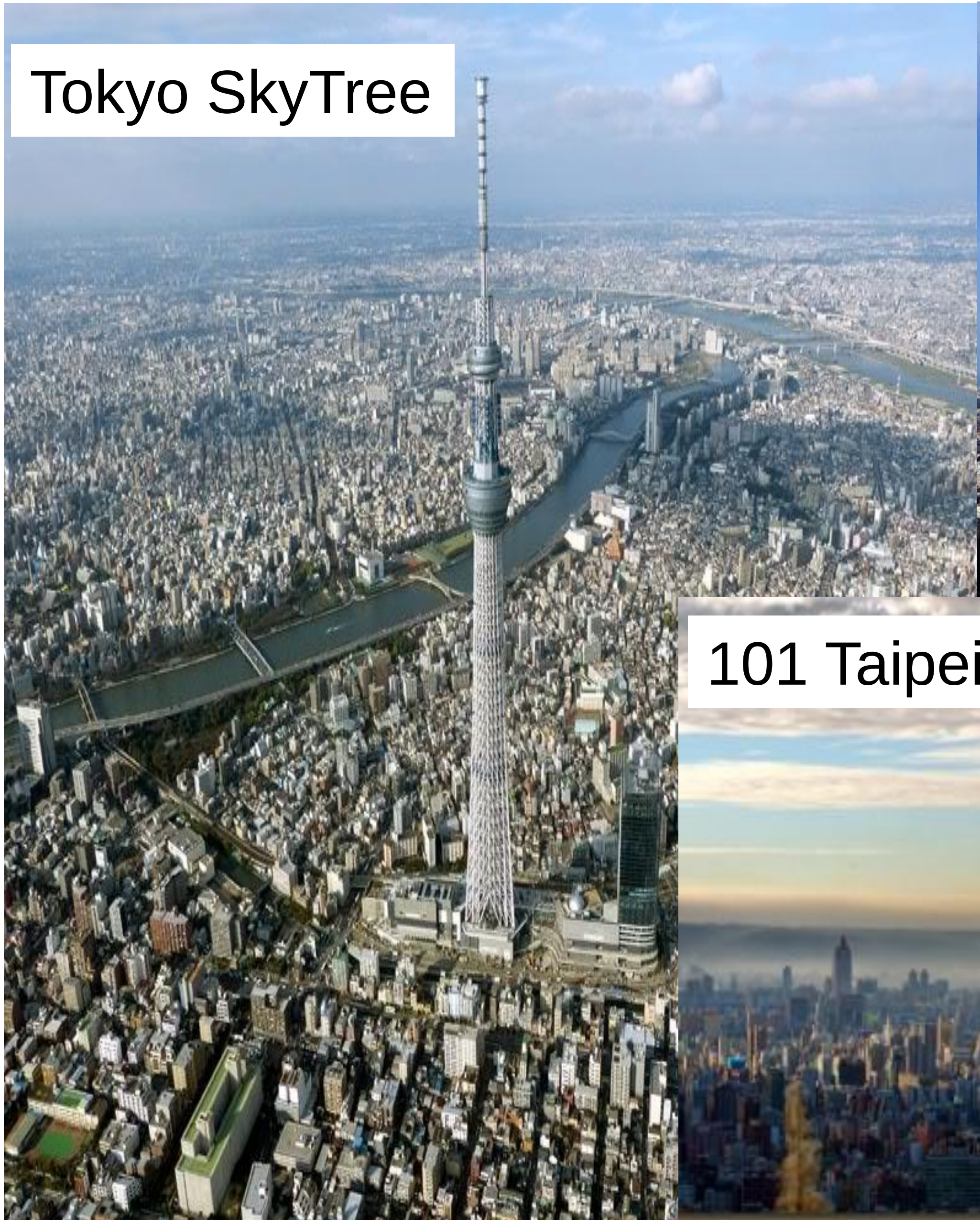
Industrialization

Economic Growth

Prosperity

Urbanization

Background



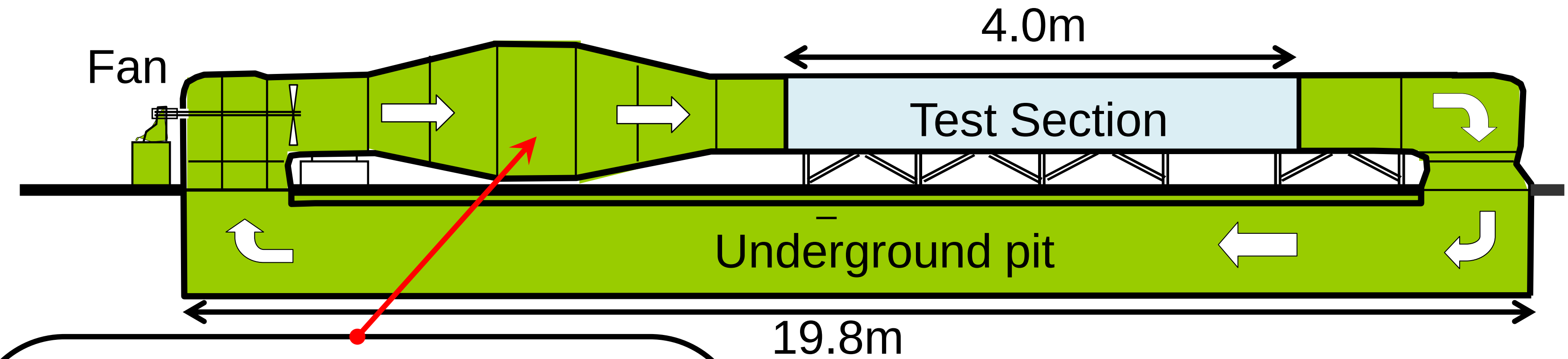
Research Motivation

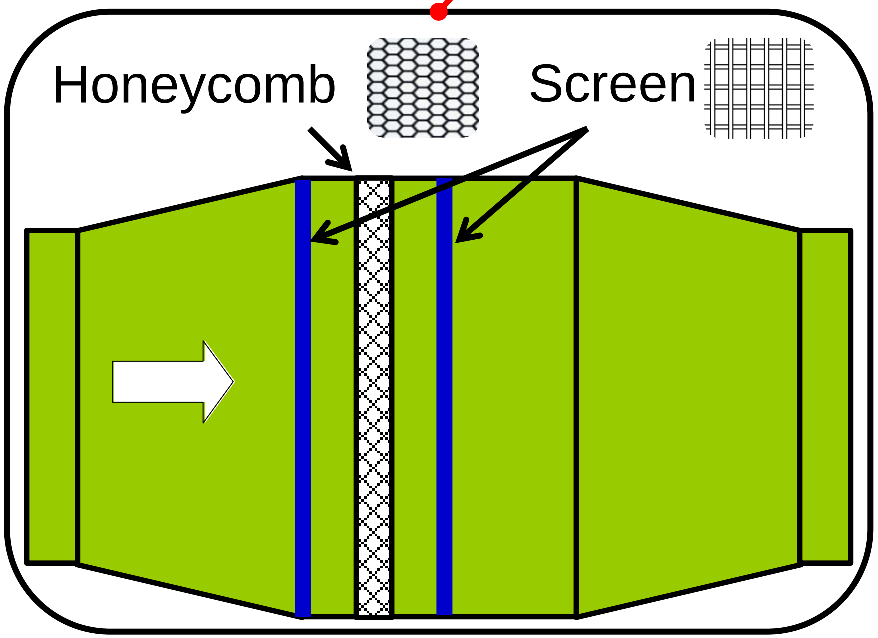
1) Geometric effects on urban wind environment
2) Flow (=velocity reduction) behind an isolated high-rise, long and slender building

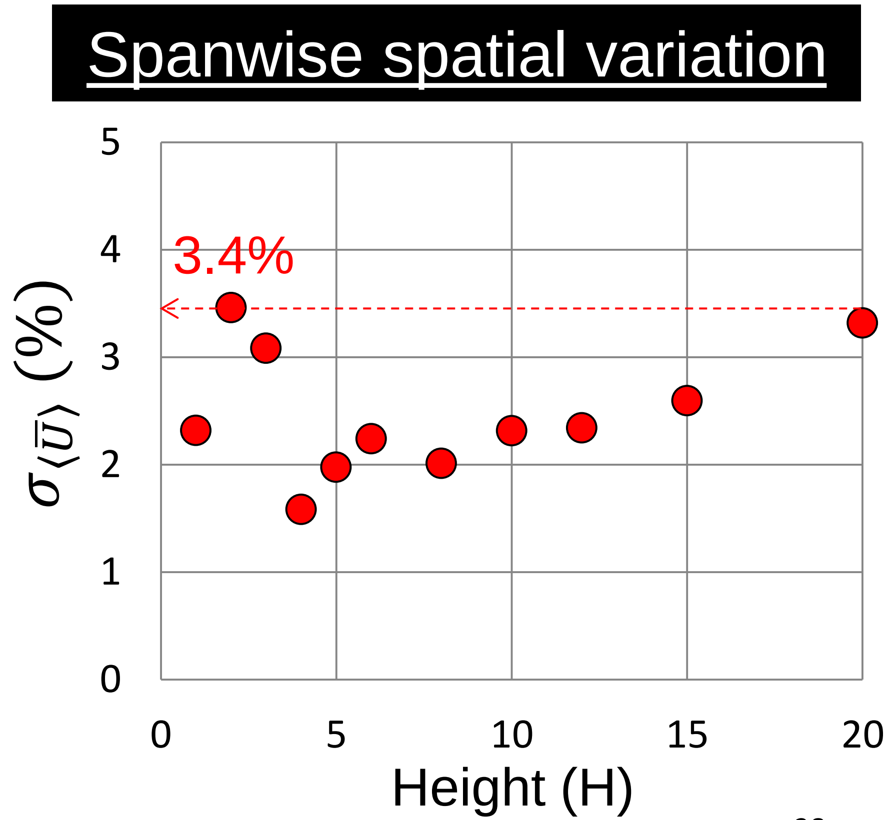
Research Objectives

1) To explore the process of turbulence generated by roughness and large obstacle which can enhance the large scale of turbulence
2) To examine the aerodynamic interaction between wake flow structure observed behind an isolated high-rise, slender building with wall shear boundary layer develops over urban roughness
3) Effects of single spire(passive device) installed normal to wall
4) Scientific oriented wind tunnel experiment

Methodology







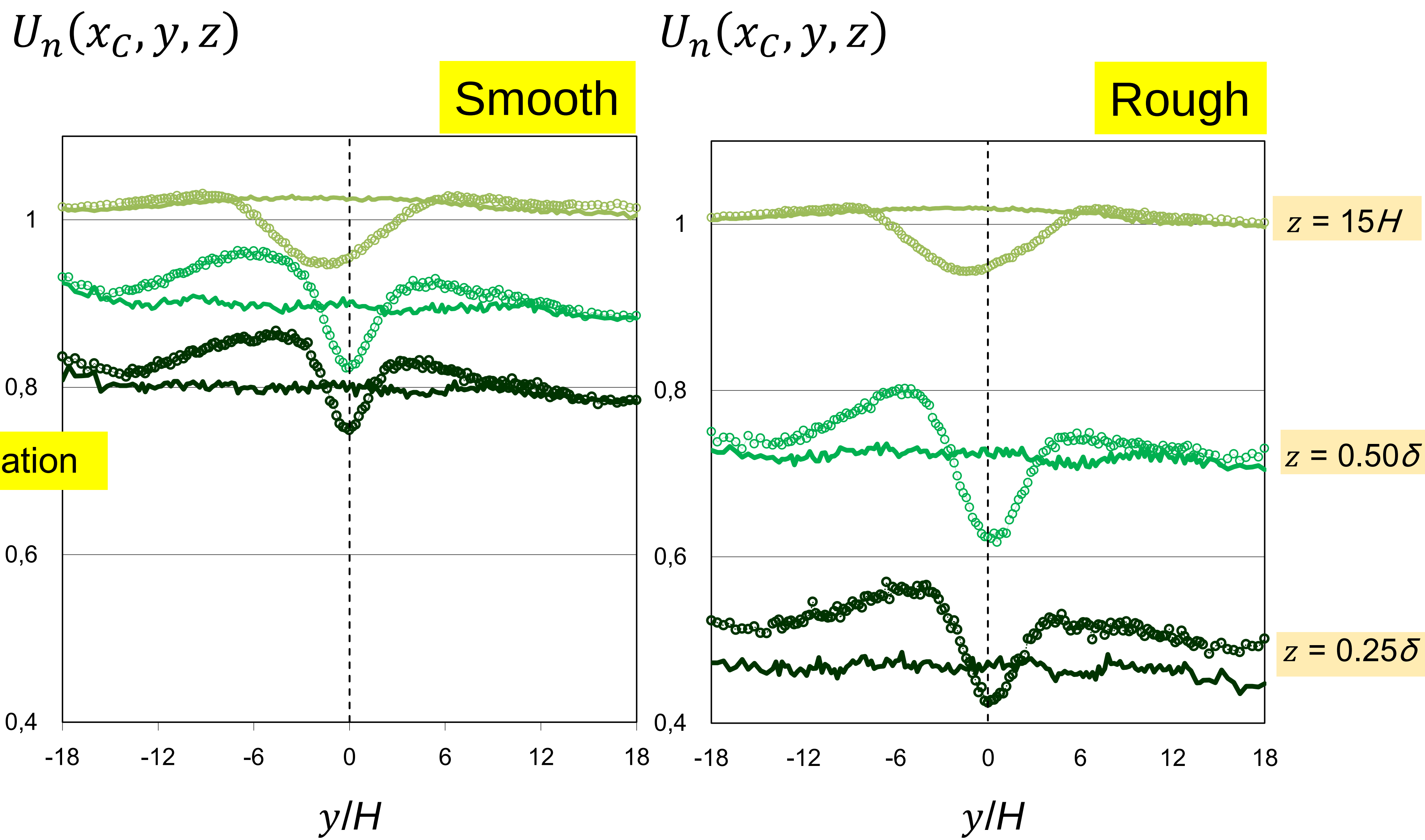
Spatial uniformity of inflow condition

Meshes, $\beta > 0.57$ to alter the inflow conditions.

(Mehta 1985 and Scheiman et al., 1980)

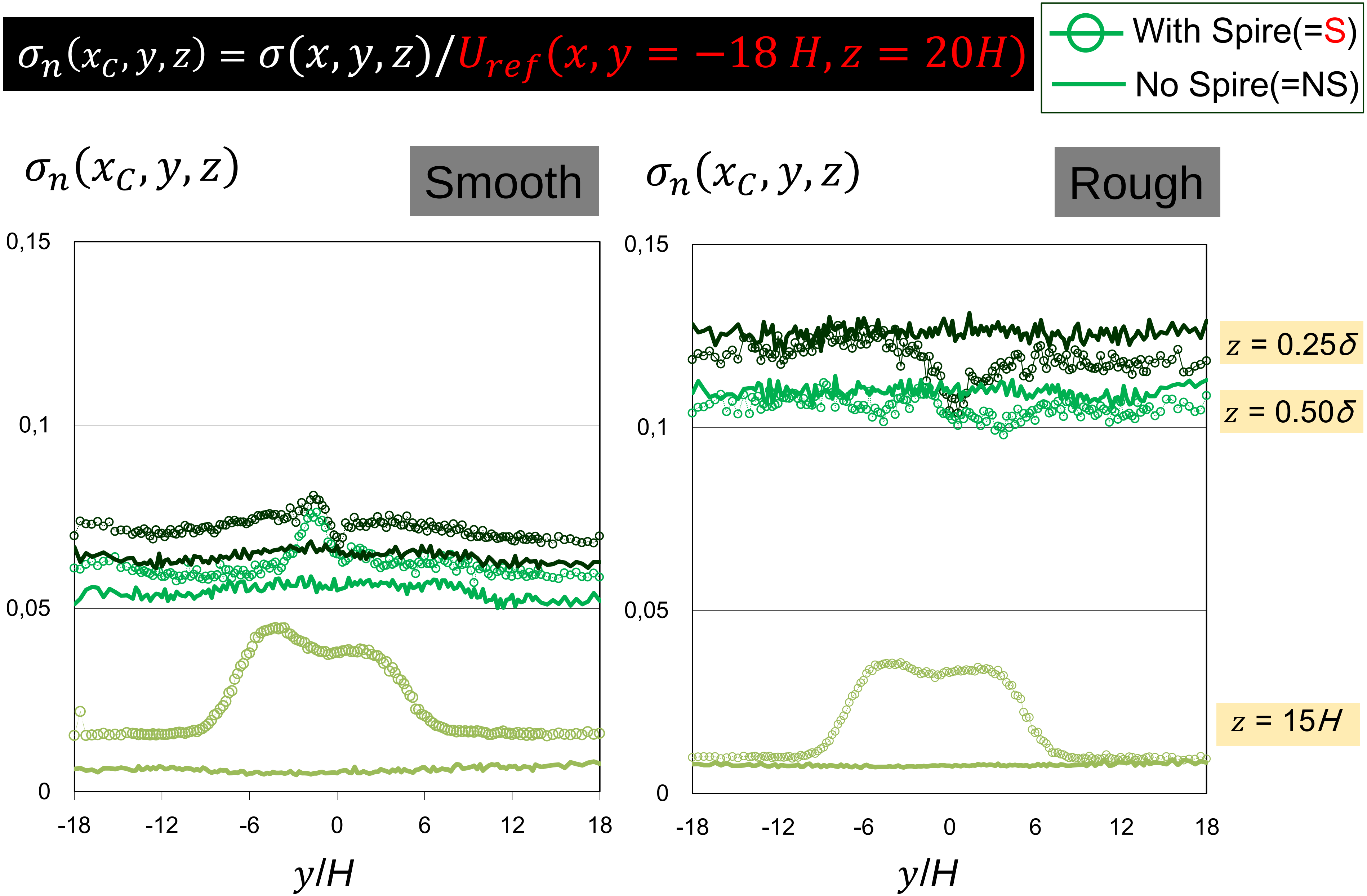
Spanwise distributions of velocity at C (x= 135.9H)

$$\boldsymbol{U_n(x_C, y, z)} = U(x, y, z)/\boldsymbol{U_{ref}(x, y = -18\ H, z = 20H)}$$

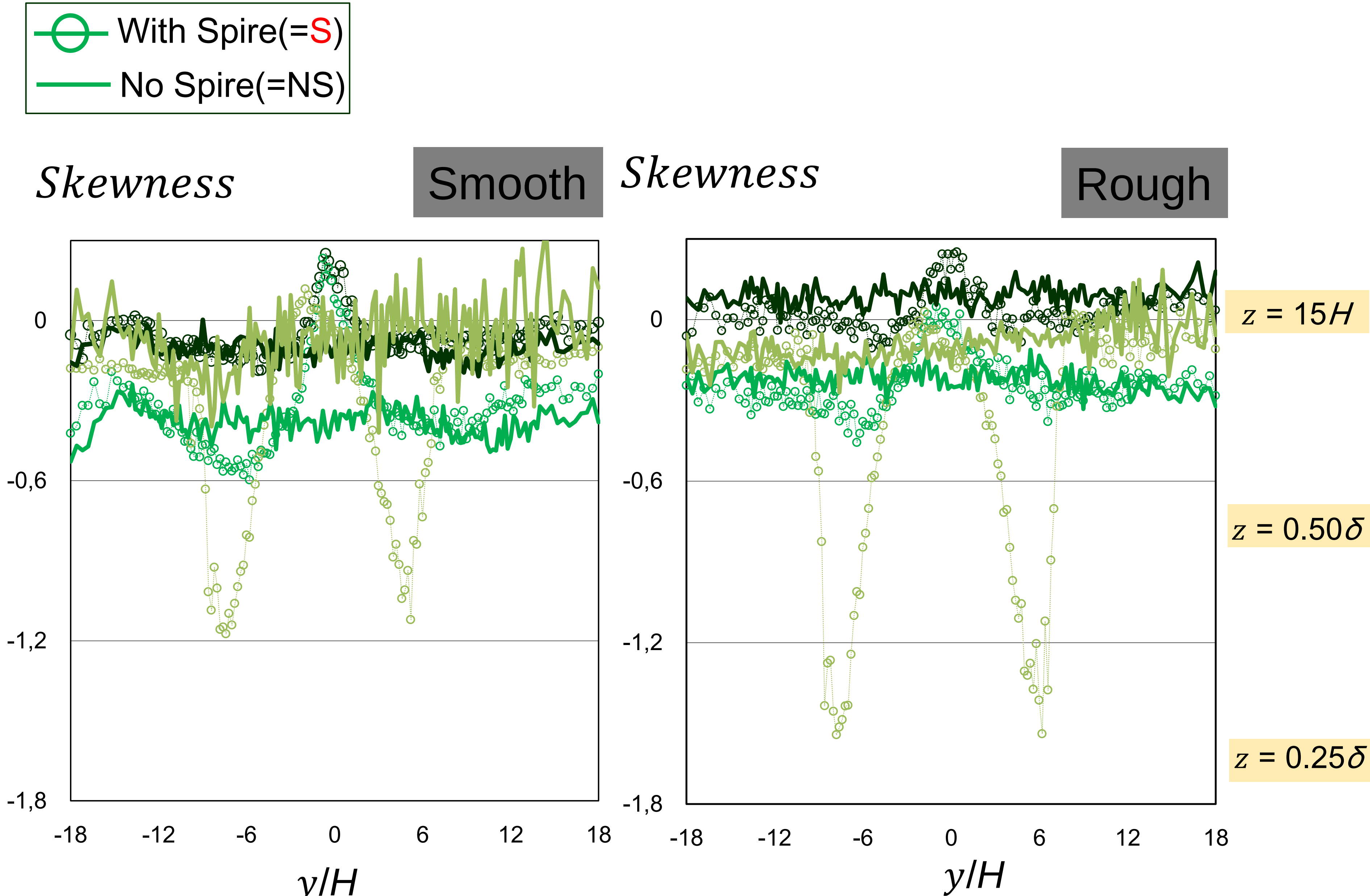


Spanwise distributions of velocity at C (x= 135.9H)

$$\sigma_n(x_C, y, z) = \sigma(x, y, z)/U_{ref}(x, y = -18\ H, z = 20H)$$



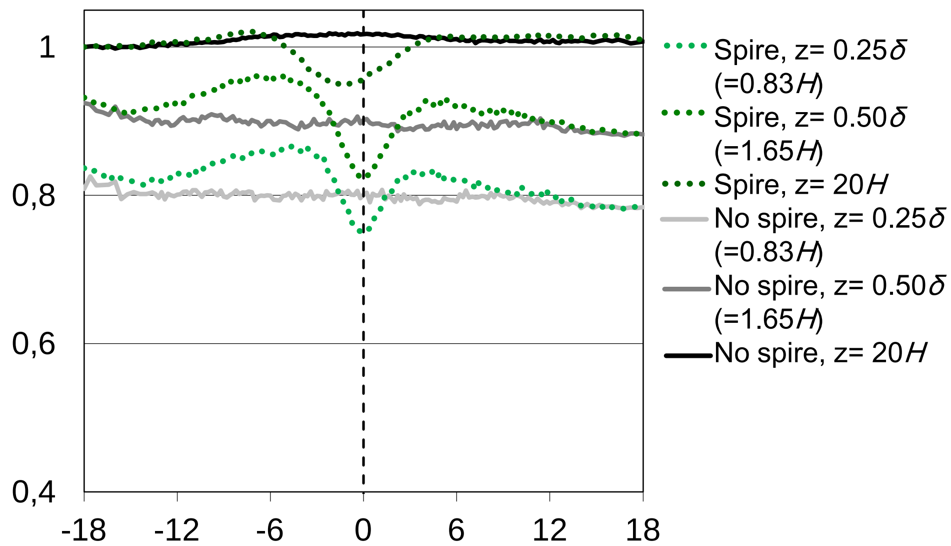
Spanwise distributions of velocity at C (x= 135.9H)

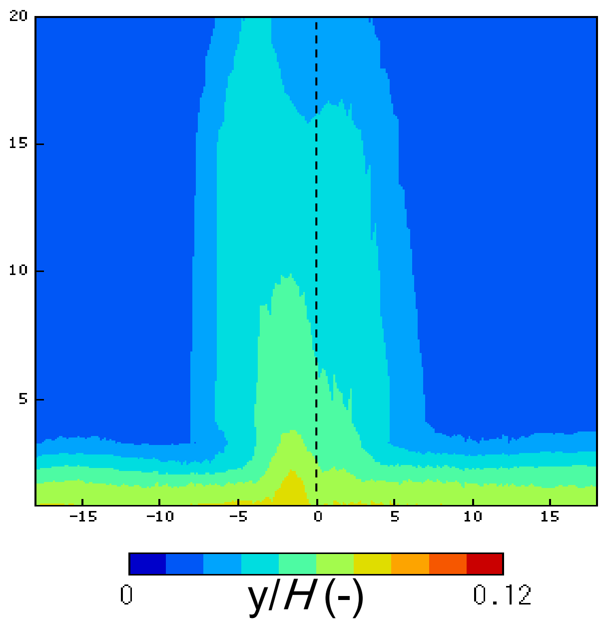


Results & Discussions : C(x= 135.9H)

