Open Channel Flows over Gravel and Vegetation Roughness Elements

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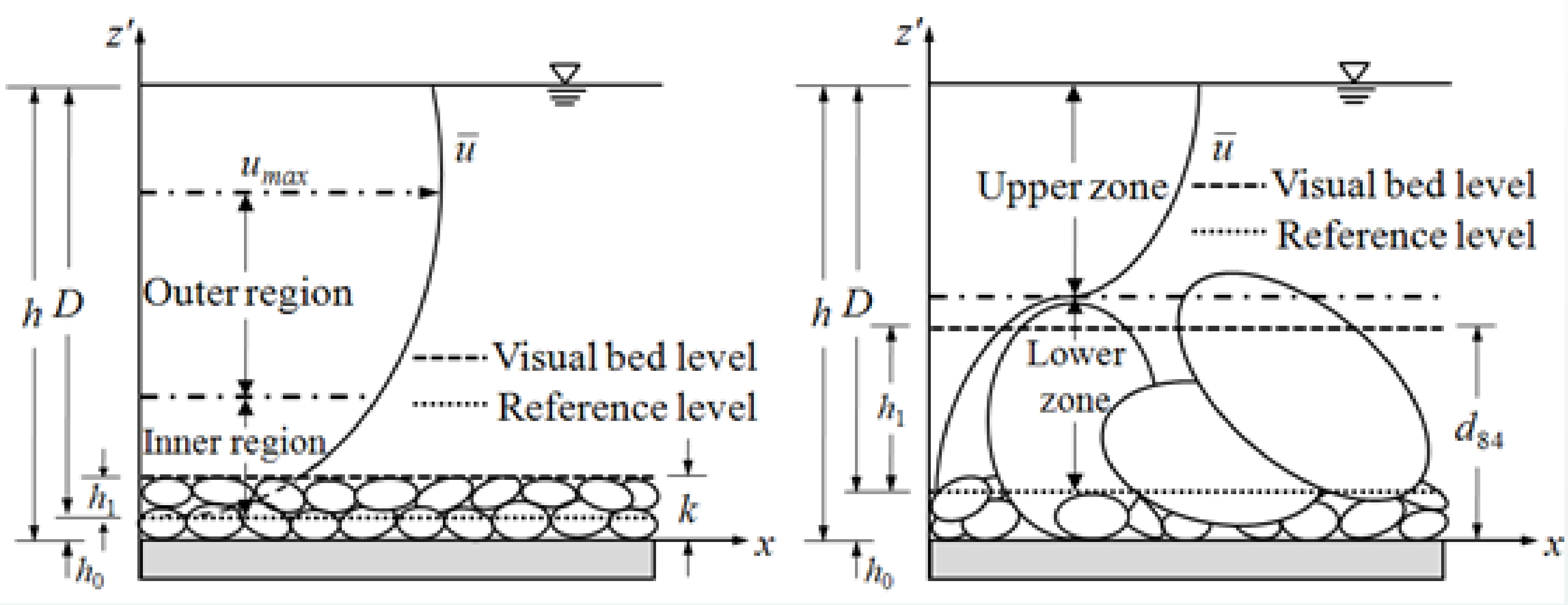
Background

- Gravels and vegetation are commonly used for channel stabilization and naturalization. They contributes to the sustainable development of aquatic environments.
- Vegetation provides food and shelter to many organisms and controls the ecological system in rivers, estuaries and coastal areas.
- Compared to smooth bed channels, gravel and vegetated channels have larger roughness and lower flow carrying capacity.
- It is important to investigate the flow and mixing characteristics of gravel and vegetated channels.



Small to medium scale roughness

Large scale roughness

Velocity