Smooth Surface

$U_n(x_C, y, z)(-)$

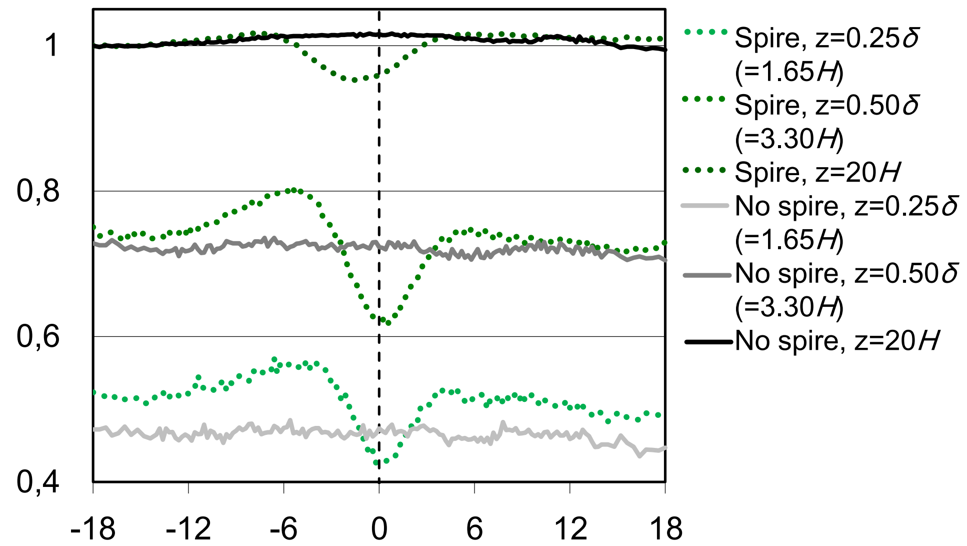


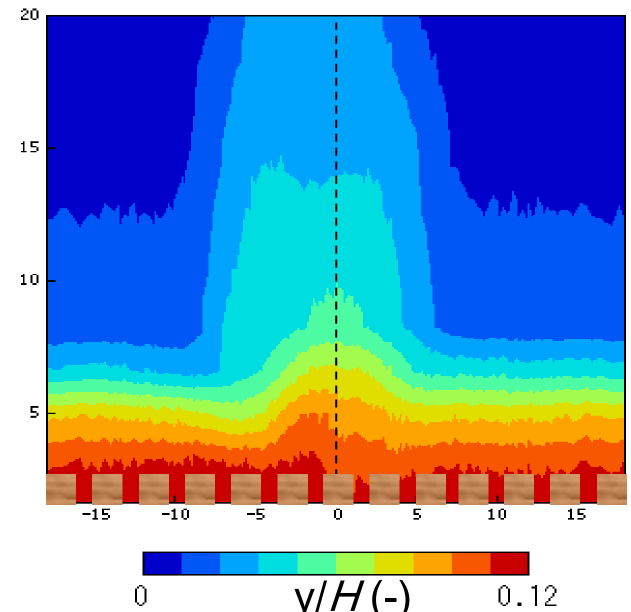


σ_u/U_{ref}

Rough surface

$U_n(x_C, y, z) = U(x, y, z)/U_{ref}(x, y = -18\ H, z = 20H)$



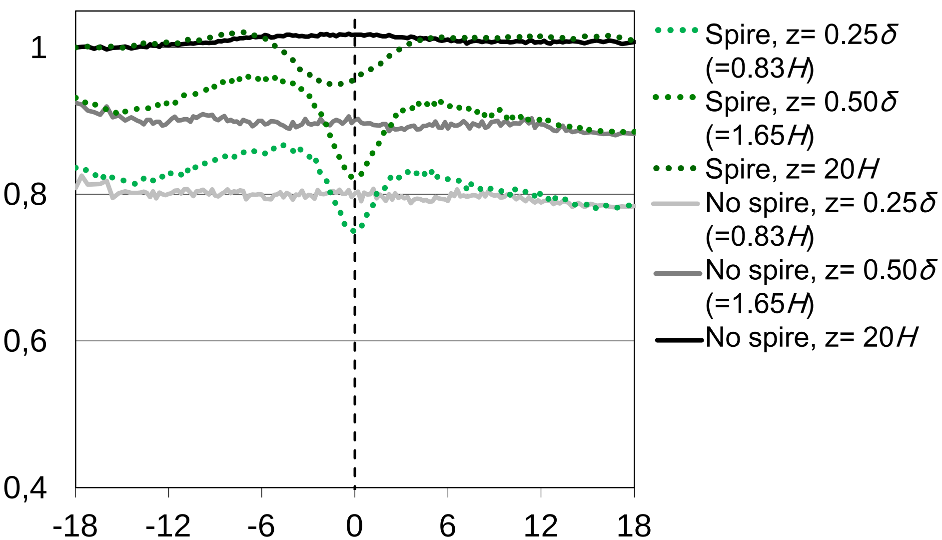


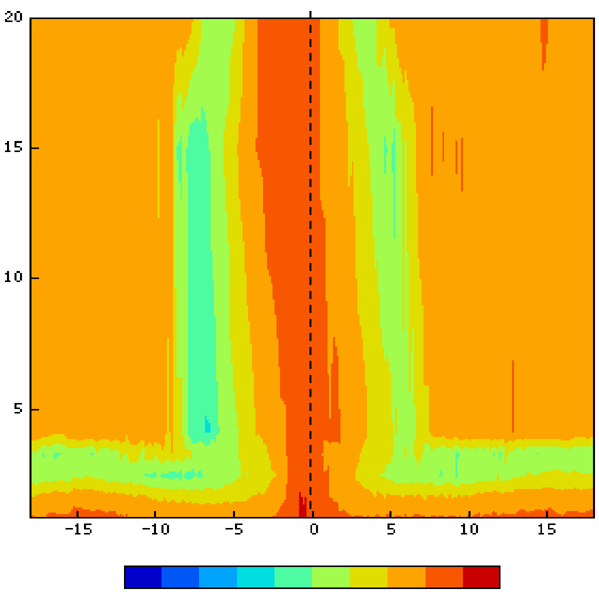
σ_u/U_{ref}

Results & Discussions : C(x= 135.9H)

Smooth Surface

$U_n(x_C, y, z)(-)$



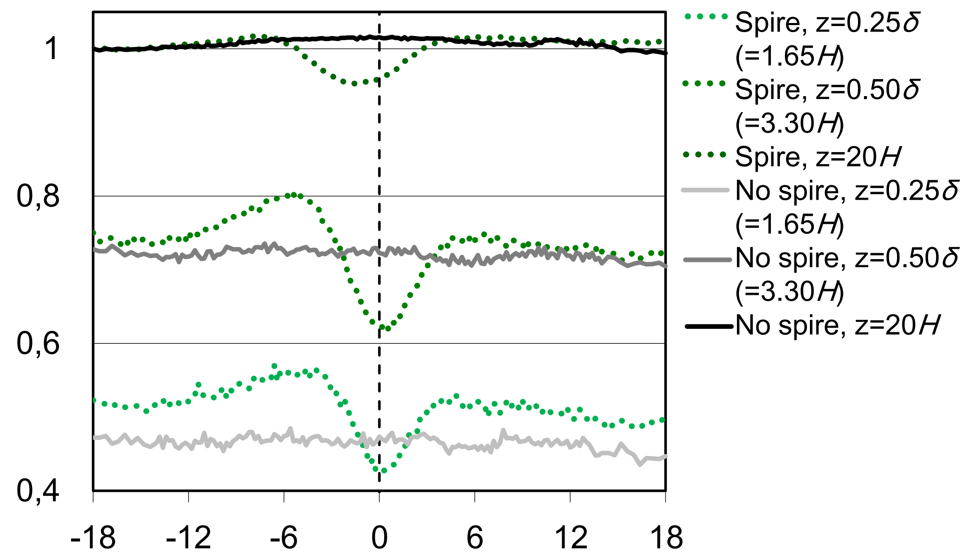


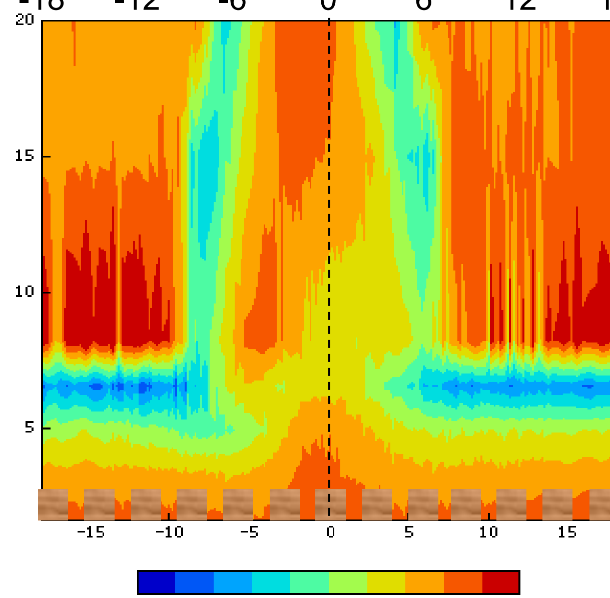
y/H (-)

Skewness

Rough surface

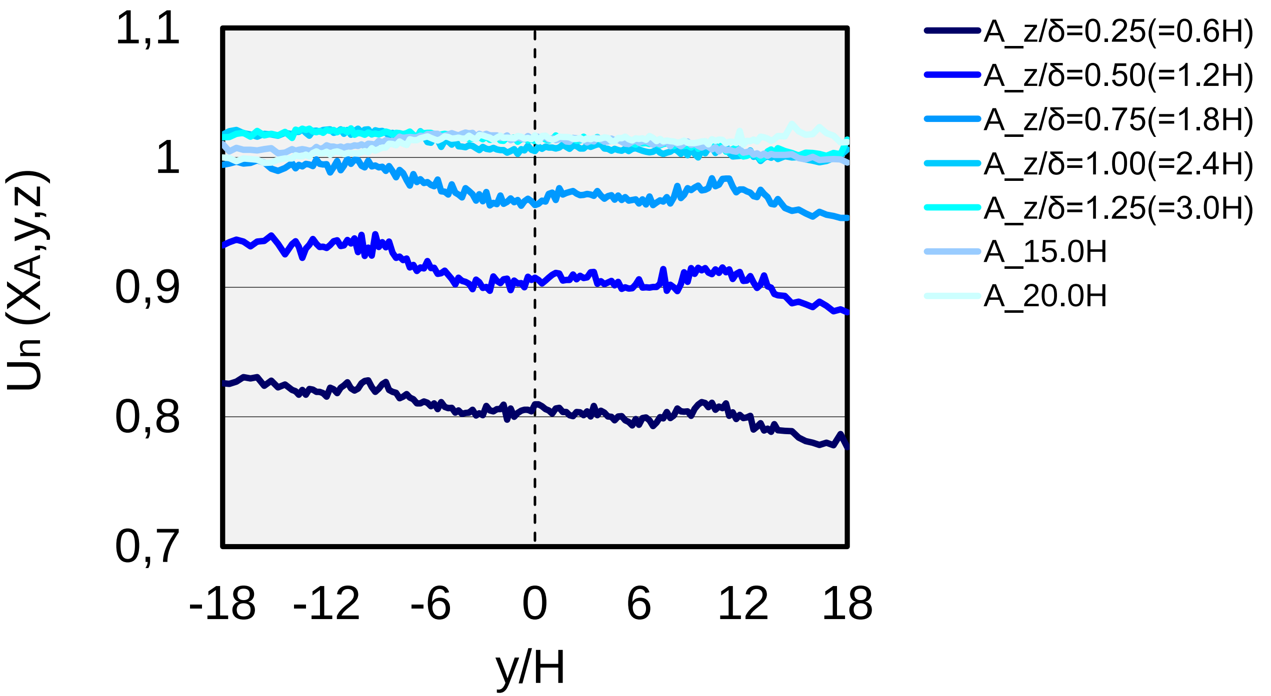
$U_n(x_C, y, z) = U(x, y, z)/U_{ref}(x, y = -18\ H, z = 20H)$





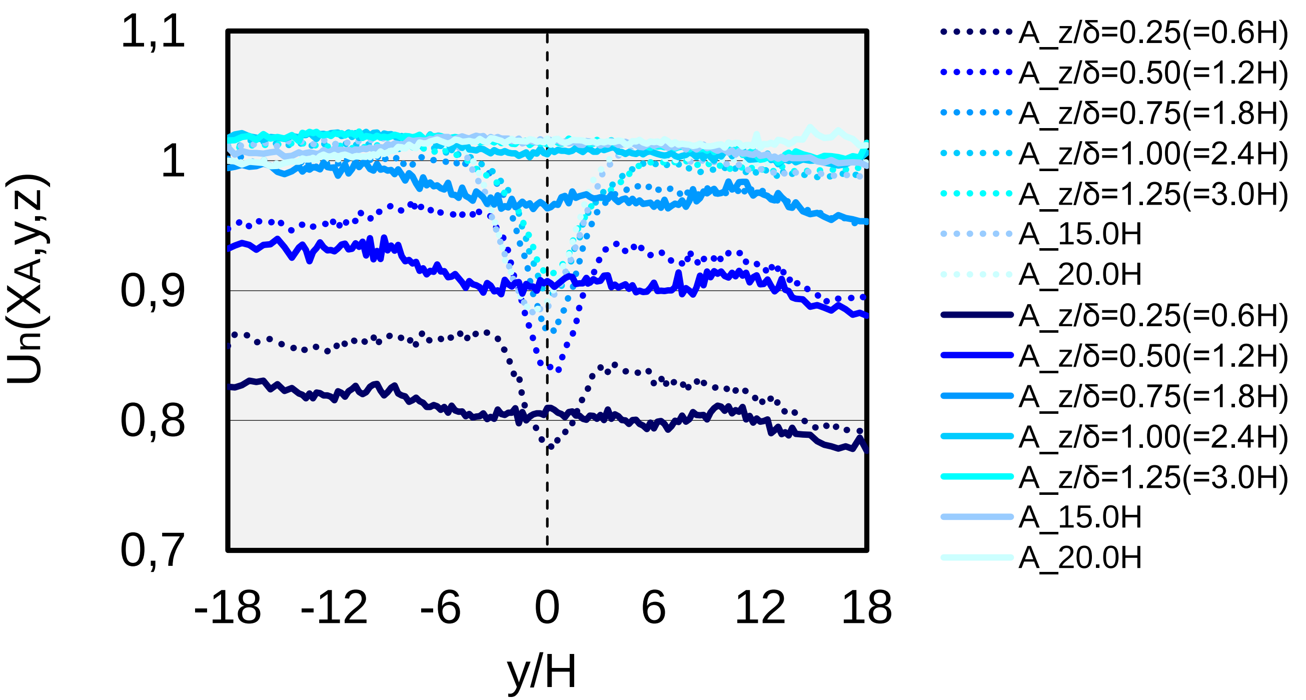
y/H (-)

Skewness



1,1
1
0,9
0,8
0,7
Un (XA,y,z)
-18 -12 -6 0 6 12 18
y/H
A_z/δ=0.25(=0.6H)
A_z/δ=0.50(=1.2H)
A_z/δ=0.75(=1.8H)
A_z/δ=1.00(=2.4H)
A_z/δ=1.25(=3.0H)
A_15.0H
A_20.0H

Smooth



1,1
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0,9
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-18 -12 -6 0 6 12 18
y/H
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A_15.0H
A_20.0H
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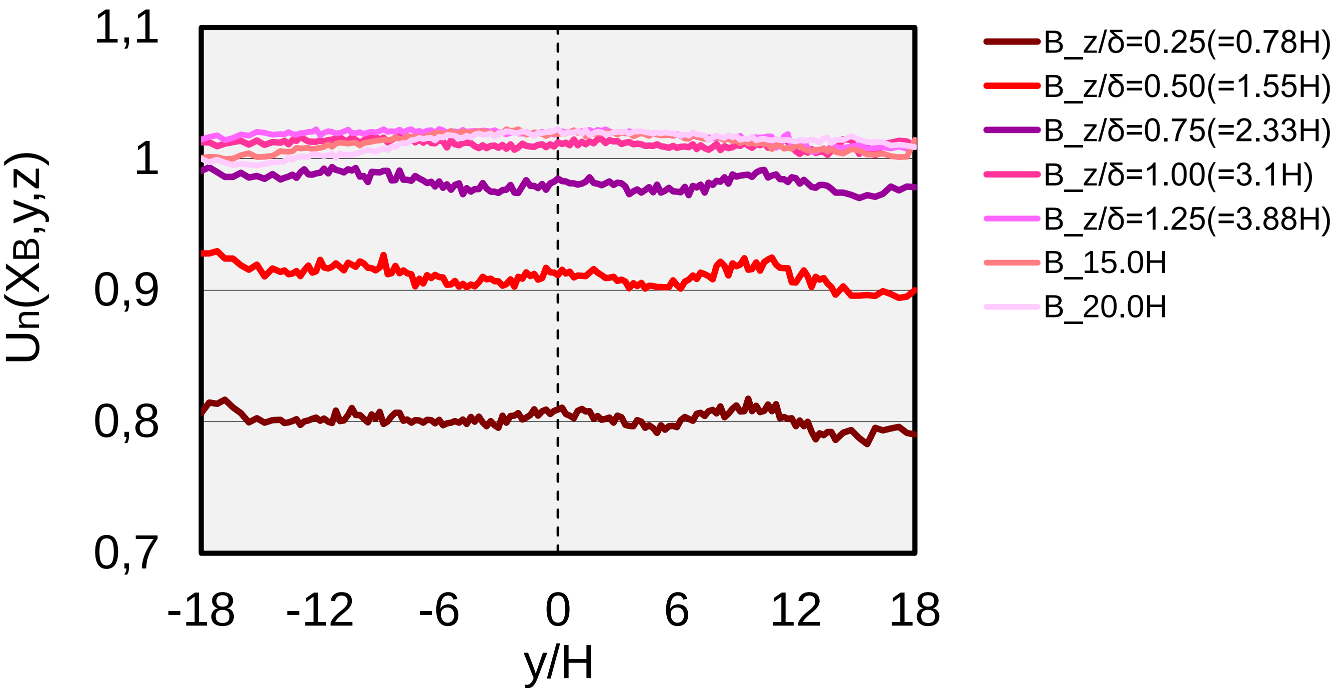
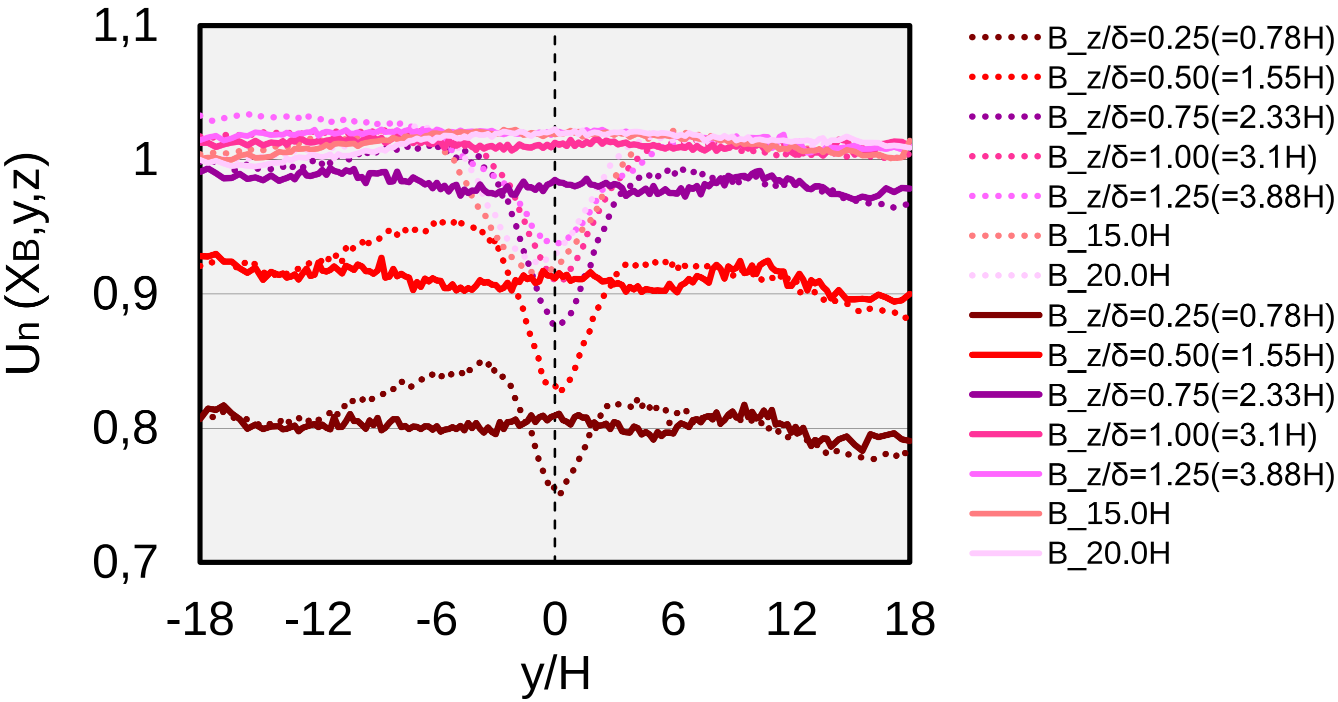
A_15.0H
A_20.0H


1,1
1
0,9
0,8
0,7
Un(XB,y,z)
-18
-12
-6
0
6
12
18
y/H
B_z/δ=0.25(=0.78H)
B_z/δ=0.50(=1.55H)
B_z/δ=0.75(=2.33H)
B_z/δ=1.00(=3.1H)
B_z/δ=1.25(=3.88H)
B_15.0H
B_20.0H

Smooth


1,1
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0,9
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Un (XB,y,z)
-18
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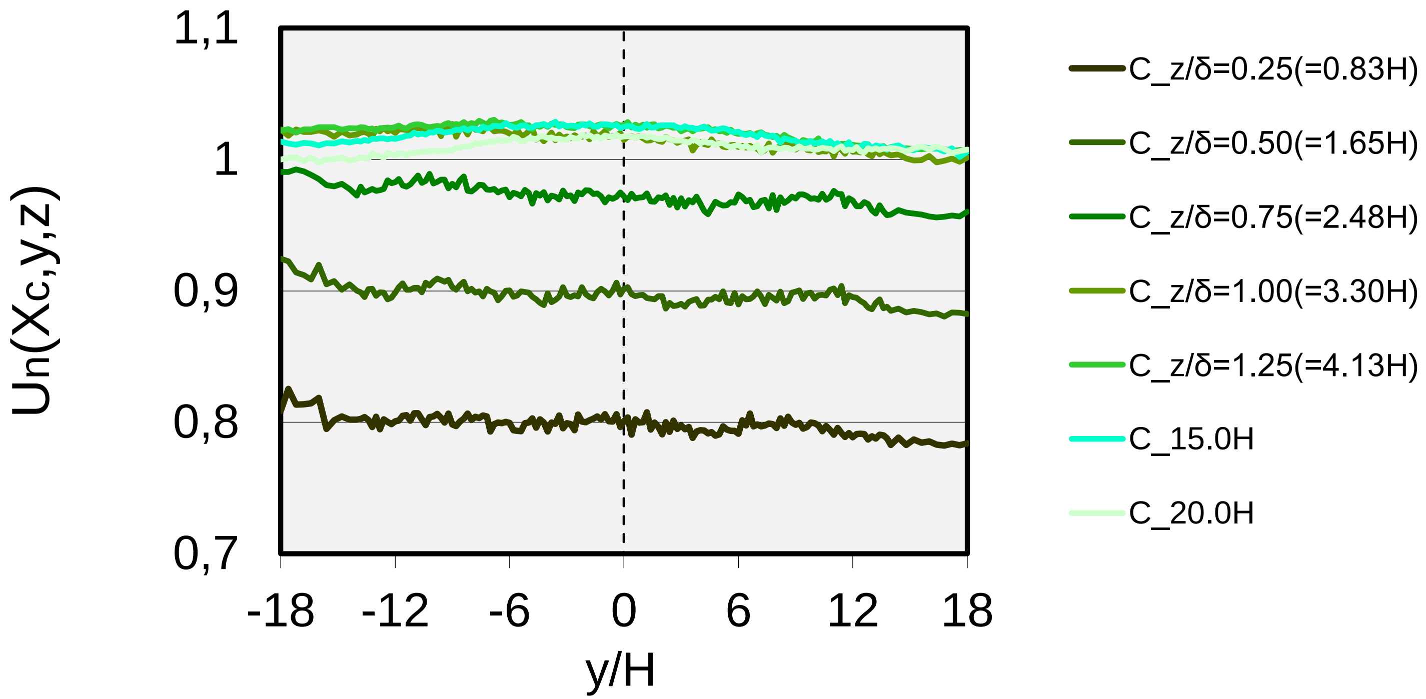
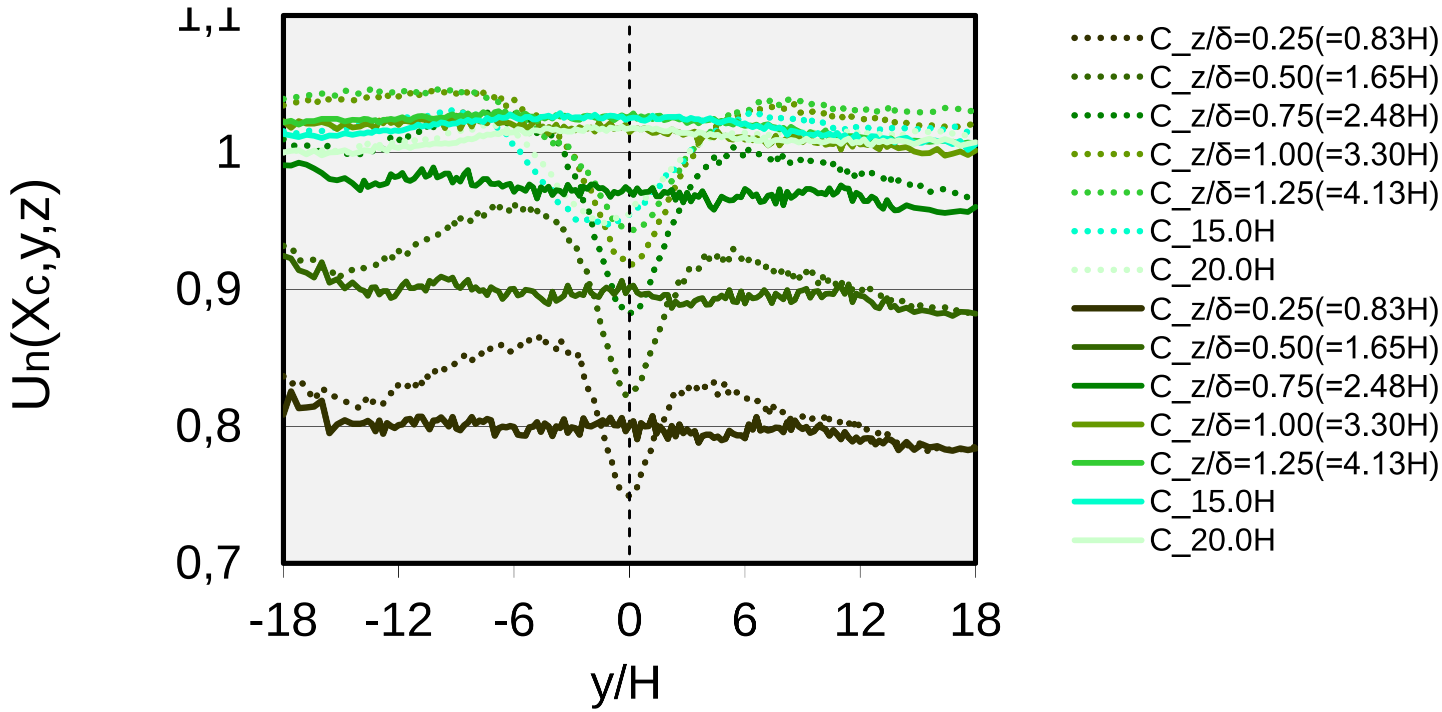
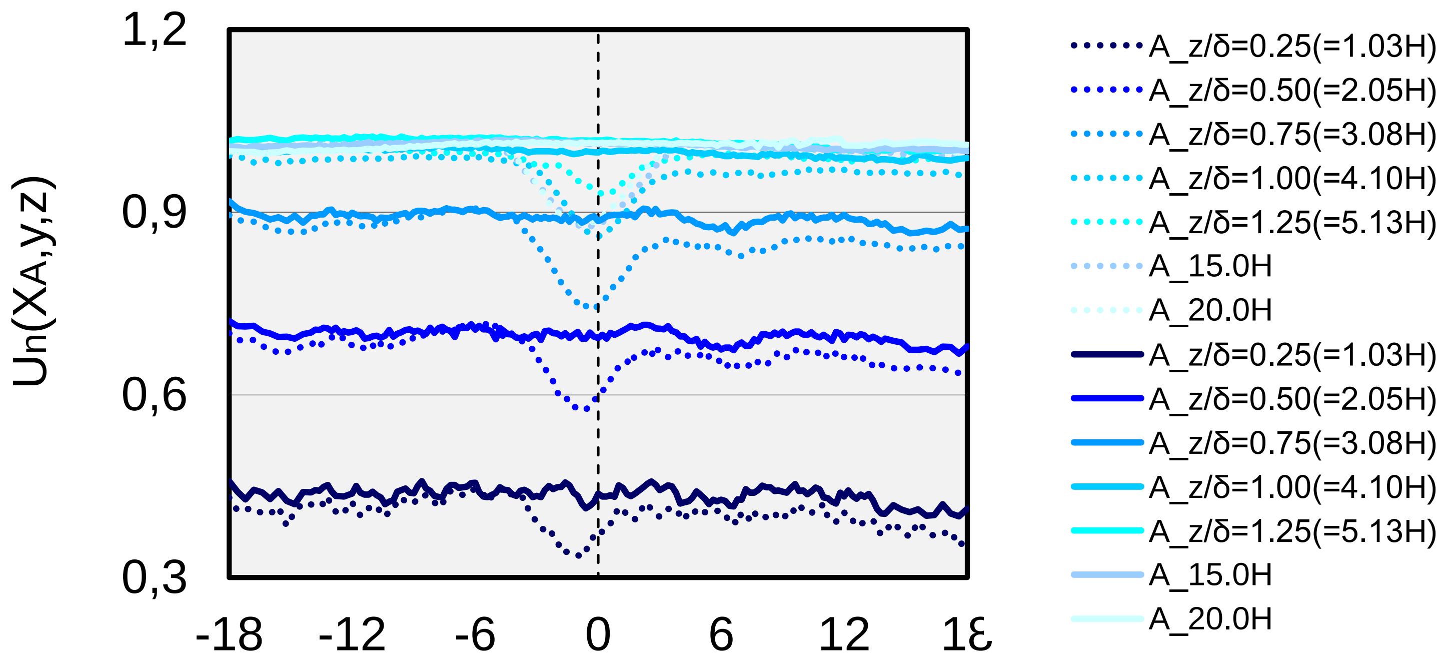
B_z/δ=0.75(=2.33H)
B_z/δ=1.00(=3.1H)
B_z/δ=1.25(=3.88H)
B_15.0H
B_20.0H
B_z/δ=0.25(=0.78H)
B_z/δ=0.50(=1.55H)
B_z/δ=0.75(=2.33H)
B_z/δ=1.00(=3.1H)
B_z/δ=1.25(=3.88H)
B_15.0H
B_20.0H

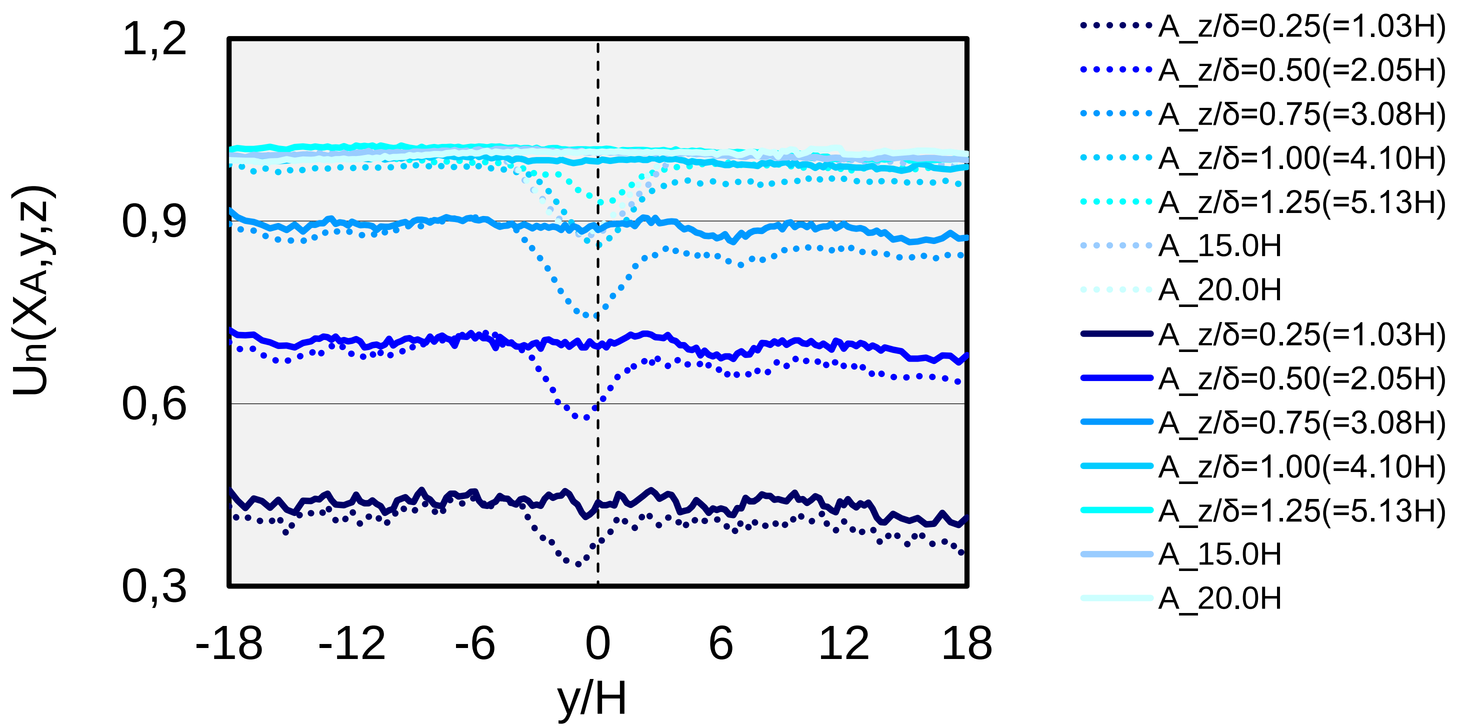

1,1
1
0,9
0,8
0,7
Un(Xc,y,z)
-18
-12
-6
0
6
12
18
y/H
C_z/δ=0.25(=0.83H)
C_z/δ=0.50(=1.65H)
C_z/δ=0.75(=2.48H)
C_z/δ=1.00(=3.30H)
C_z/δ=1.25(=4.13H)
C_15.0H
C_20.0H

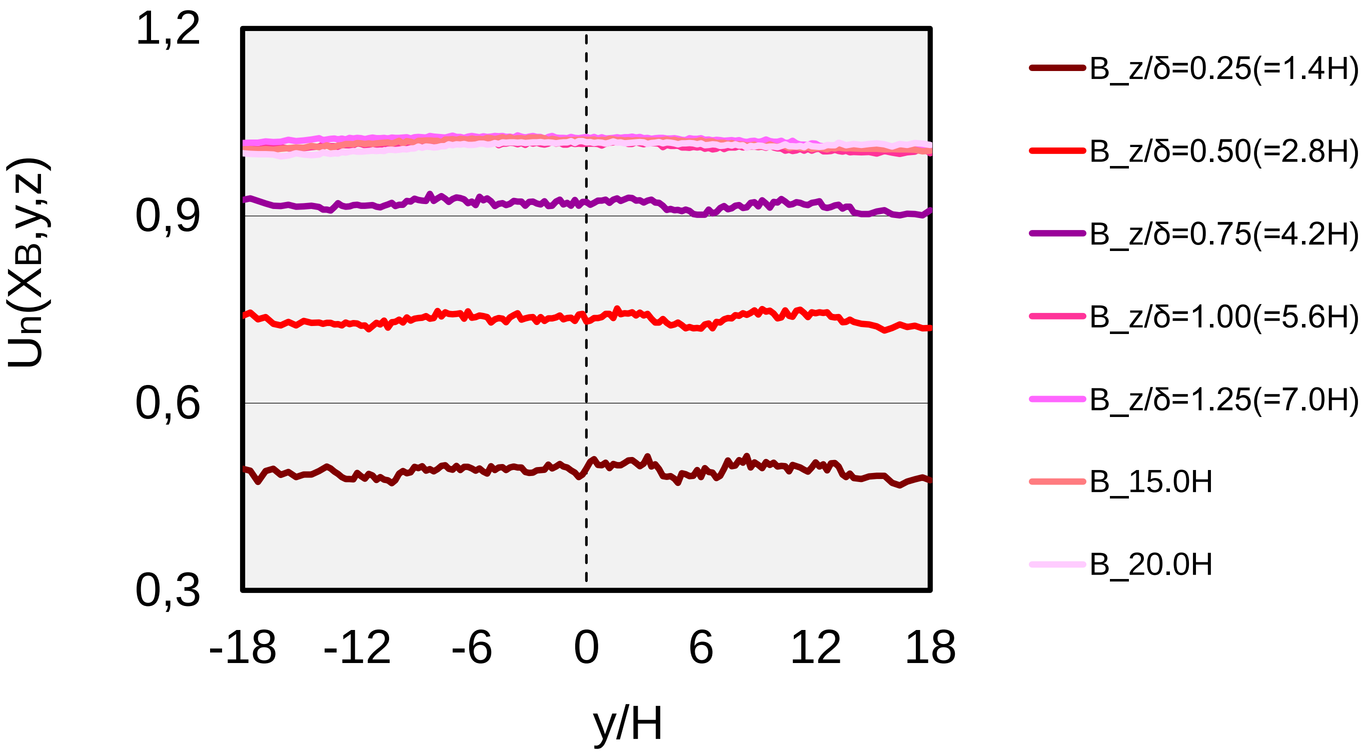
Smooth


1,1
1
0,9
0,8
0,7
Un(Xc,y,z)
-18
-12
-6
0
6
12
18
y/H
C_z/δ=0.25(=0.83H)
C_z/δ=0.50(=1.65H)
C_z/δ=0.75(=2.48H)
C_z/δ=1.00(=3.30H)
C_z/δ=1.25(=4.13H)
C_15.0H
C_20.0H
C_z/δ=0.25(=0.83H)
C_z/δ=0.50(=1.65H)
C_z/δ=0.75(=2.48H)
C_z/δ=1.00(=3.30H)
C_z/δ=1.25(=4.13H)
C_15.0H
C_20.0H

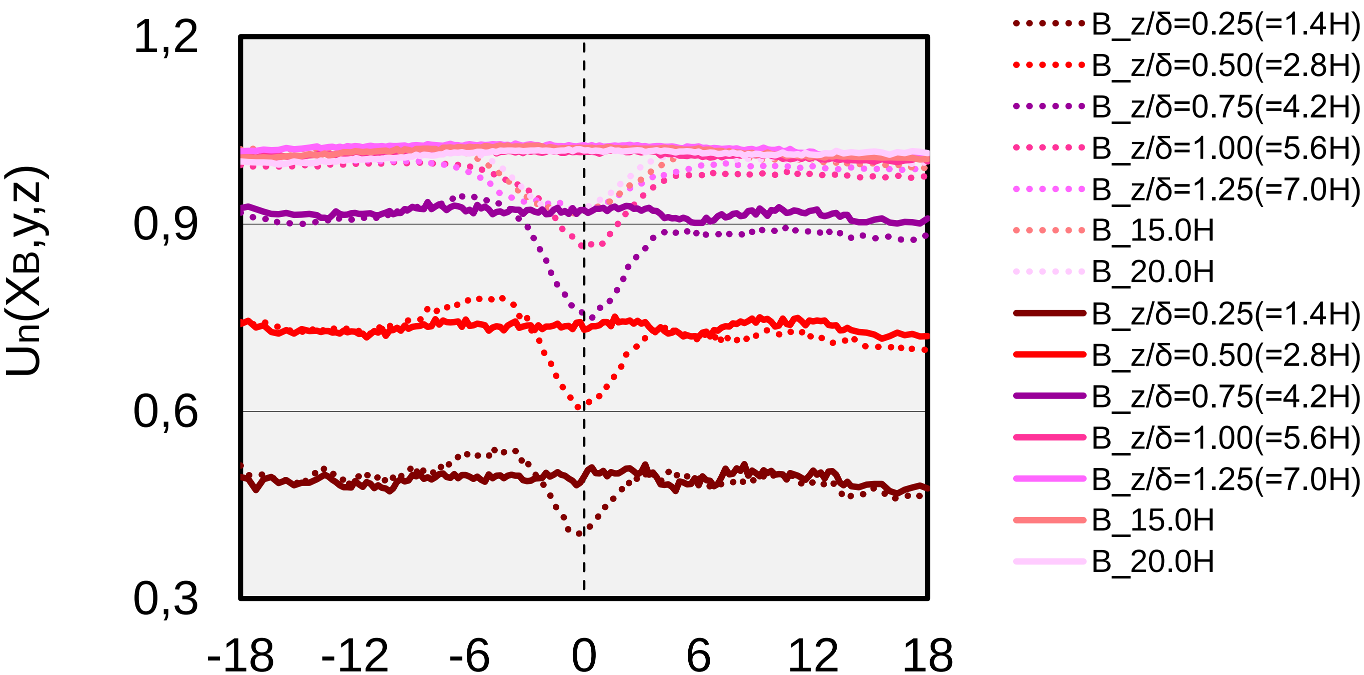

Un(XA,y,z)
1,2
0,9
0,6
0,3
-18
-12
-6
0
6
12
A_z/δ=0.25(=1.03H)
A_z/δ=0.50(=2.05H)
A_z/δ=0.75(=3.08H)
A_z/δ=1.00(=4.10H)
A_z/δ=1.25(=5.13H)
A_15.0H
A_20.0H
A_z/δ=0.25(=1.03H)
A_z/δ=0.50(=2.05H)
A_z/δ=0.75(=3.08H)
A_z/δ=1.00(=4.10H)
A_z/δ=1.25(=5.13H)
A_15.0H
A_20.0H

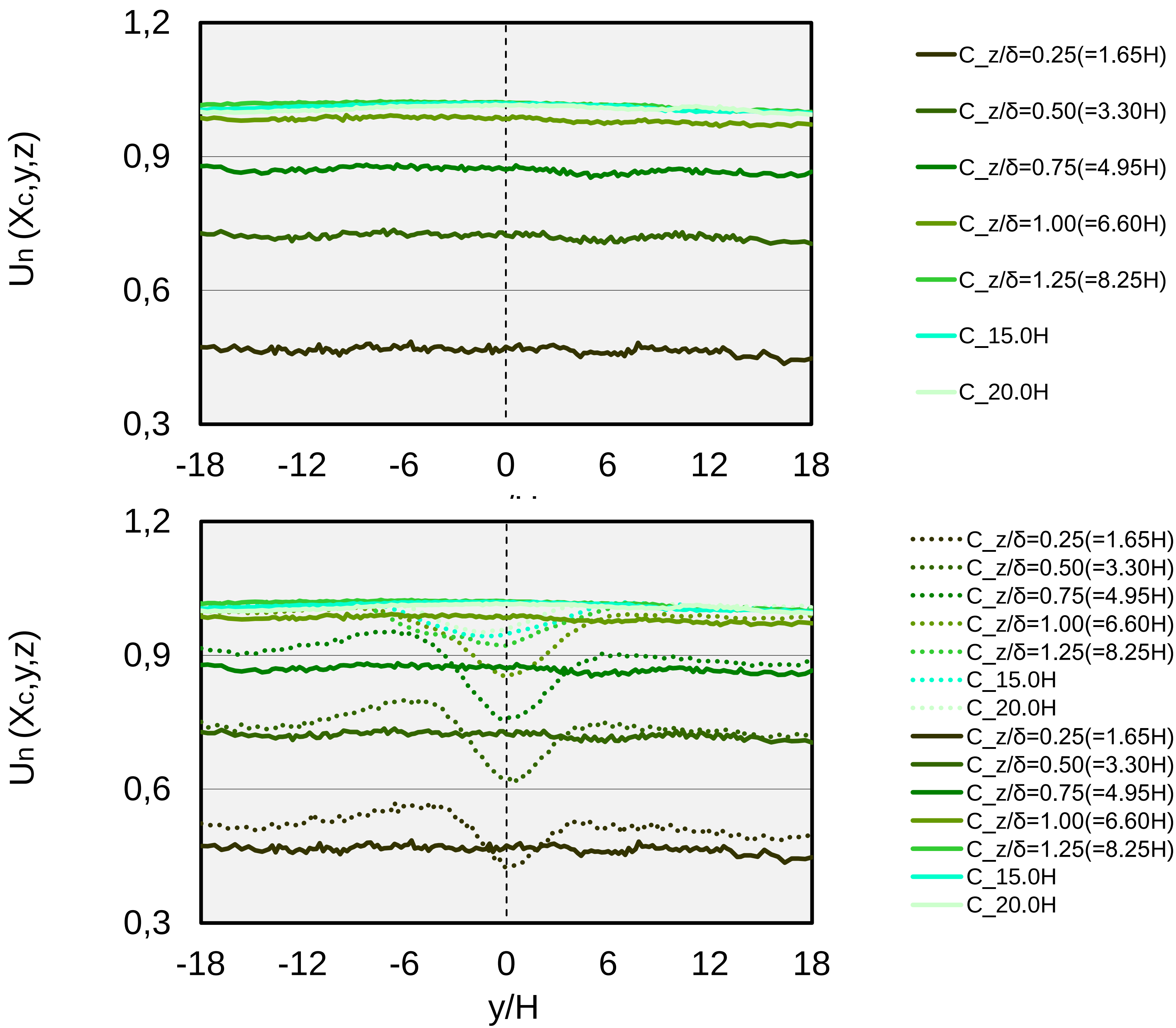
Rough


Un(XA,y,z)
1,2
0,9
0,6
0,3
-18
-12
-6
0
6
12
18
y/H
A_z/δ=0.25(=1.03H)
A_z/δ=0.50(=2.05H)
A_z/δ=0.75(=3.08H)
A_z/δ=1.00(=4.10H)
A_z/δ=1.25(=5.13H)
A_15.0H
A_20.0H
A_z/δ=0.25(=1.03H)
A_z/δ=0.50(=2.05H)
A_z/δ=0.75(=3.08H)
A_z/δ=1.00(=4.10H)
A_z/δ=1.25(=5.13H)
A_15.0H
A_20.0H


1,2
0,9
0,6
0,3
Un(XB,y,z)
-18
-12
-6
0
6
12
18
y/H
B_z/δ=0.25(=1.4H)
B_z/δ=0.50(=2.8H)
B_z/δ=0.75(=4.2H)
B_z/δ=1.00(=5.6H)
B_z/δ=1.25(=7.0H)
B_15.0H
B_20.0H

Rough


1,2
0,9
0,6
0,3
Un(XB,y,z)
-18
-12
-6
0
6
12
18
B_z/δ=0.25(=1.4H)
B_z/δ=0.50(=2.8H)
B_z/δ=0.75(=4.2H)
B_z/δ=1.00(=5.6H)
B_z/δ=1.25(=7.0H)
B_15.0H
B_20.0H
B_z/δ=0.25(=1.4H)
B_z/δ=0.50(=2.8H)
B_z/δ=0.75(=4.2H)
B_z/δ=1.00(=5.6H)
B_z/δ=1.25(=7.0H)
B_15.0H
B_20.0H

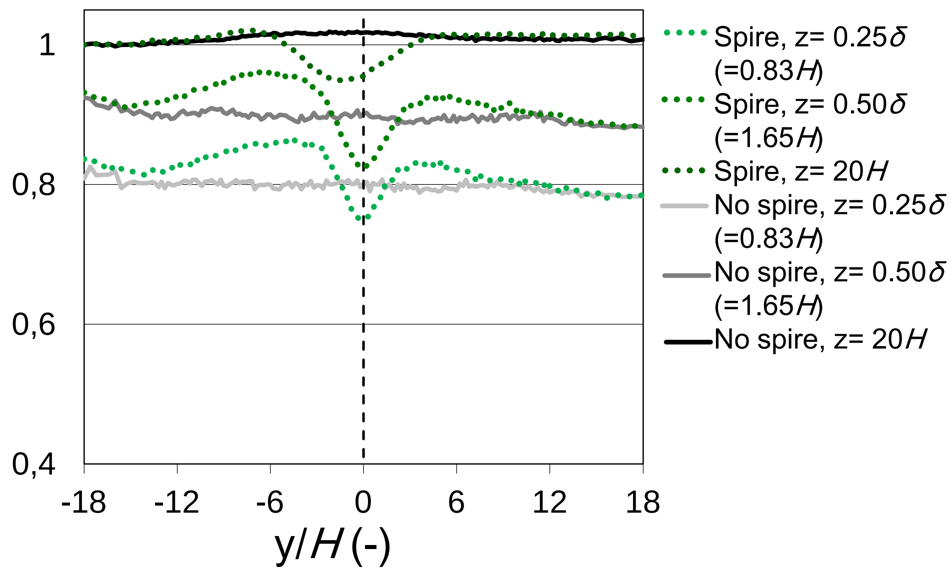

1,2
0,9
0,6
0,3
Un (Xc,y,z)
-18
-12
-6
0
6
12
18
y/H
C_z/δ=0.25(=1.65H)
C_z/δ=0.50(=3.30H)
C_z/δ=0.75(=4.95H)
C_z/δ=1.00(=6.60H)
C_z/δ=1.25(=8.25H)
C_15.0H
C_20.0H

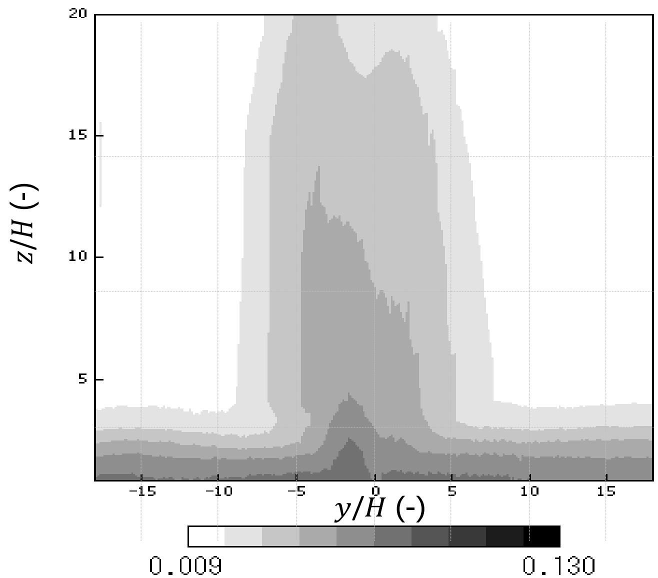
Rough

Results & Discussions : C(x= 135.9H)

Smooth Surface

$U_n(x_C, y, z)(-)$

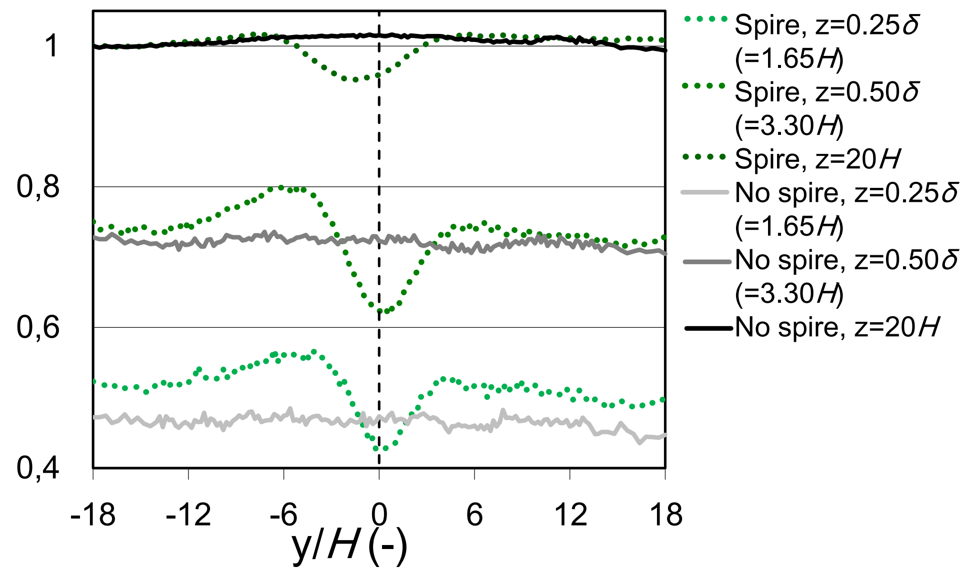


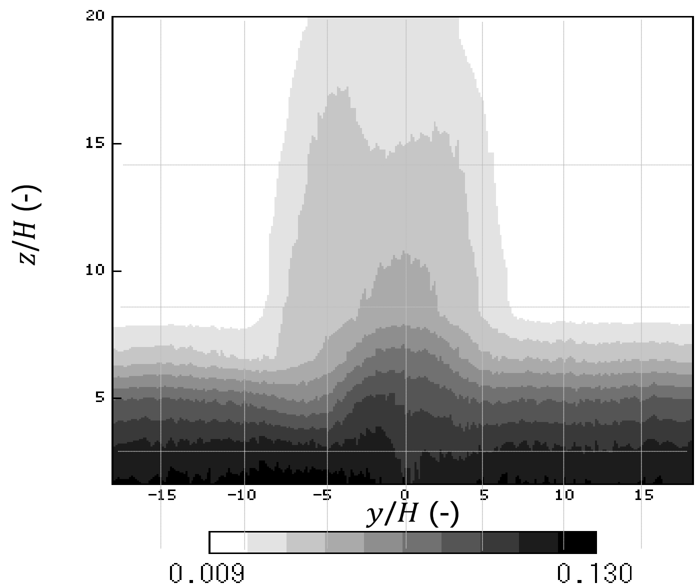


σ_u / U_{ref}

Rough surface

$U_n(x_C, y, z) = U(x, y, z) / U_{ref}(x, y = -18\,H, z = 20H)$



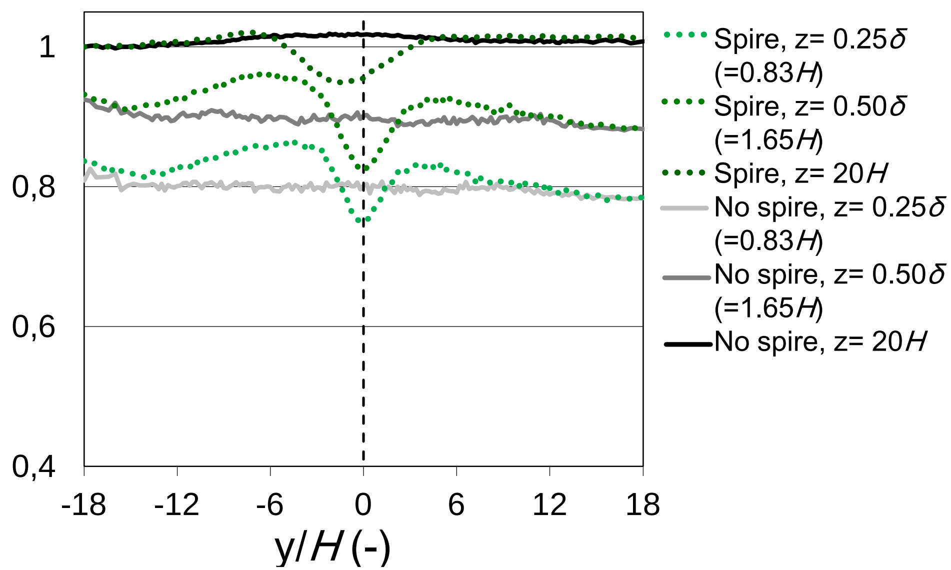


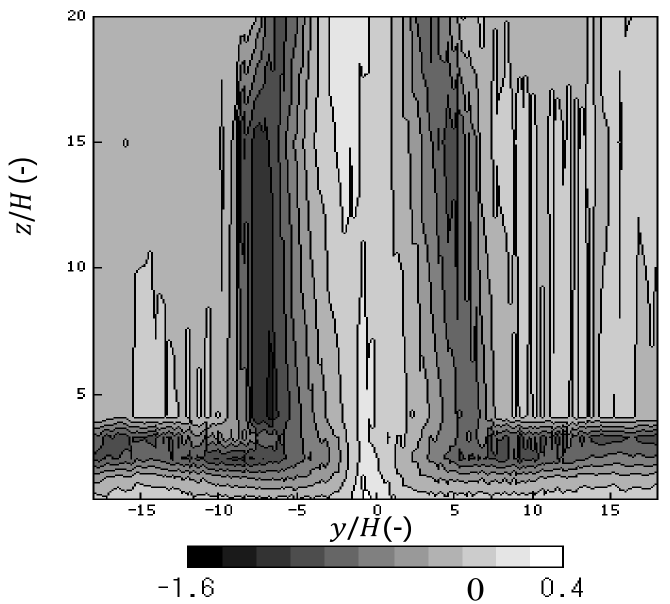
σ_u / U_{ref}

Results & Discussions : C(x= 135.9H)

Smooth Surface

$U_n(x_C, y, z)(-)$

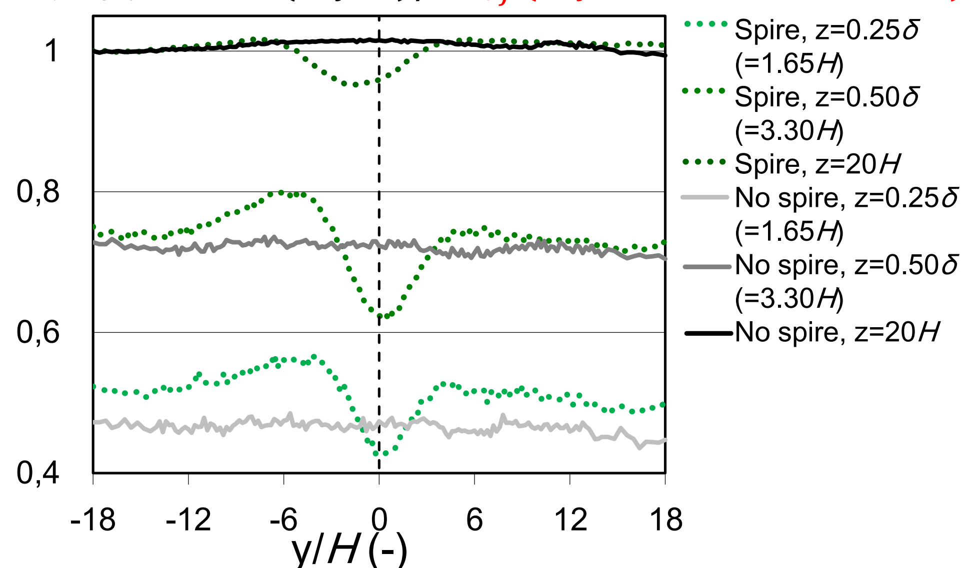


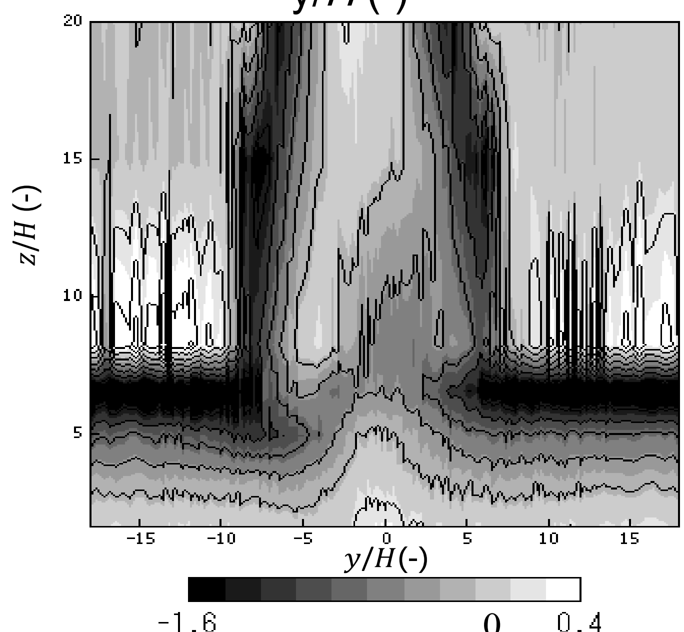


Skewness

Rough surface

$U_n(x_C, y, z) = U(x, y, z)/U_{ref}(x, y = -18\,H, z = 20H)$





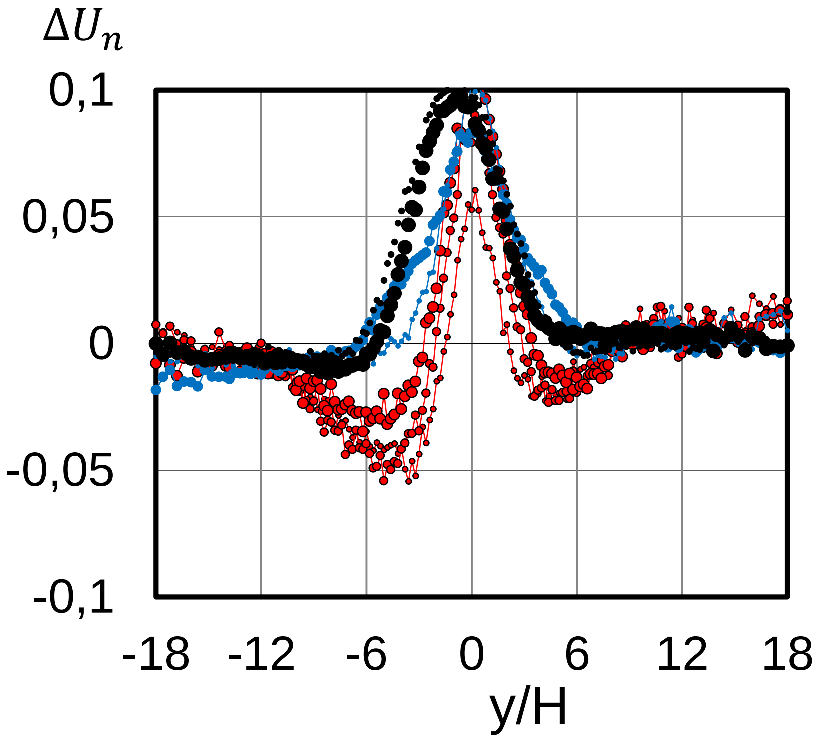
Skewnesss

B positions

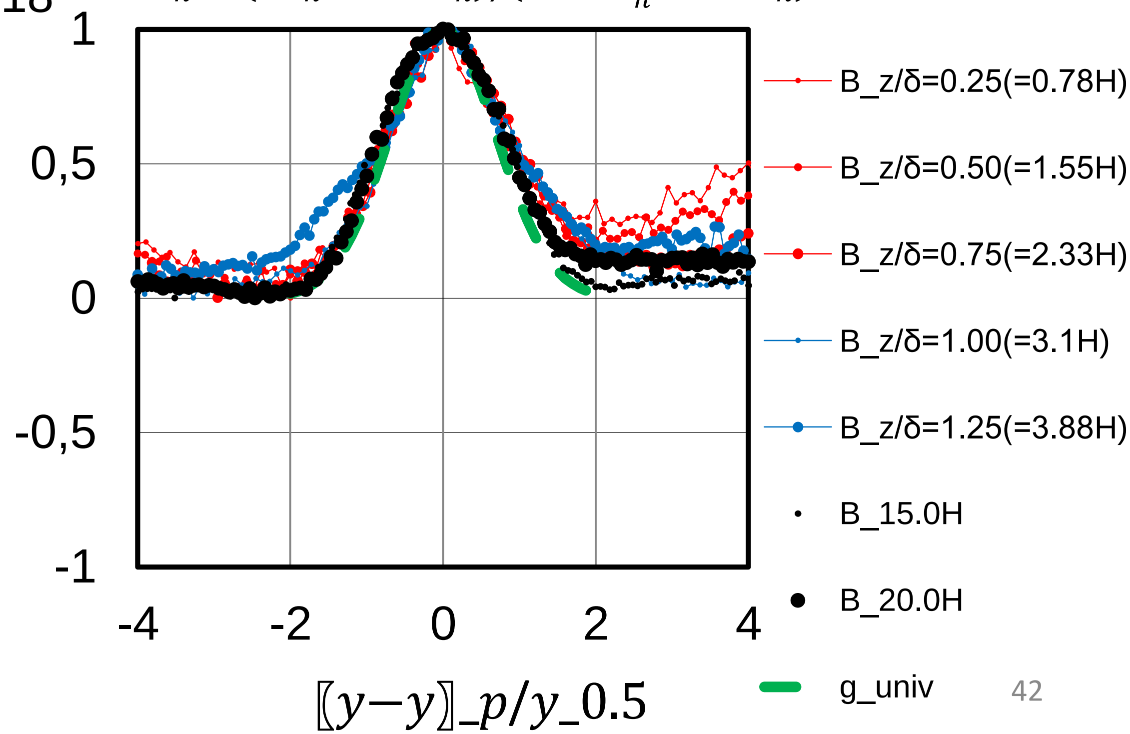
Within BL

Near BLH

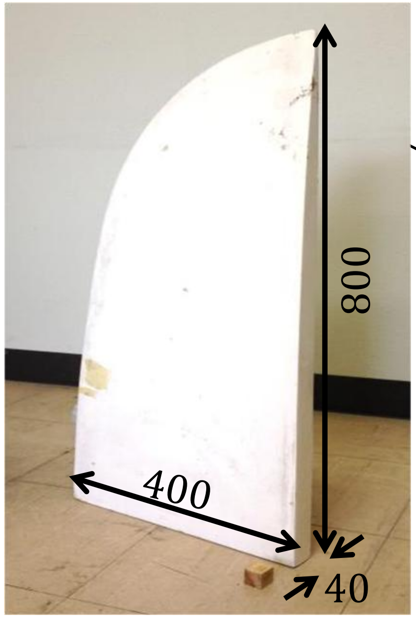
Above BLH



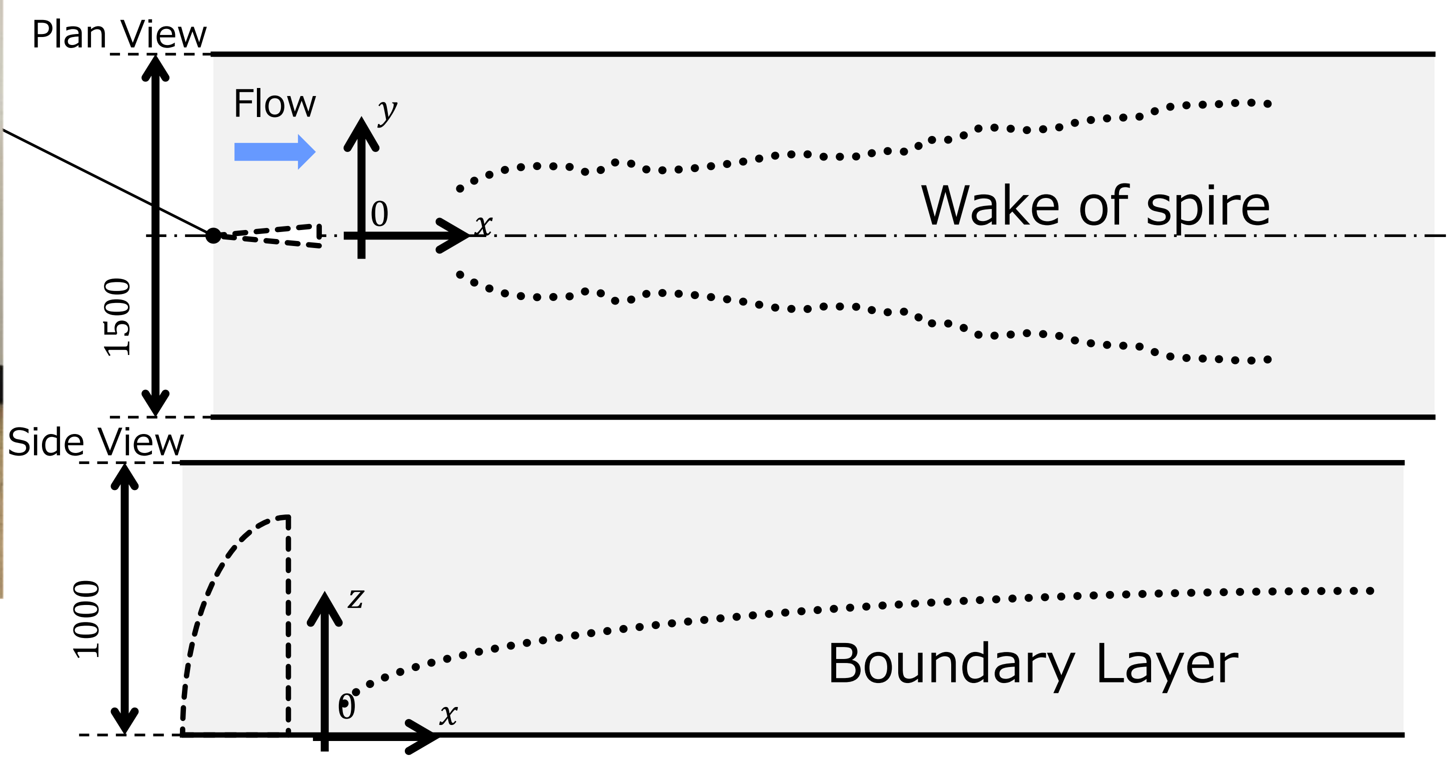
$\varnothing_n = (\Delta U_n - \Delta U^{min}{}_n)/(\Delta U^{max}{}_n - \Delta U^{min}{}_n)$



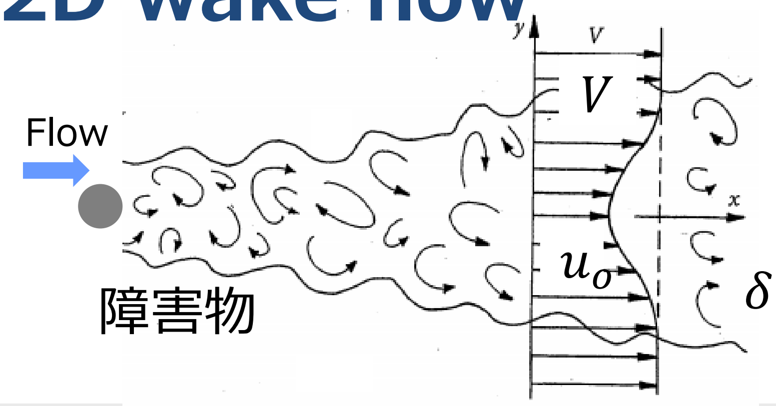
EXPERIMENTAL DETAILS



Elliptic wedge generator (=Spire)



2D wake flow



Vel. deficit: $V - u_x(x,y) = u_o(x) g\left(\frac{y}{\delta(x)}\right)$

Self similar Gradient- diffusion

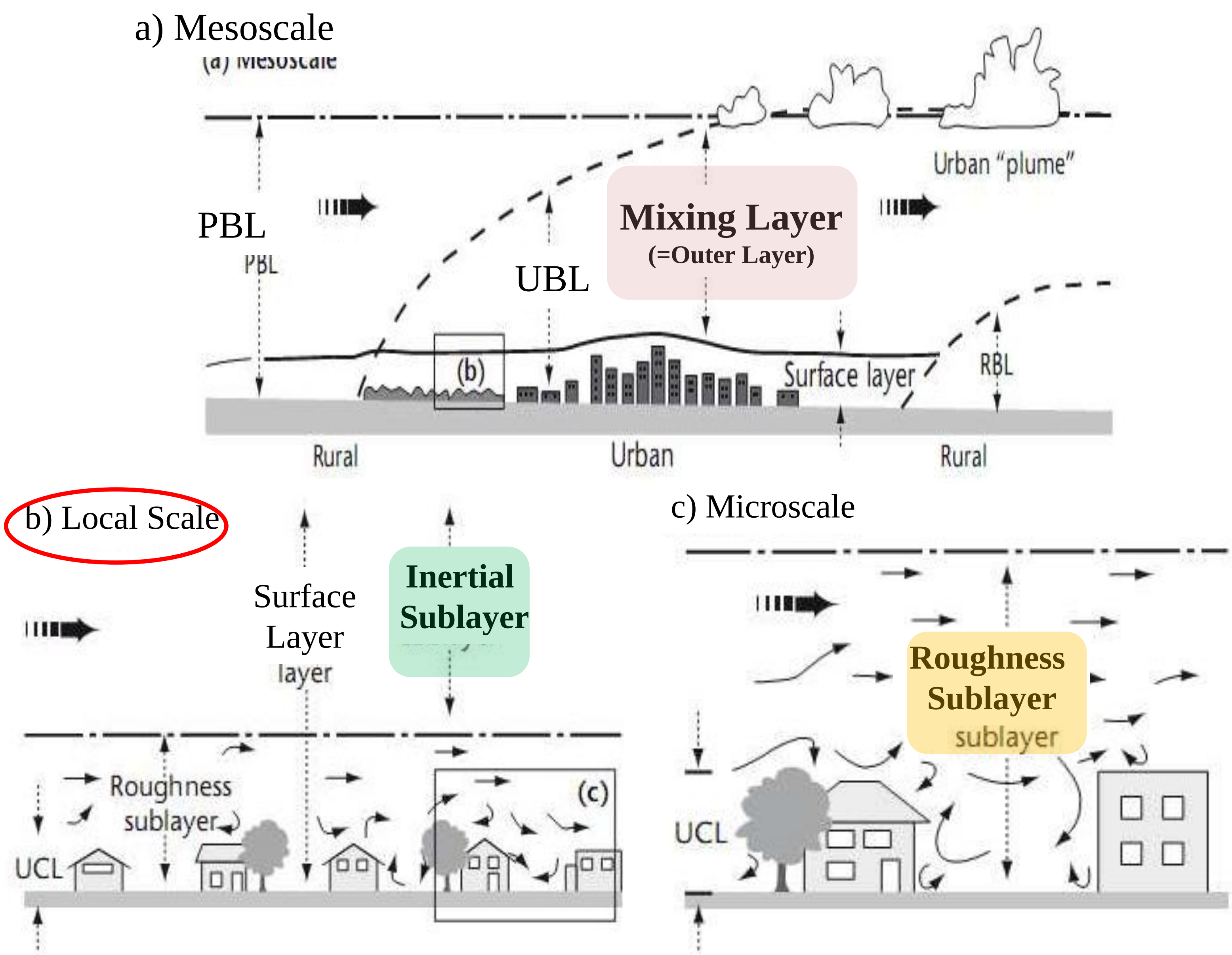
model : $g(y/\delta(x)) = exp\left(-\left(\frac{y}{\delta}\right)^2\right)$

Max Vel. deficit: $V - u_o(x) \propto x^{-0.5}$

Half wake width: $\delta(x) \propto x^{0.5}$

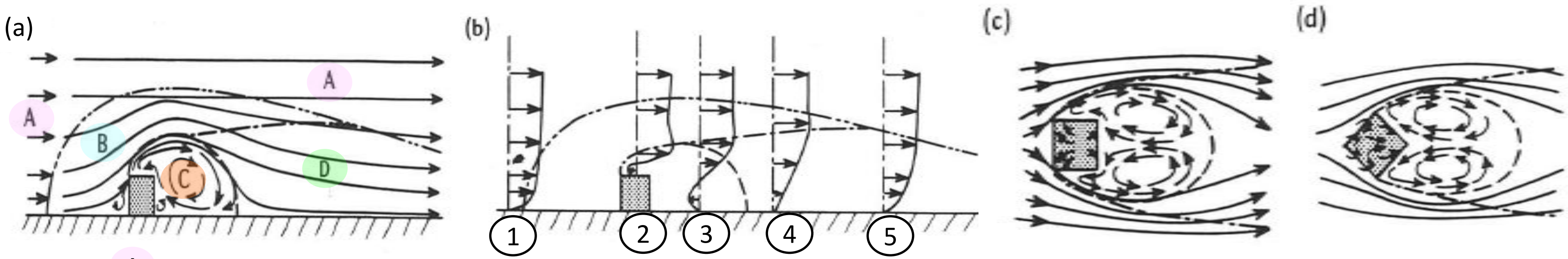
*Turbulence, Oxford University Press, P.A. Davidson

Vertical Urban Boundary Layer Structure



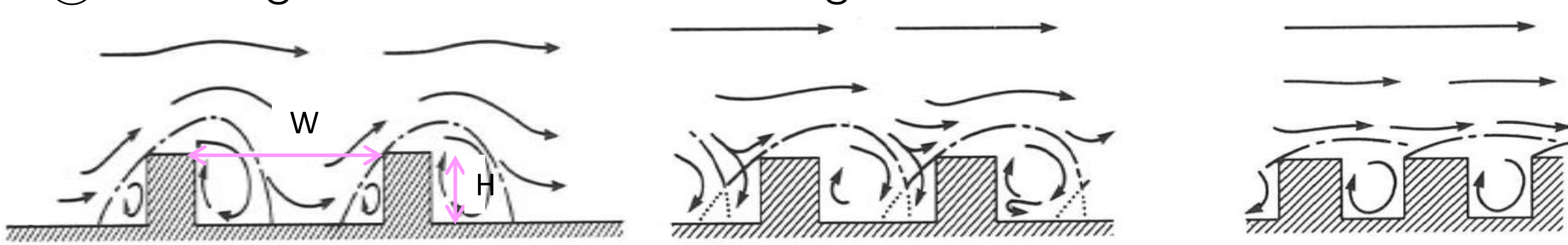
Airflow around buildings (Oke et. al, 1988)

① Flow pattern around building



A undisturbed
B displacement
C cavity
D wake

② Flow regimes with different urban geometries



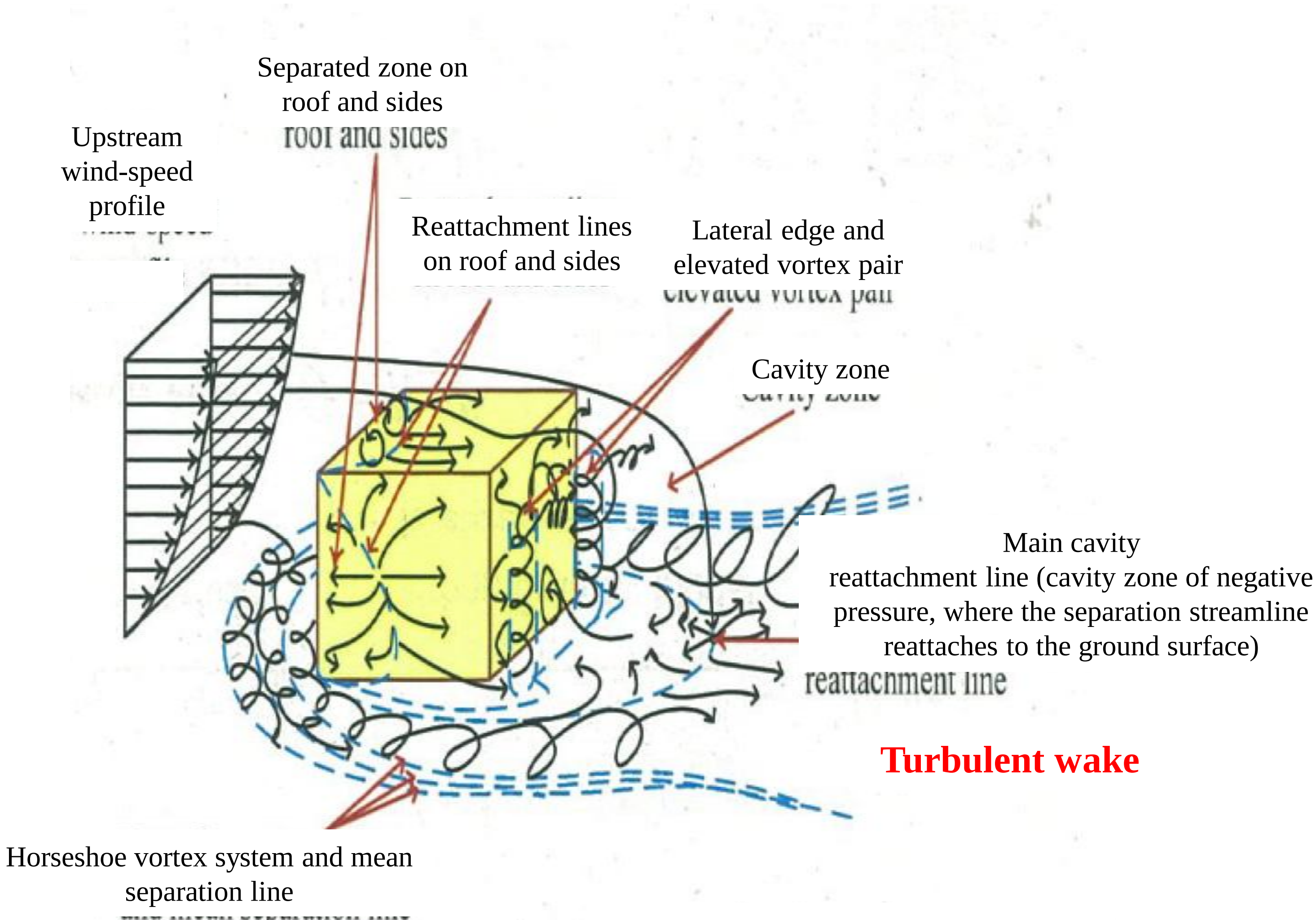
(a) Isolated roughness flow
H/W < 0.3

(b) Wake interference flow
0.3 < H/W < 0.7

(c) Skimming flow
H/W > 0.7

Theory

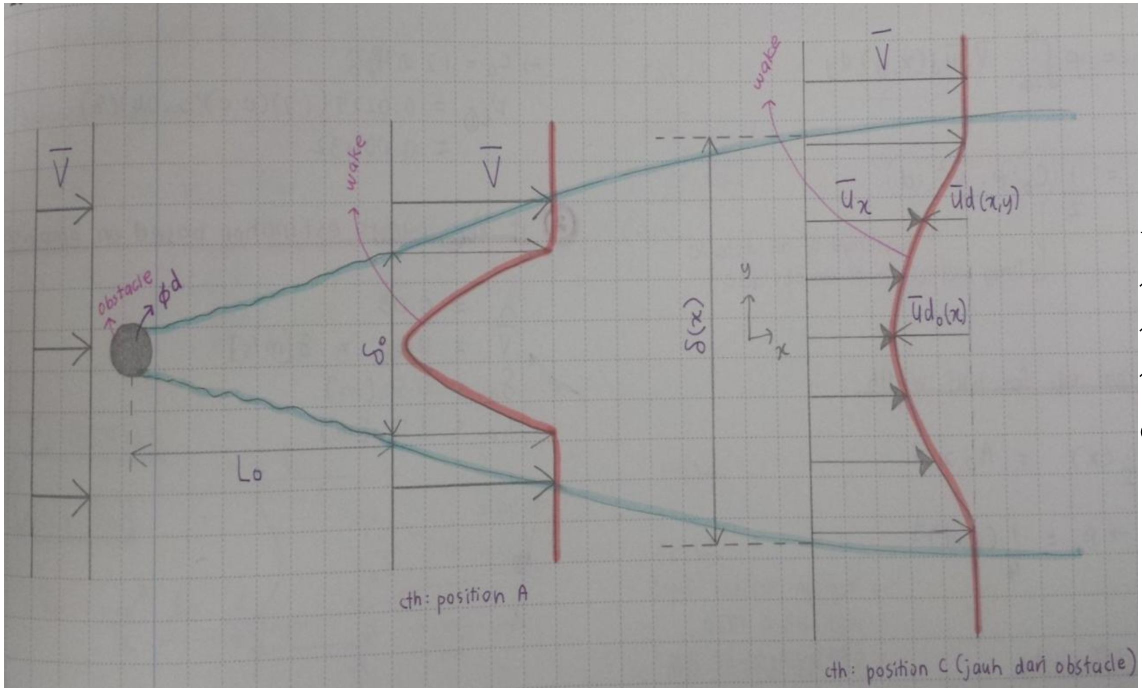
Isolated block



Recirculating streamlines can be found in separation zones

Hosker (1979)

THEORY



$\bar{V}$: Velocity out of wake region
$\bar{u}_x(x, y)$: streamwise velocity
$\bar{u}_d(x, y) = \bar{V} - \bar{u}_x(x, y)$: velocity deficit
$\bar{u}_{d_0}(x) = \bar{u}_{d_0}(x, 0)$: maximum deficit
$\delta(x)$: width of wake

1) Axial gradients in the Re. stress : $\frac{\partial \tau_{ij}{}^R}{\partial x}$

2) Axial eq. of motions :

$$\rho(\bar{u} - \nabla)\bar{u}_x = \frac{\partial}{\partial y}\left[\tau_{xy}{}^R\right] - \cancel{\frac{\partial \bar{p}}{\partial x}}$$

** longitudinal gradients in Re. stresses can be neglected

** $\nabla \cdot \bar{u} = 0$;

3) Simplified momentum eq. for wake;

$$\frac{\partial}{\partial x}\left[\rho \bar{u}_x(\bar{V} - \bar{u}_x)\right] + \frac{\partial}{\partial y}\left[\rho \bar{u}_y(\bar{V} - \bar{u}_x)\right] = -\frac{\partial \tau_{xy}{}^R}{\partial y}$$

4) $\bar{V} - \bar{u}_x$ (velocity deficit) tend to be 0 for large |y|;

Momentum deficit balances with drag on an obstacle,

$$D = \int_{-\infty}^{\infty} \rho \bar{u}_x(\bar{V} - \bar{u}_x)dy = constant$$

Conclusions

aerodynamic interaction between the wall shear boundary layer and wake flow behind isolated slender obstacle

1) spanwise variations of $\emptyset_n$ behind a spire above the wall boundary layer show good agreement with the 2D self-similar profile for a 2D wake flow in a free shear flow, despite the weak asymmetrical inflow condition of the wind tunnel

2) spanwise distribution of the wake within or near the BL showed different trends from that of 2D wake flow:
   - the expansion of the $y_{0.5}$ is compressed in the lateral direction by the turbulence of the wall boundary layer
   - velocity deficit of the wake is sustained far from the spire

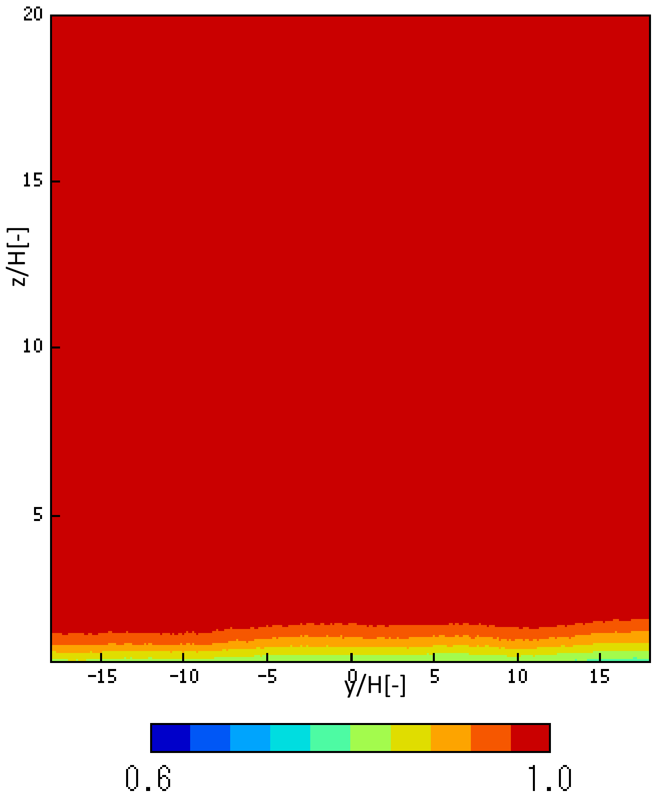
<u>Future task</u>

The turbulent statistical information of not only the streamwise velocity component, but also the lateral component would be essential for elucidating the mechanism of the interference of the spanwise expansion of the wake due to the wall boundary turbulence

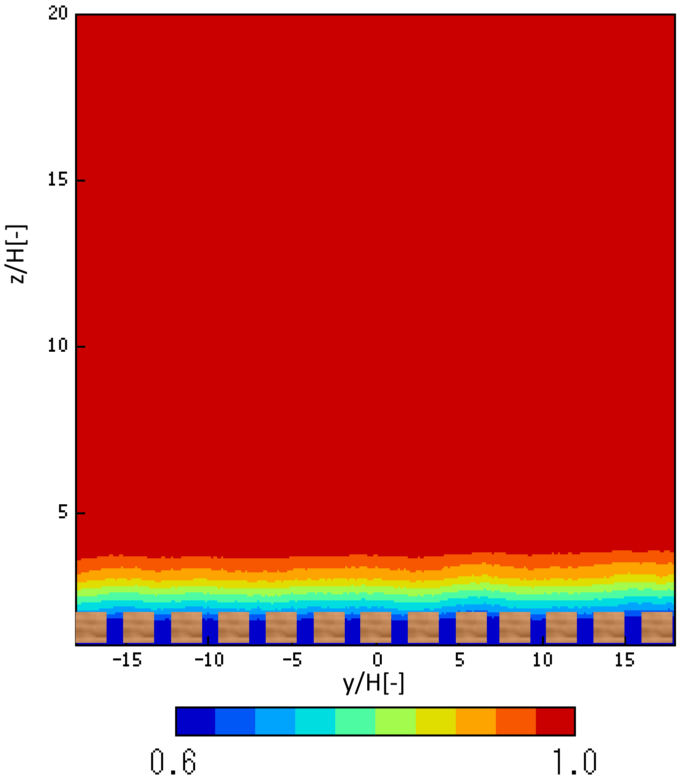
A

NO SPIRE (A position)
Unn

SMOOTH SURFACE

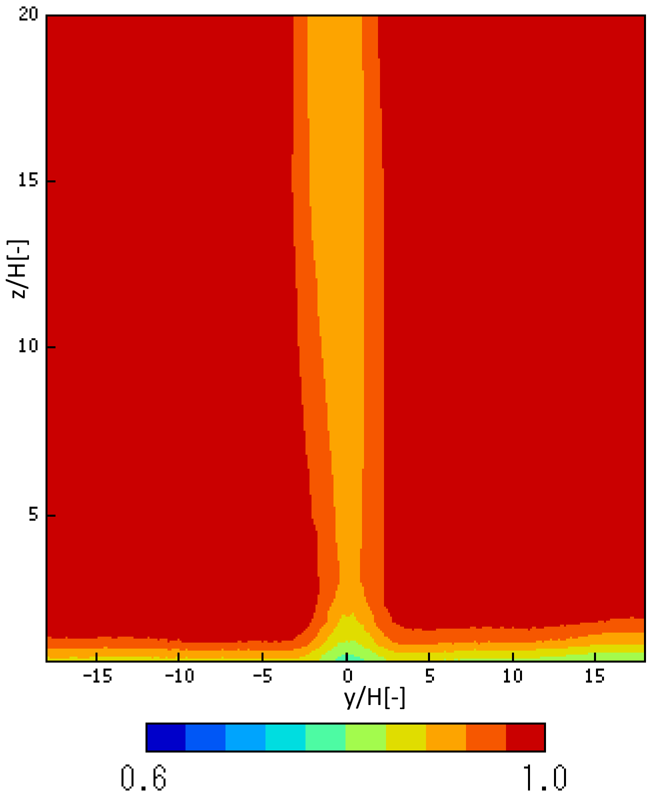


ROUGH SURFACE

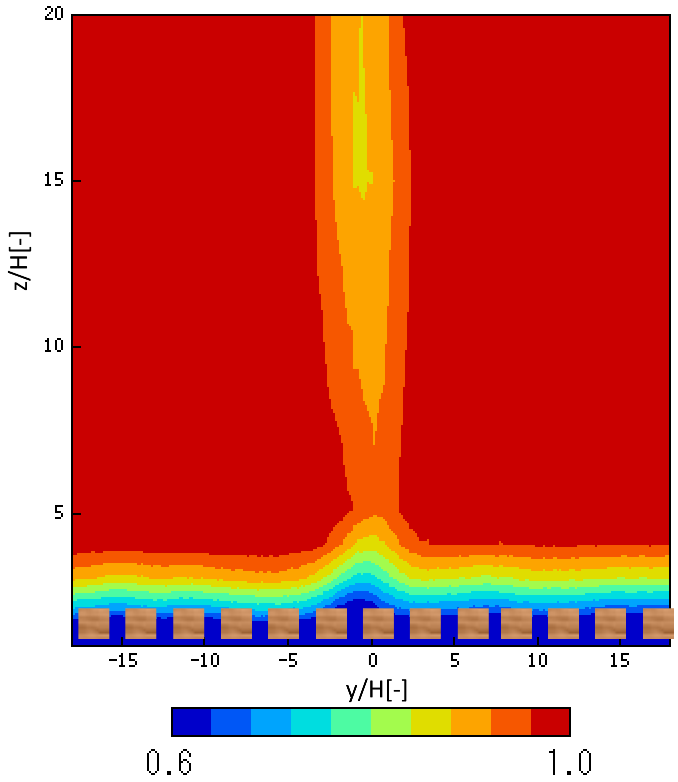


WITH SPIRE (A position)
Unn

SMOOTH SURFACE

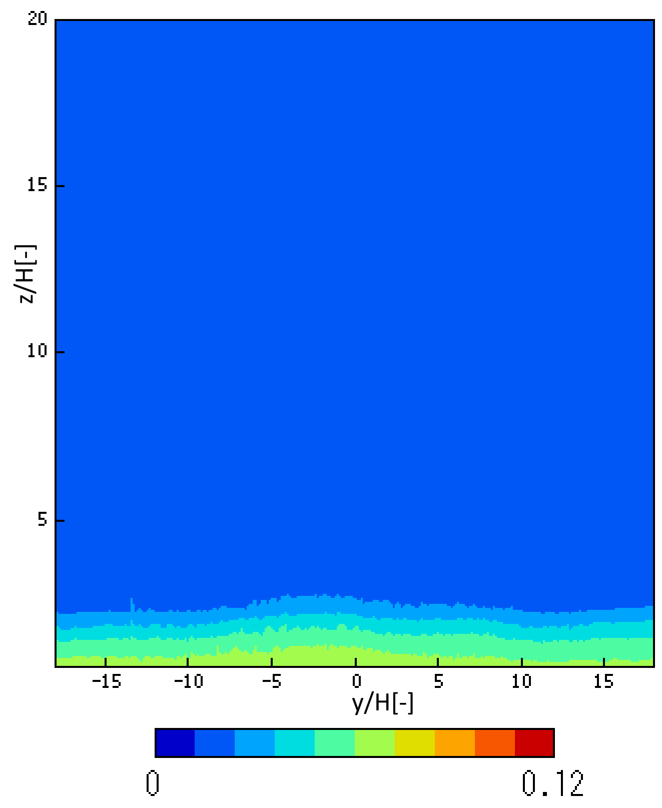


ROUGH SURFACE

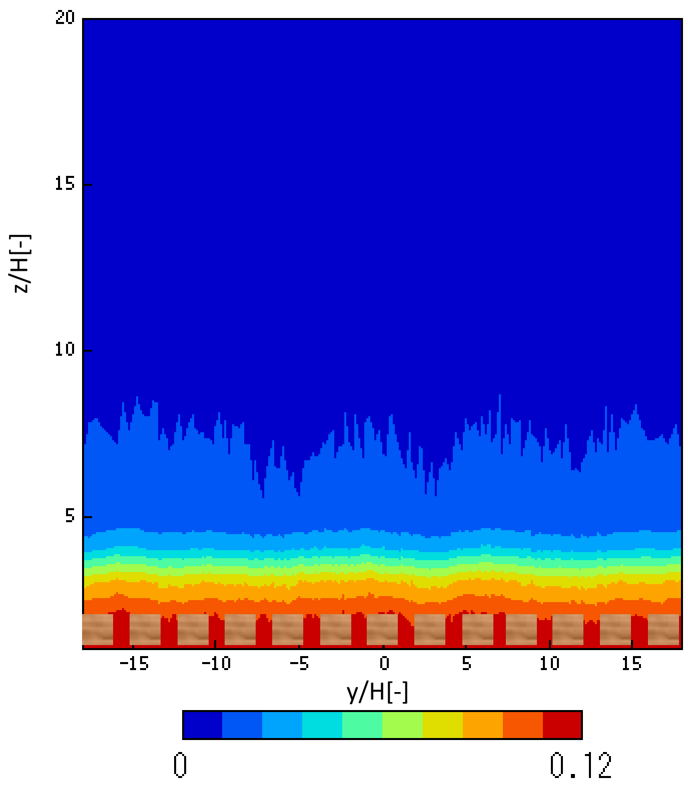


NO SPIRE (A position)
Standard deviation (x,y=-18,z=20H)

SMOOTH SURFACE

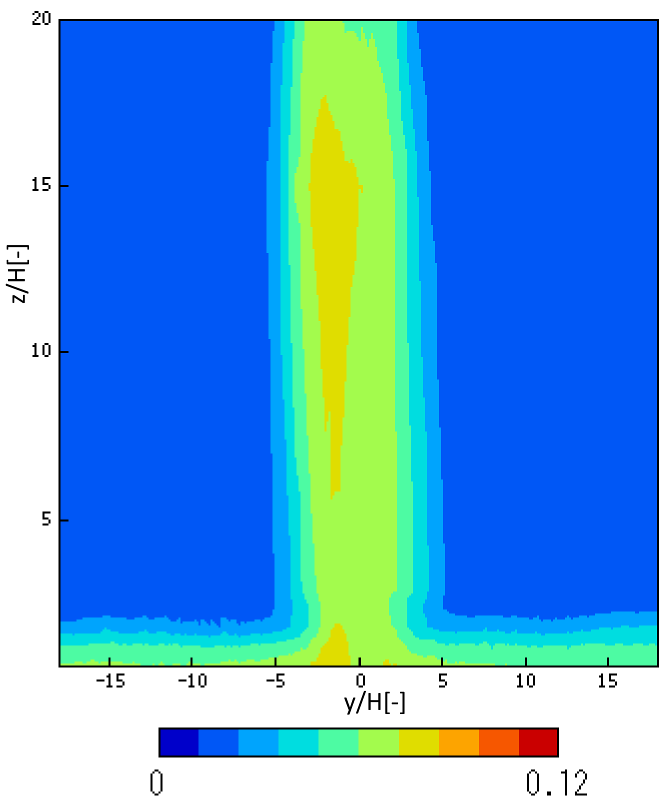


ROUGH SURFACE



WITH SPIRE (A position)
Standard deviation (x,y=-18,z=20H)

SMOOTH SURFACE



ROUGH SURFACE

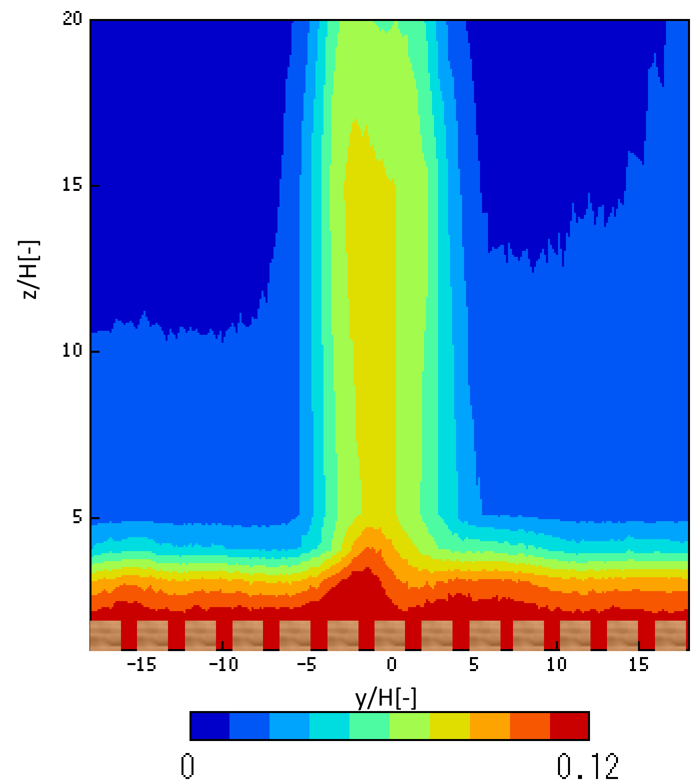
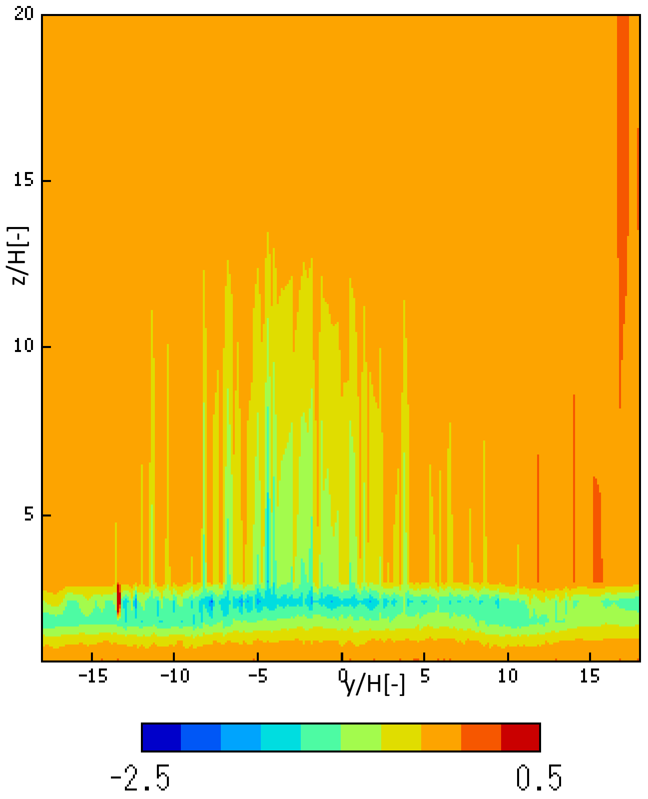


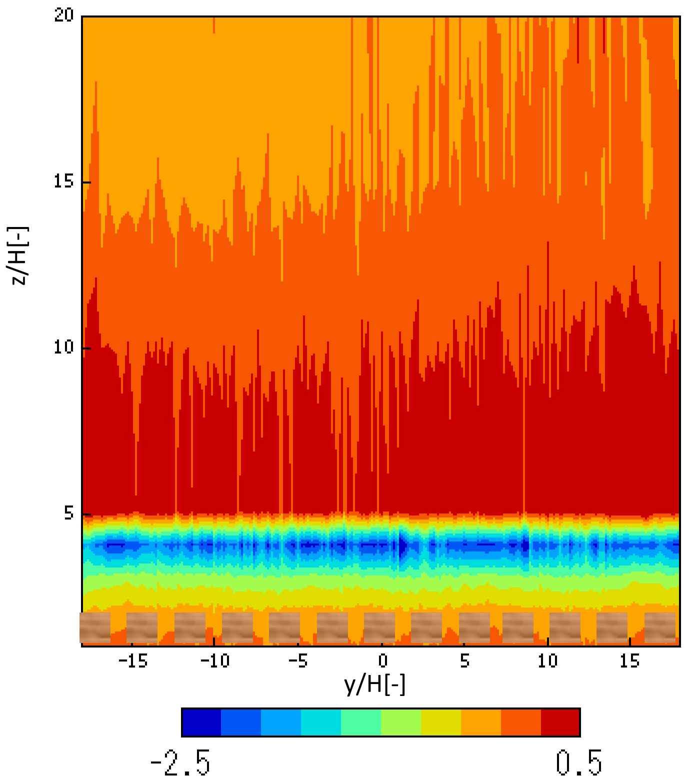
Fig. X_b Spanwise distributions of standard deviation at *C* (x = 135.9*H*)

NO SPIRE (A position)
Skewness

SMOOTH SURFACE

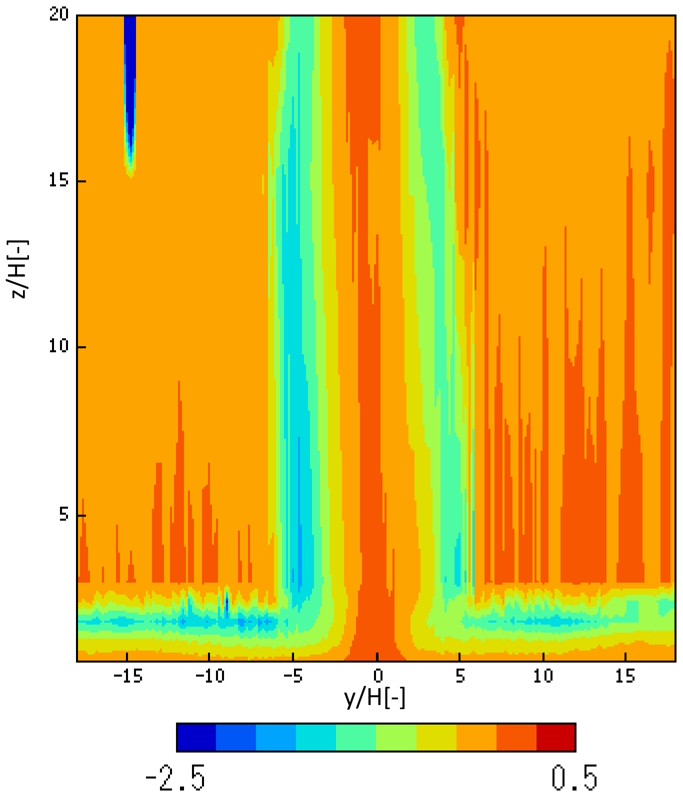


ROUGH SURFACE

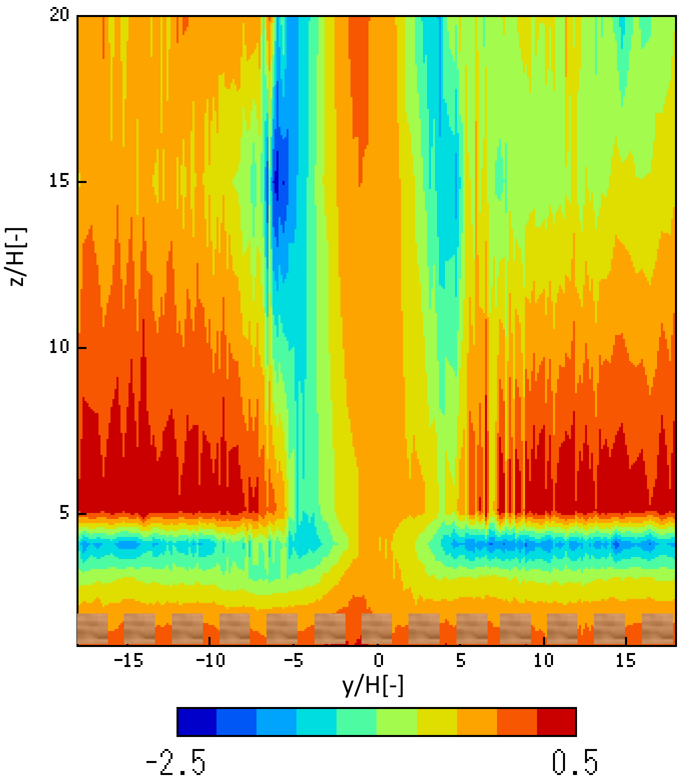


WITH SPIRE (A position)
Skewness

SMOOTH SURFACE



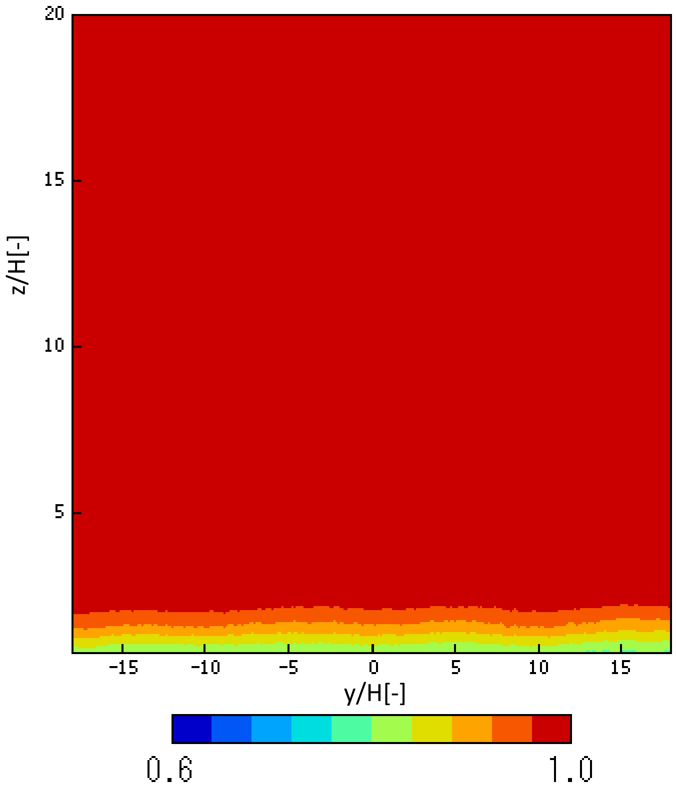
ROUGH SURFACE



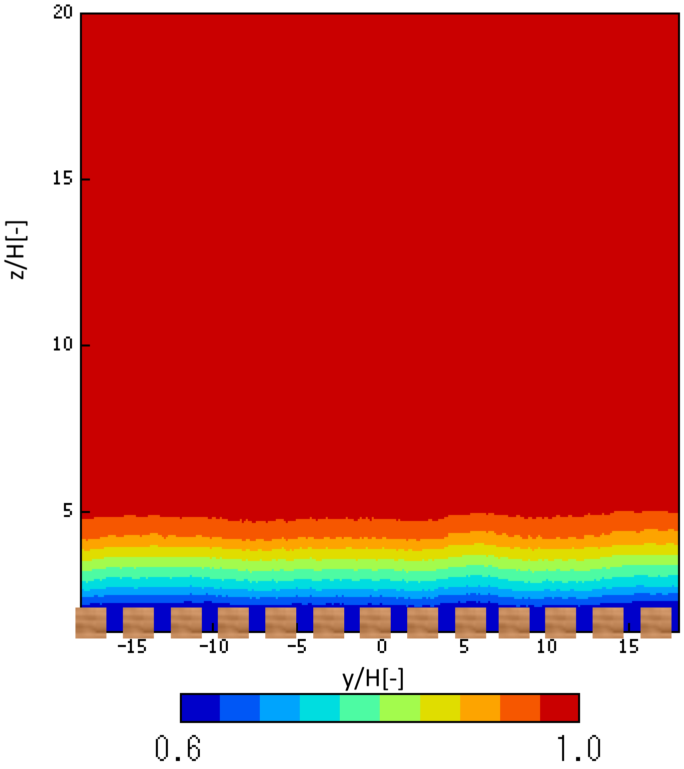
B

NO SPIRE (B position)
Unn

SMOOTH SURFACE

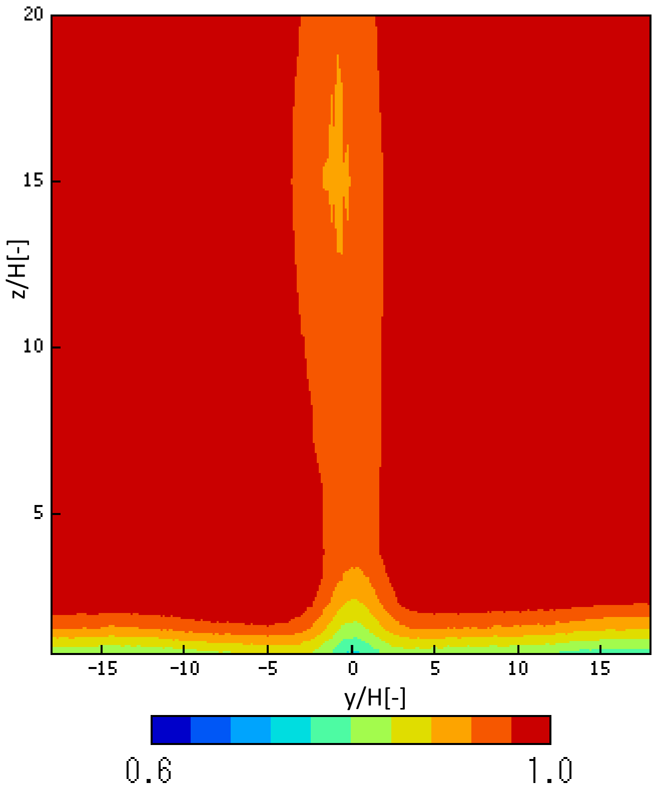


ROUGH SURFACE

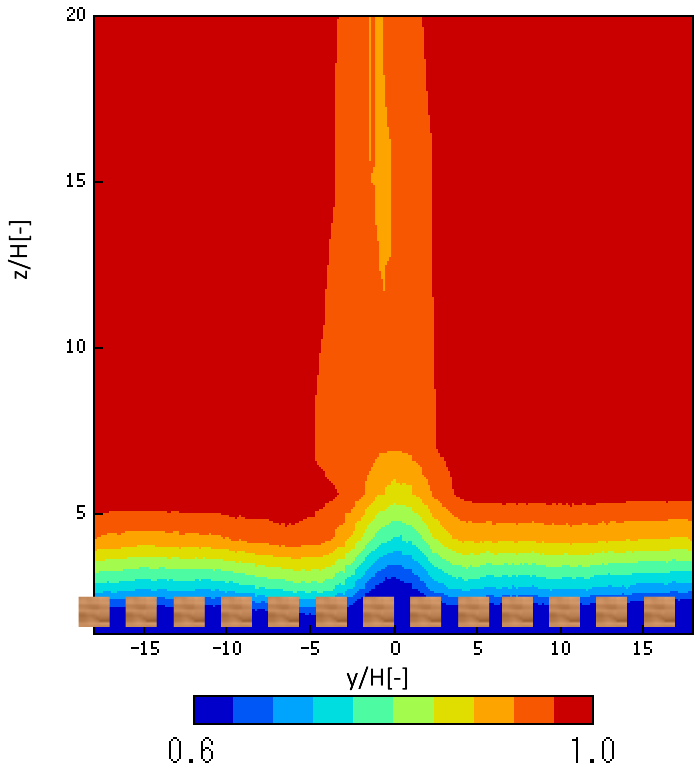


WITH SPIRE (B position)
Unn

SMOOTH SURFACE

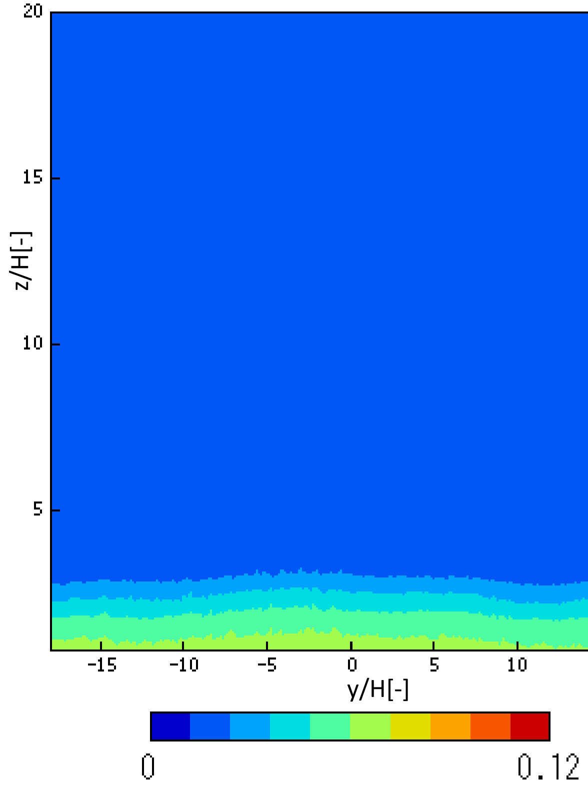


ROUGH SURFACE

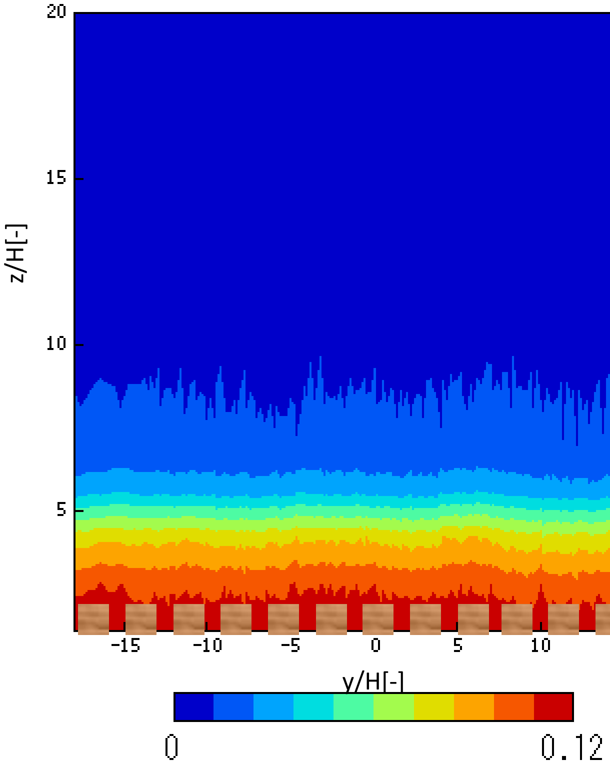


NO SPIRE (B position)
Standard deviation (x,y=-18,z=20H)

SMOOTH SURFACE

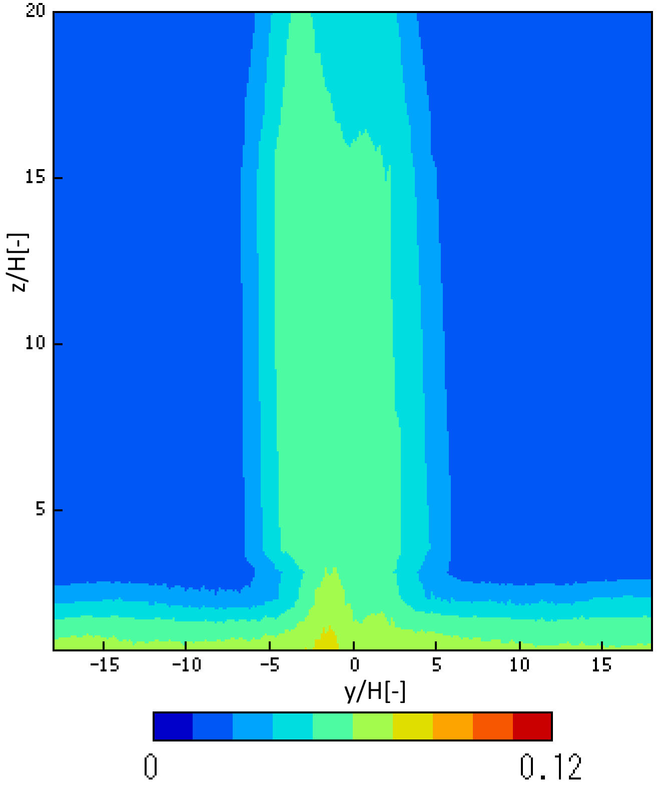


ROUGH SURFACE



WITH SPIRE (B position)
Standard deviation (x,y=-18,z=20H)

SMOOTH SURFACE



ROUGH SURFACE

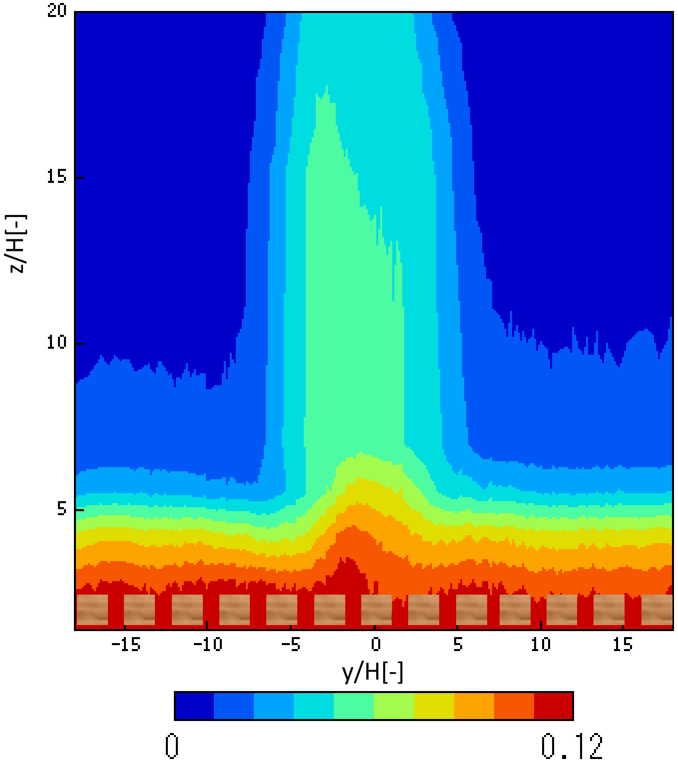
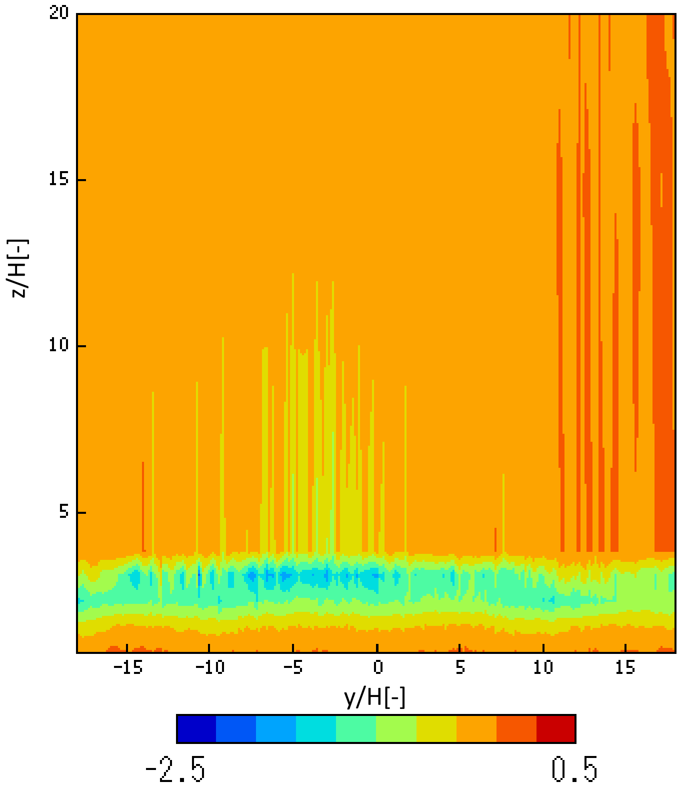


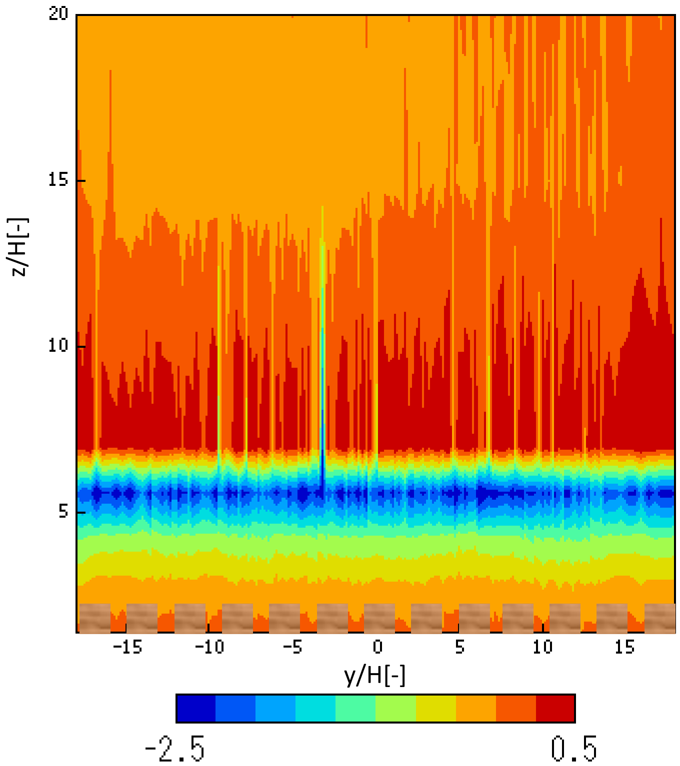
Fig. X_b Spanwise distributions of standard deviation at *C* (x = 135.9*H*)

NO SPIRE (B position)
Skewness

SMOOTH SURFACE

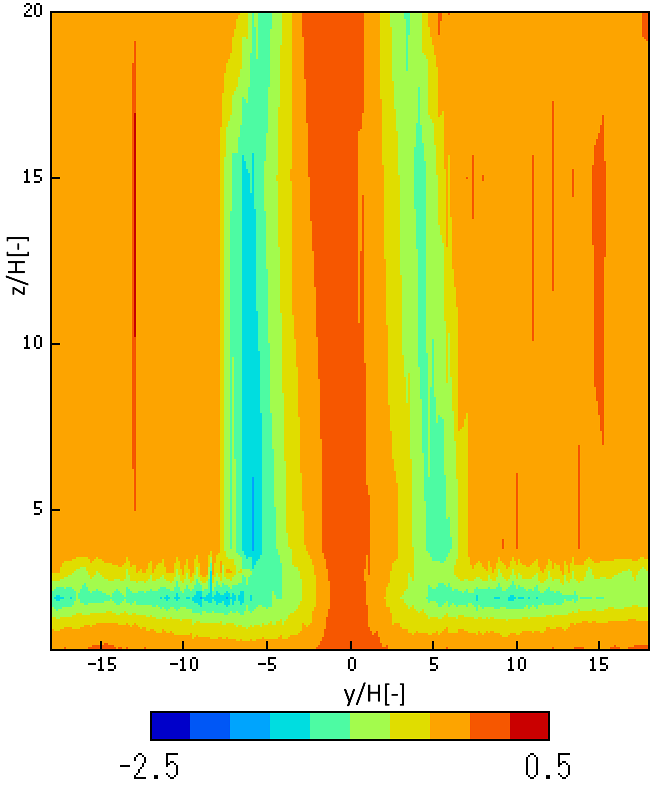


ROUGH SURFACE

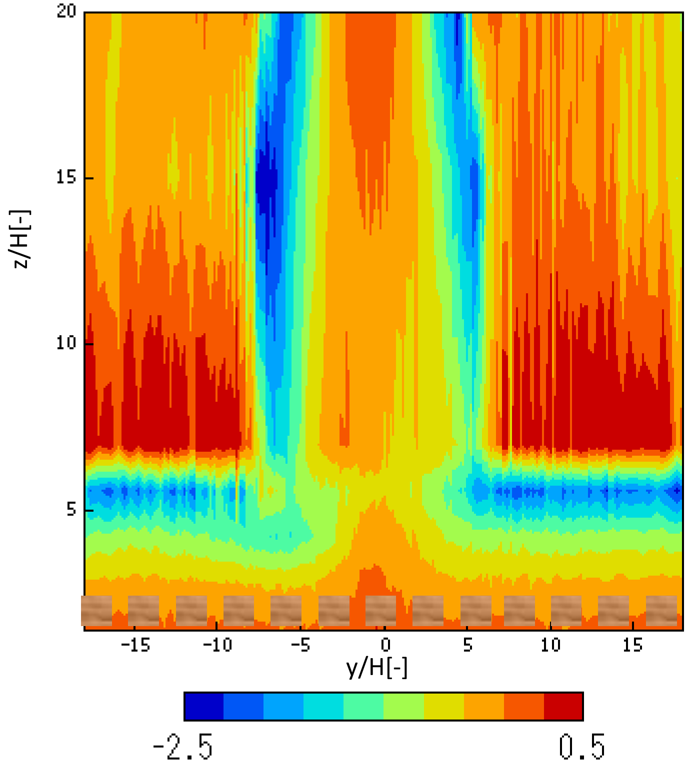


WITH SPIRE (B position)
Skewness

SMOOTH SURFACE

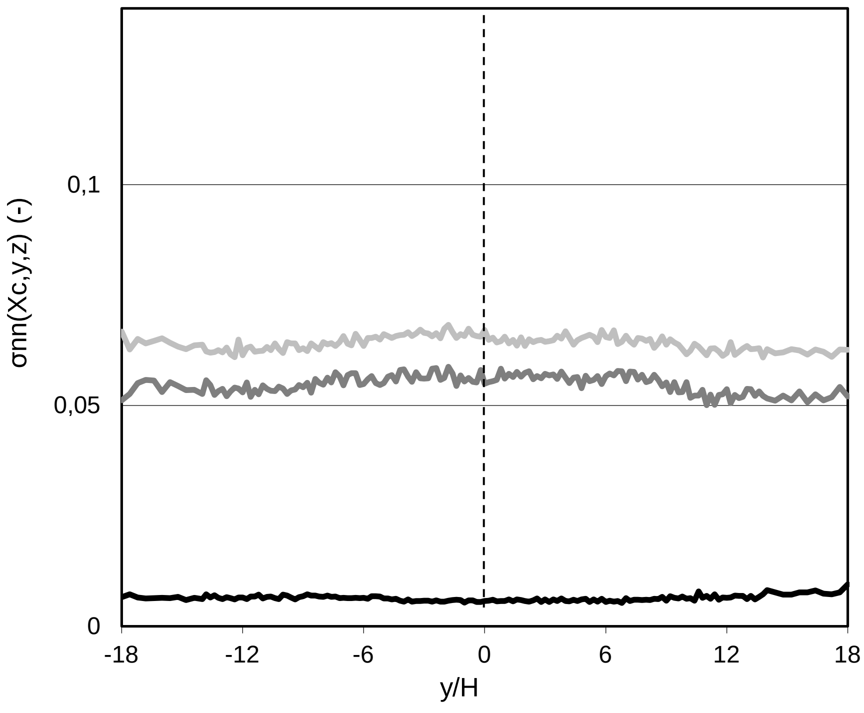


ROUGH SURFACE

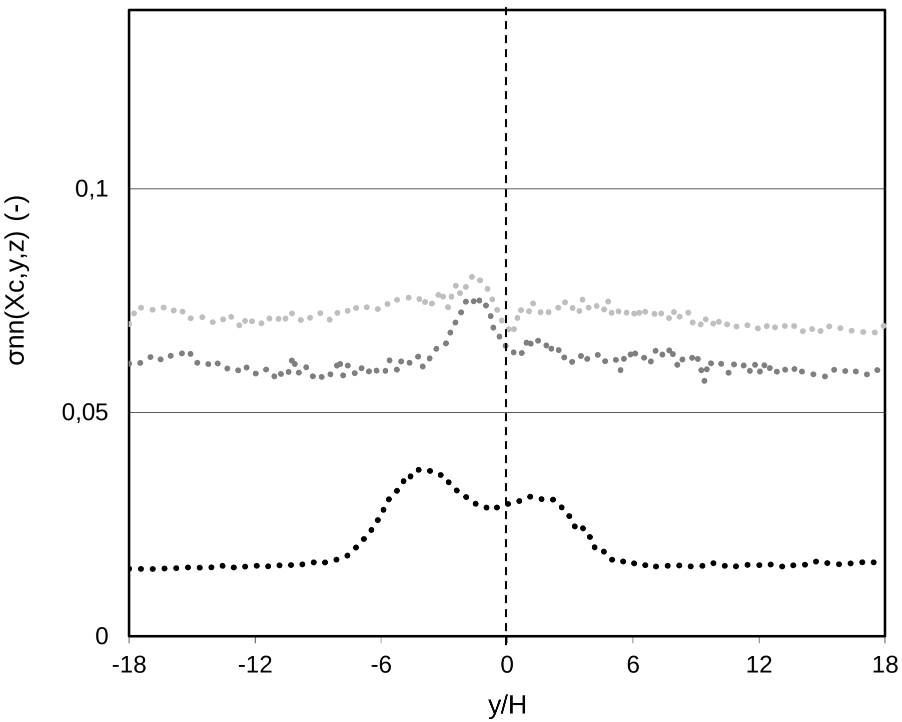


C

Smooth Surface(C position)
Standard deviation (x,y=-18,z=20H)

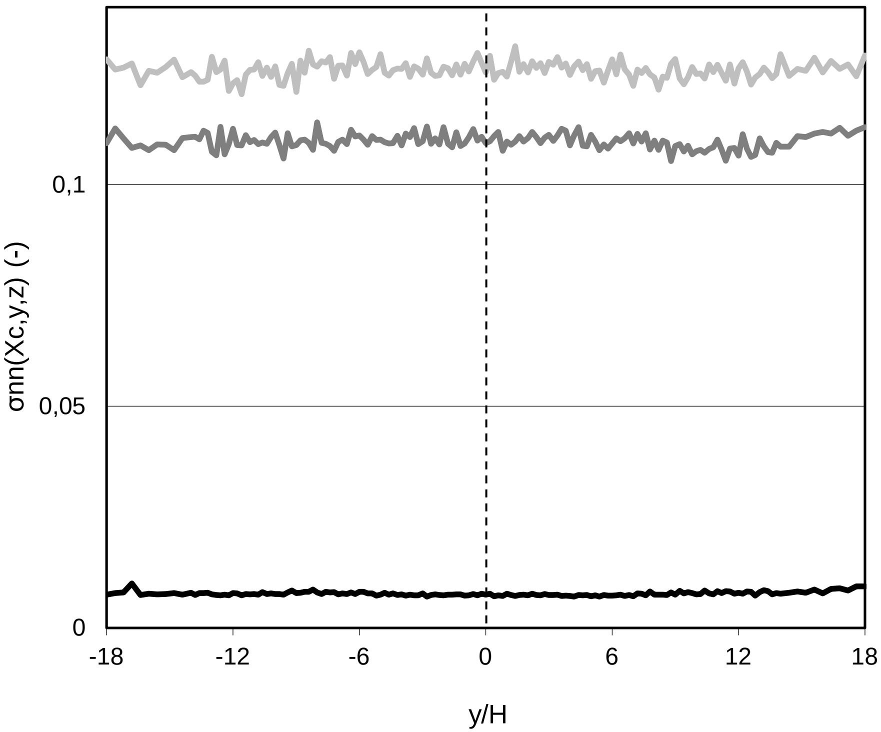


(a) Smooth surface



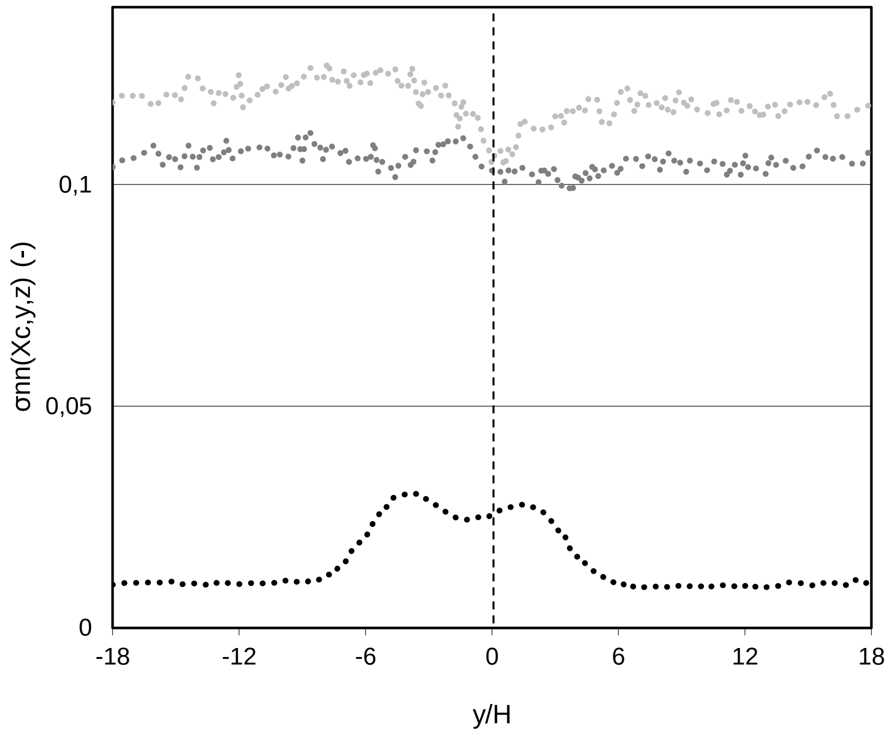
(a) Smooth surface

Rough Surface(C position)
Standard deviation (x,y=-18,z=20H)



(b) Rough surface

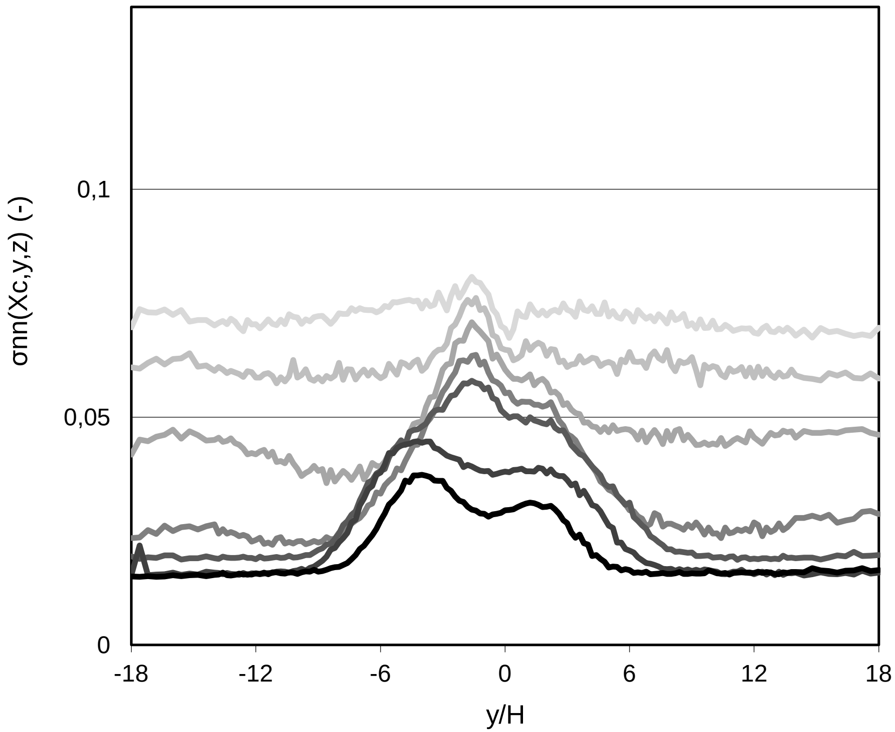
without a spire, z = 0.25δ (=1.65H)
without a spire, z = 0.50δ (=3.30H)
without a spire, z = 20H



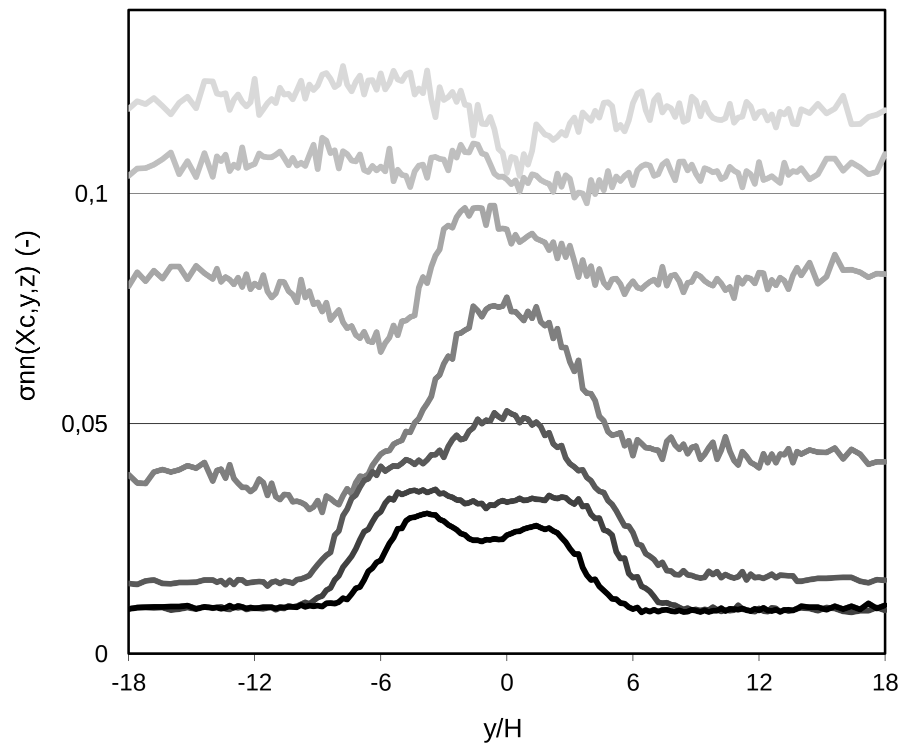
(b) Rough surface

with a spire, z = 0.25δ (=1.65H)
with a spire, z = 0.50δ (=3.30H)
with a spire, z = 20H

WITH SPIRE (C position)_ full heights
Standard deviation (x,y=-18,z=20H)



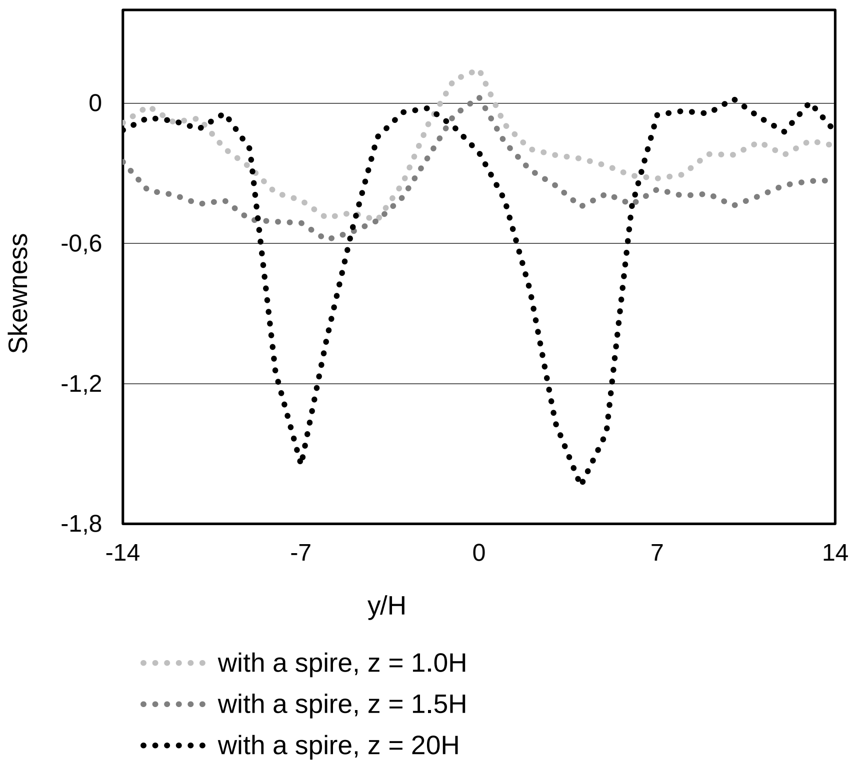
(a) Smooth surface



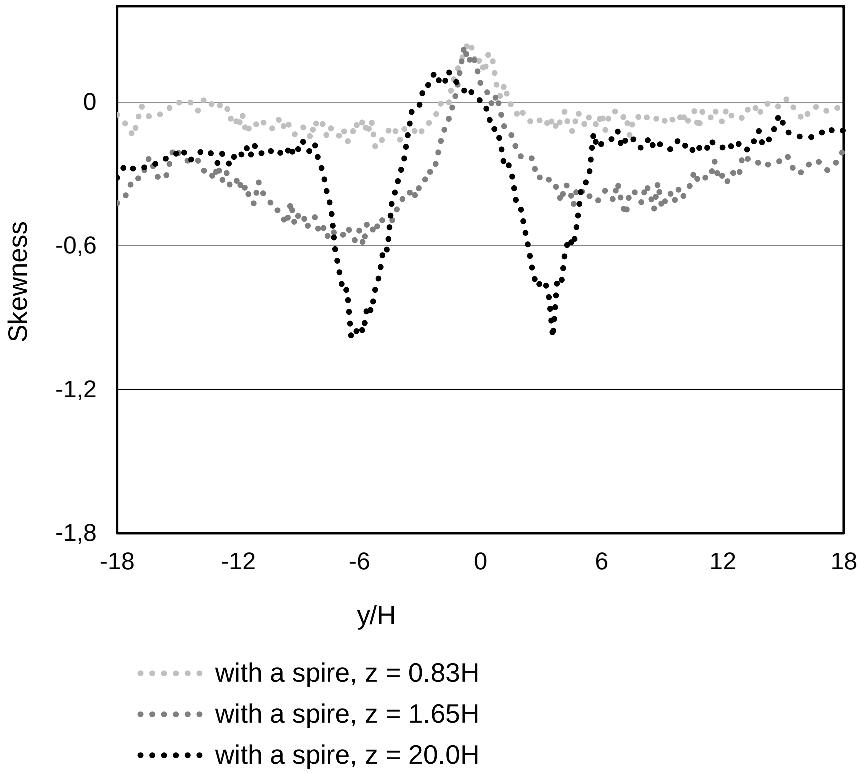
(b) Rough surface

Smooth Surface_ 1 spire (C position) Skewness

Imamura&Atikha (2014)

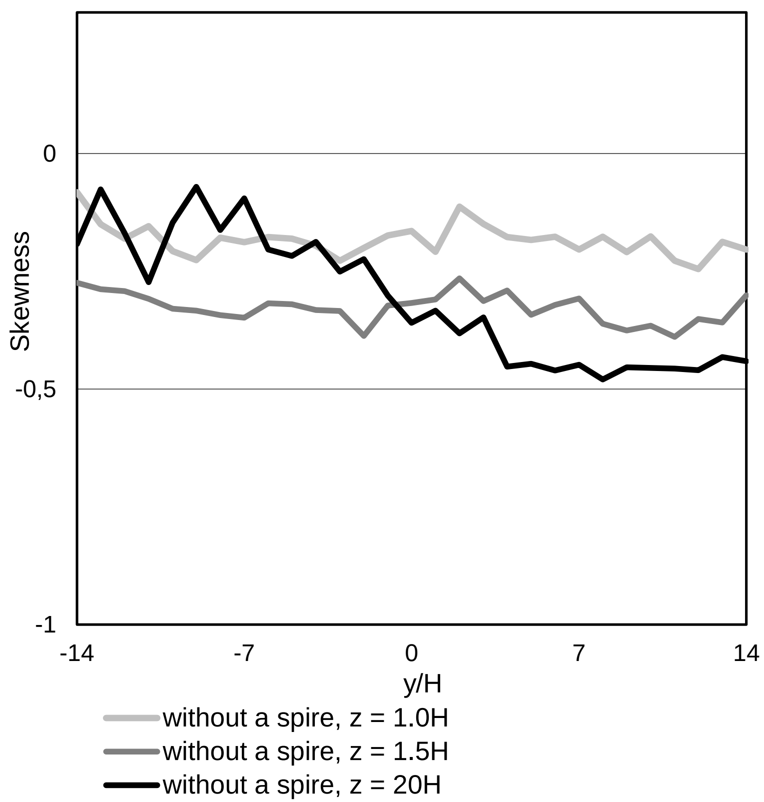


Atikha (2014)

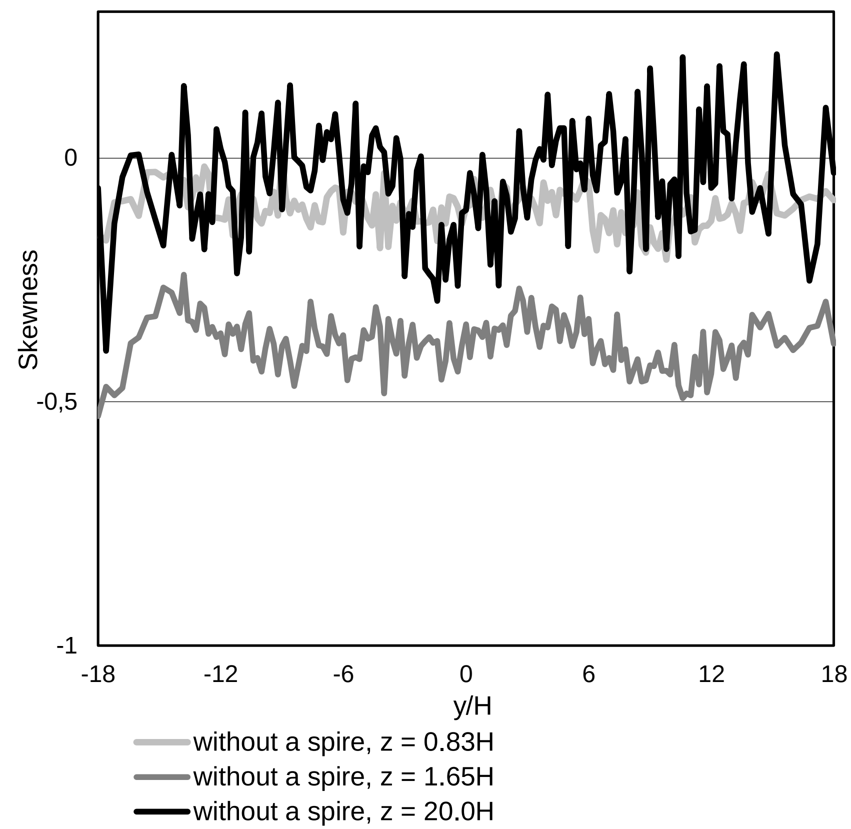


Smooth Surface_ No spire (C position)
Skewness

Imamura&Atikha (2014)

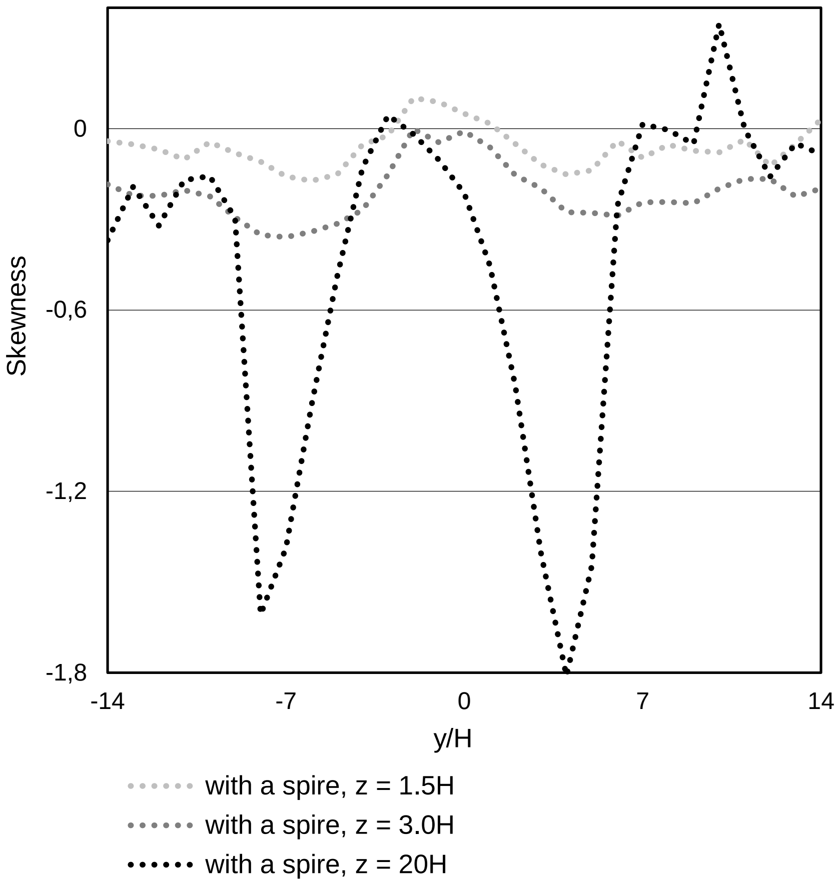


Atikha (2014)

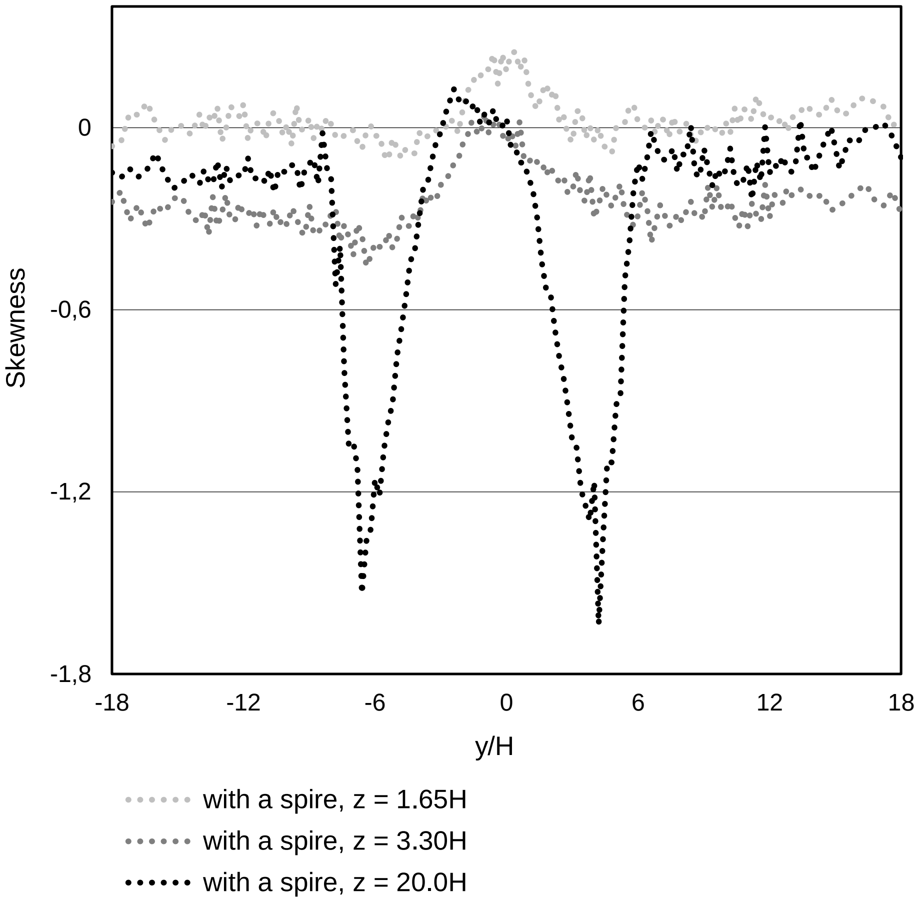


Rough Surface_ 1 spire (C position)
Skewness

Imamura&Atikha (2014)

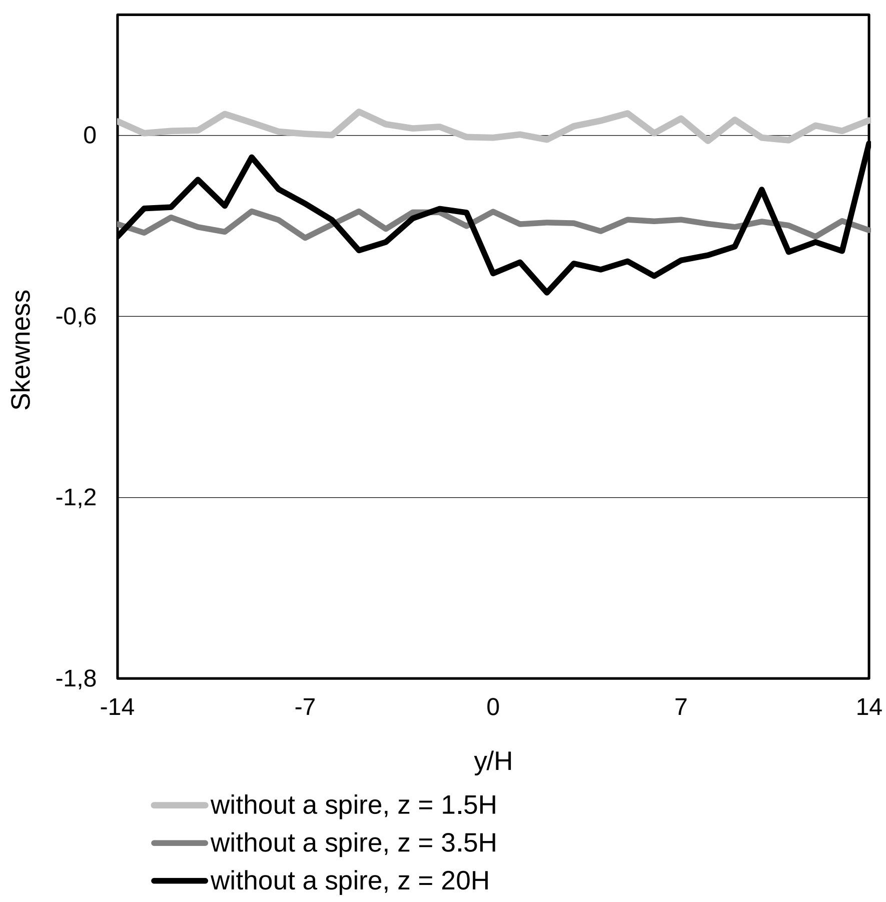


Atikha (2014)

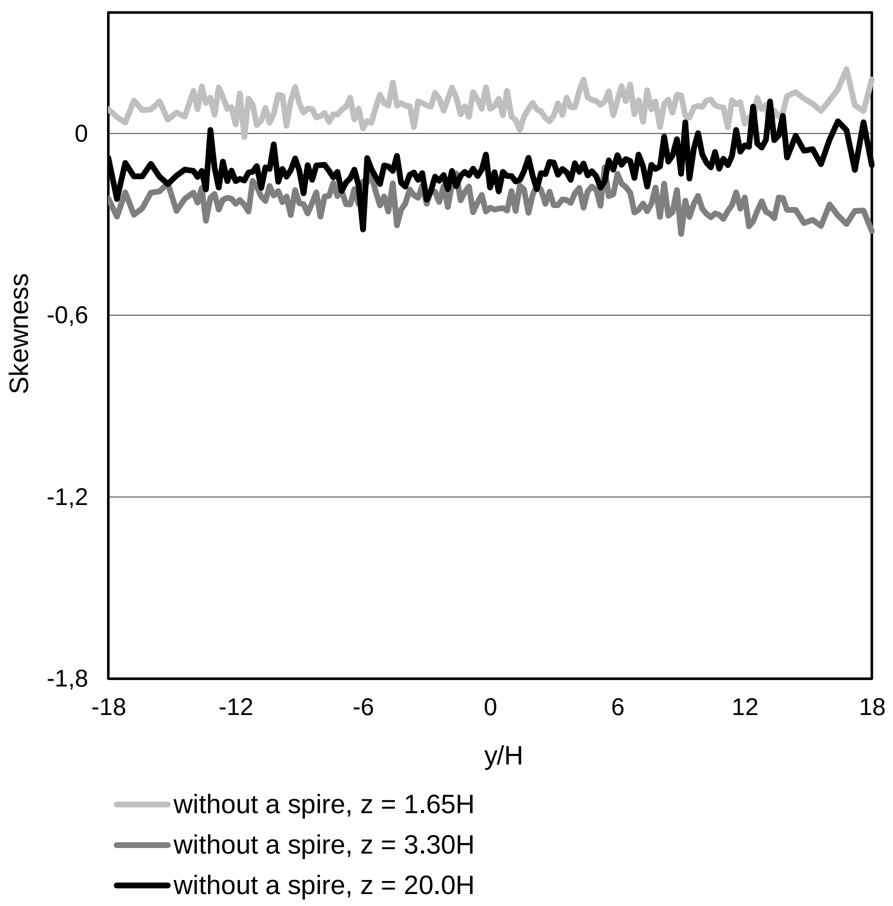


Rough Surface_ No spire (C position)
Skewness

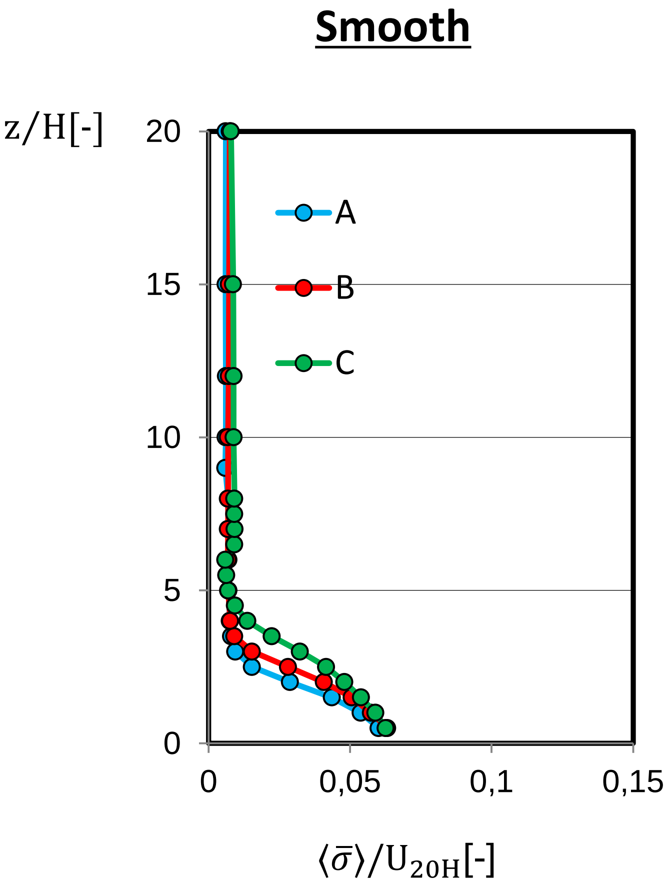
Imamura&Atikha (2014)

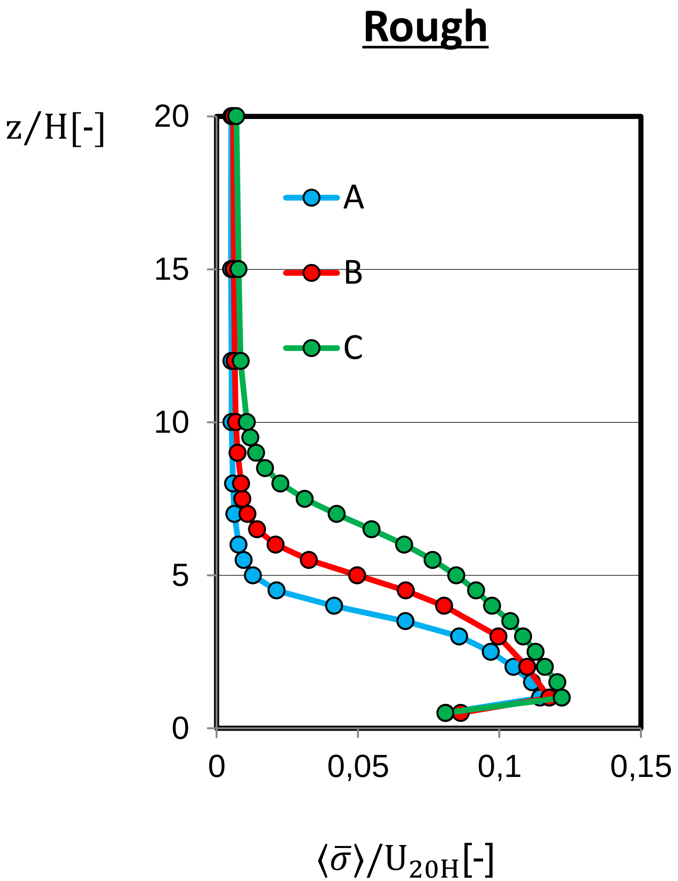


Atikha (2014)

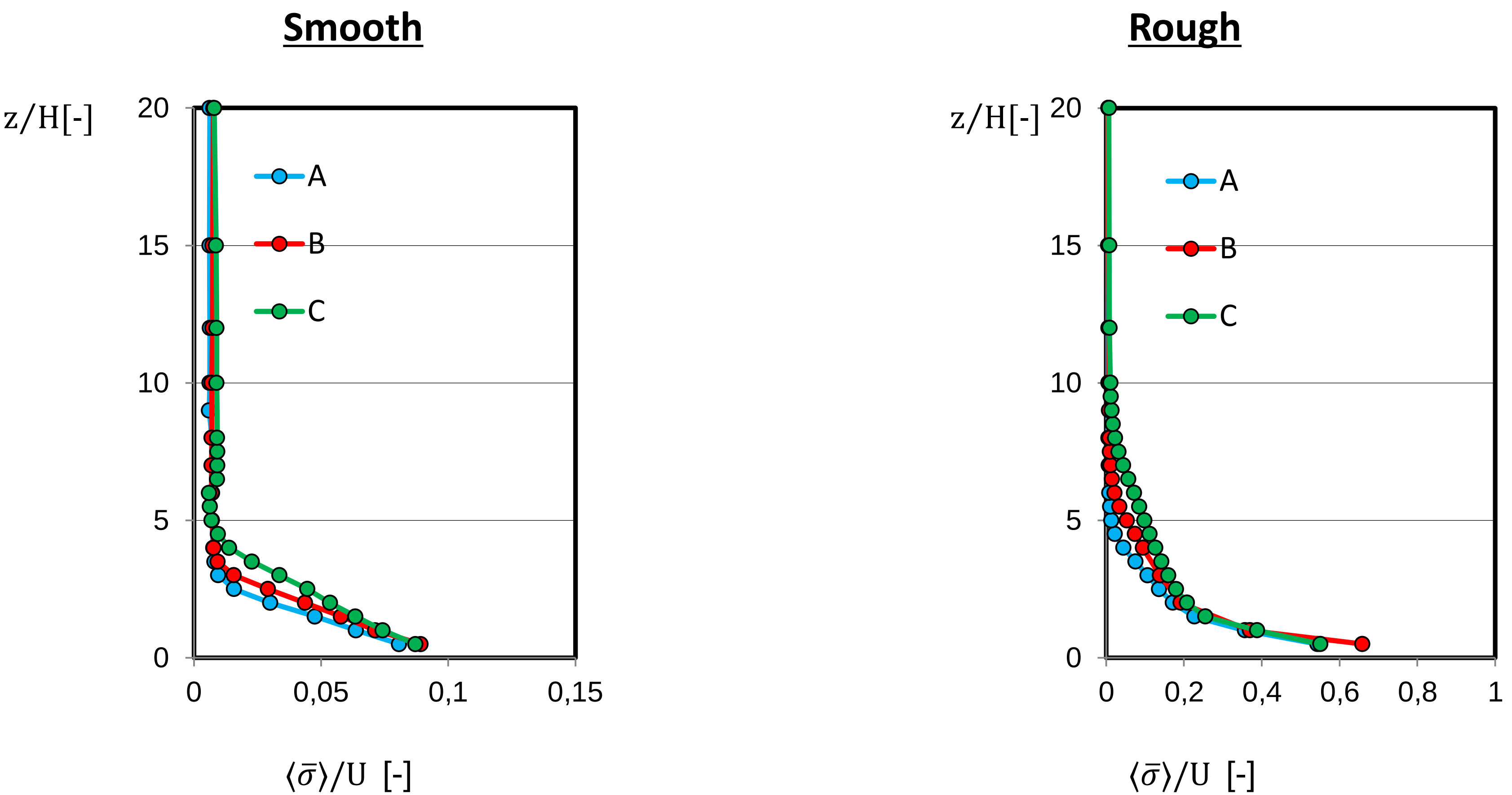


$\langle\bar{\sigma}\rangle/\mathrm{U}_{20\mathrm{H}}$[-]



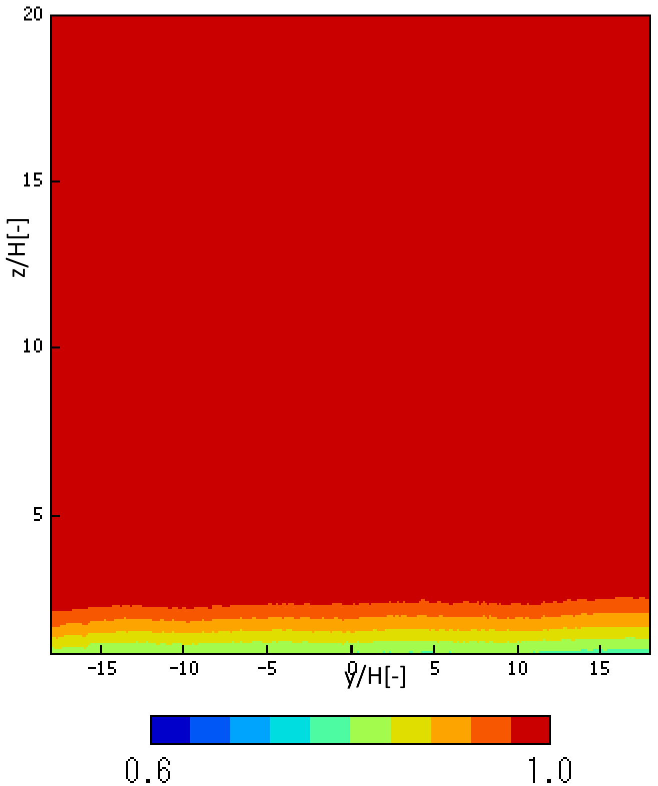


$\langle\bar{\sigma}\rangle/U$ [-]

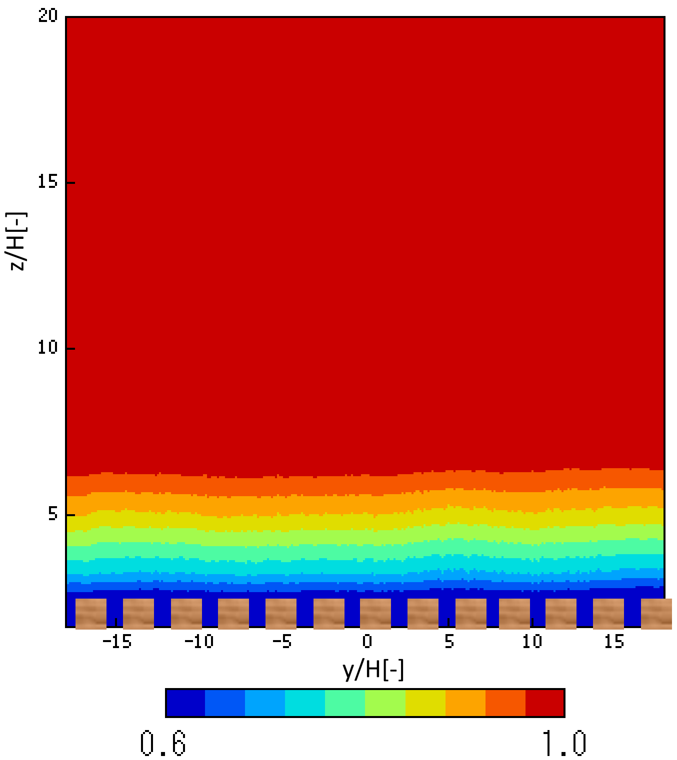


NO SPIRE (C position)
Unn

SMOOTH SURFACE

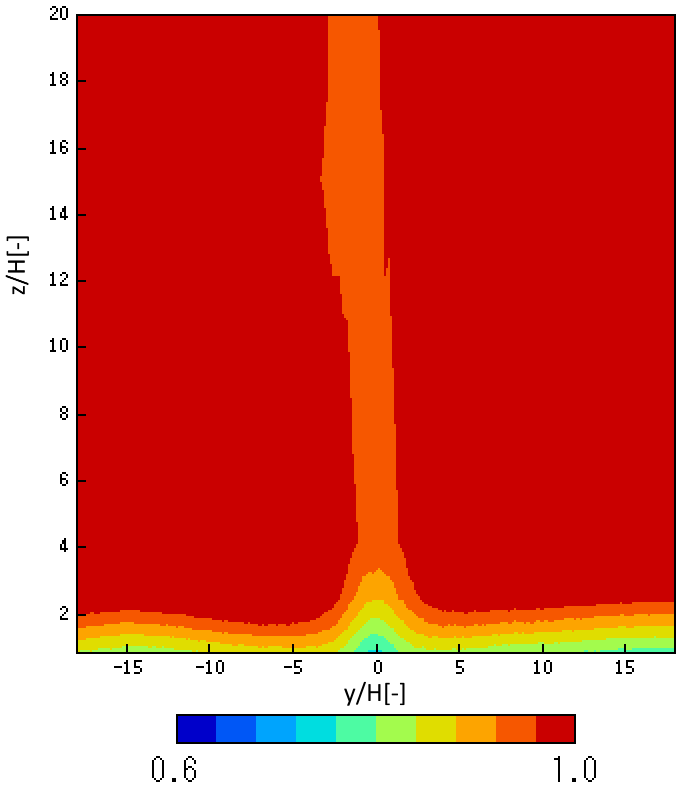


ROUGH SURFACE

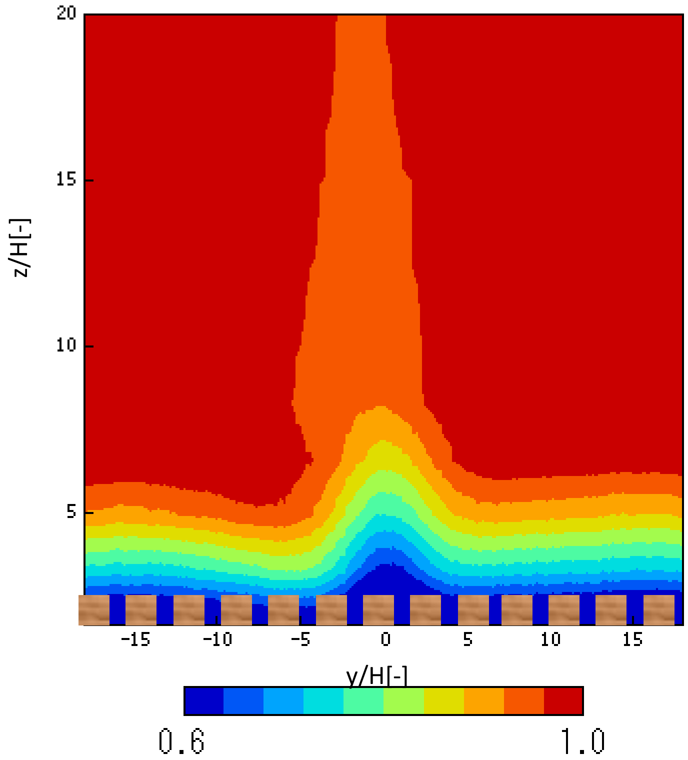


WITH SPIRE (C position)
Unn

SMOOTH SURFACE

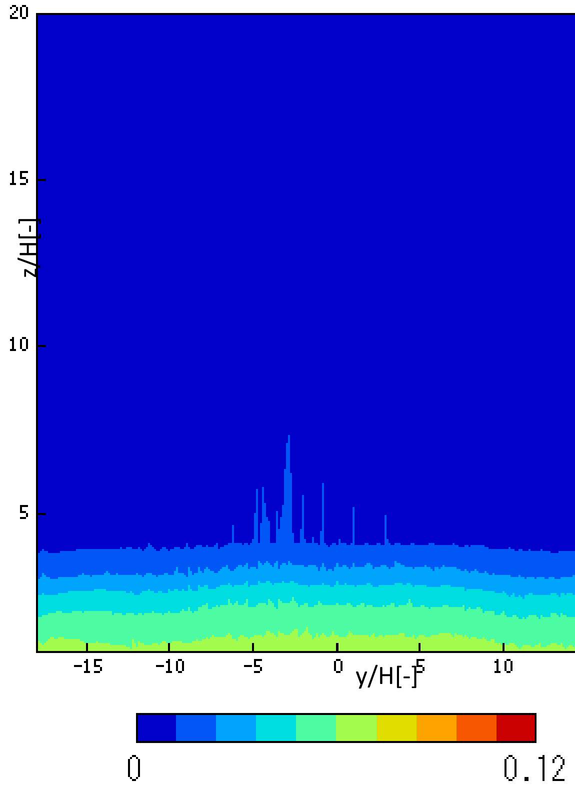


ROUGH SURFACE

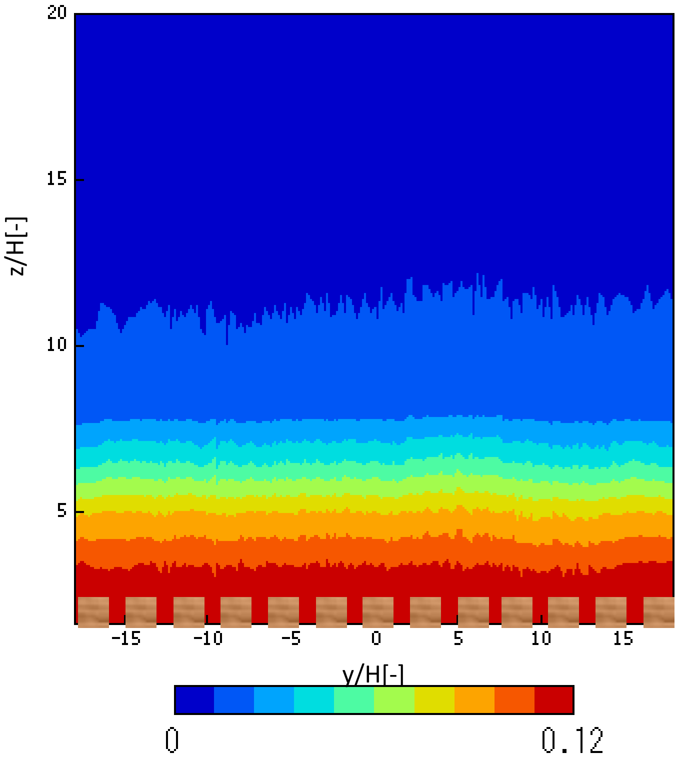


NO SPIRE (C position)
Standard deviation (x,y=-18,z=20H)

SMOOTH SURFACE

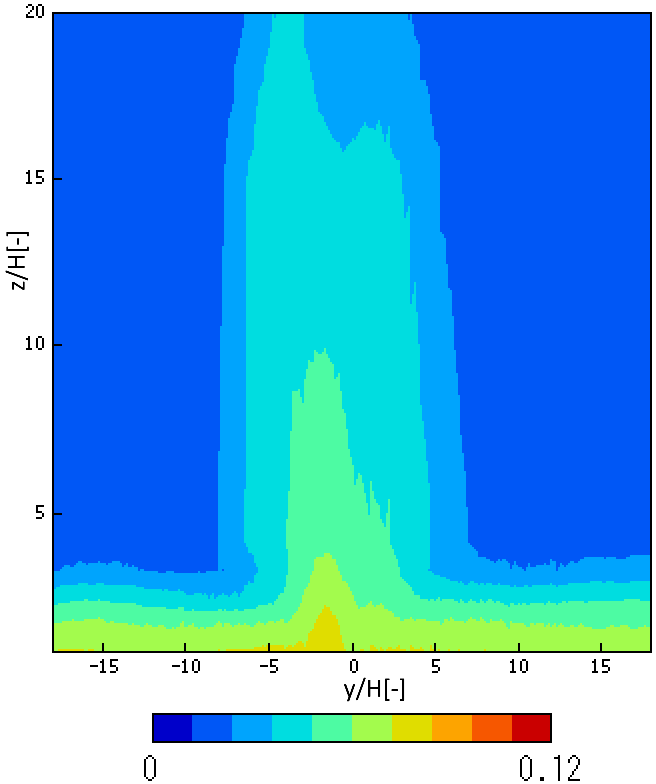


ROUGH SURFACE



WITH SPIRE (C position)
Standard deviation (x,y=-18,z=20H)

SMOOTH SURFACE



ROUGH SURFACE

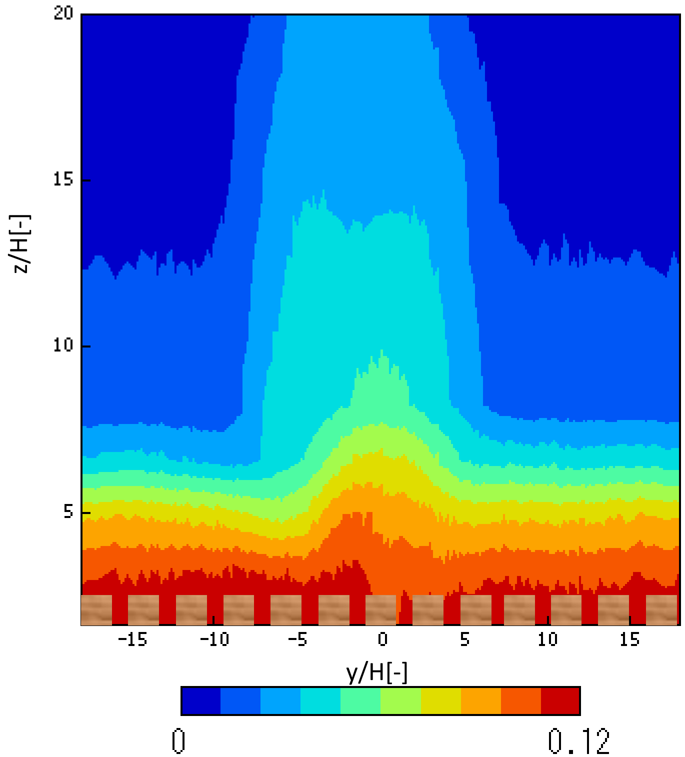
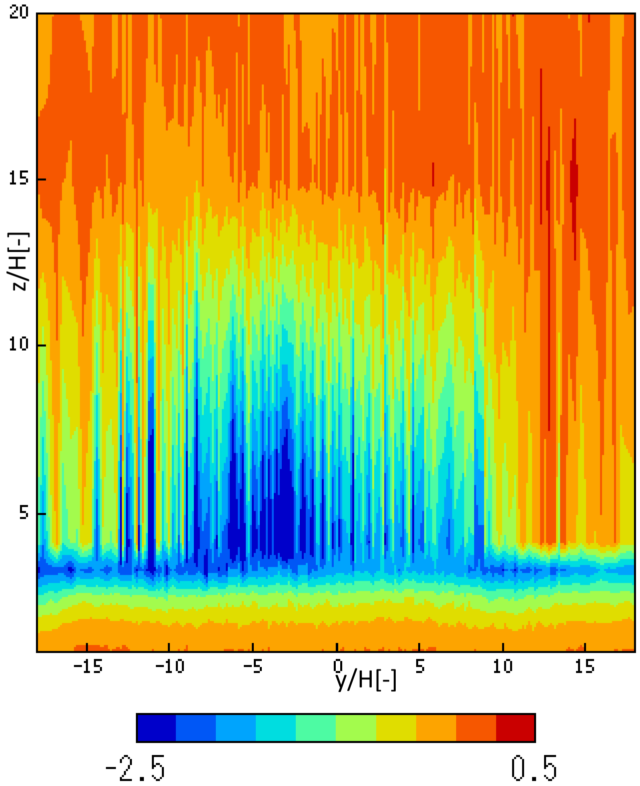


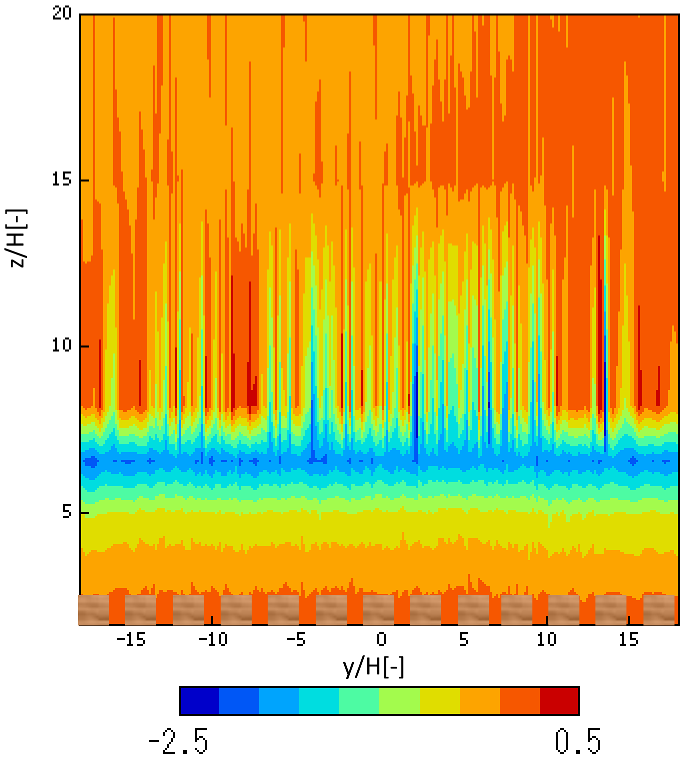
Fig. X_b Spanwise distributions of standard deviation at *C* (x = 135.9*H*)

NO SPIRE (C position)
Skewness

SMOOTH SURFACE

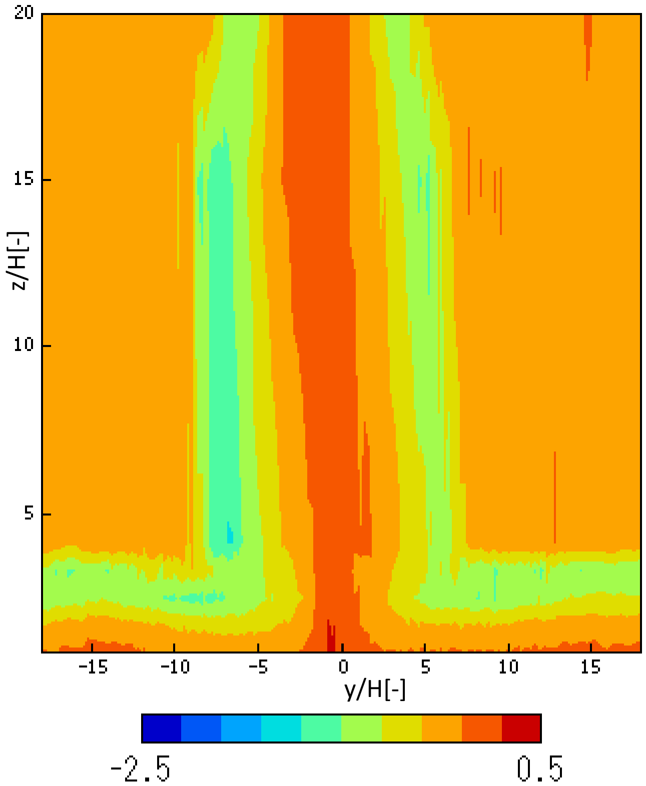


ROUGH SURFACE



WITH SPIRE (C position)
Skewness

SMOOTH SURFACE



ROUGH SURFACE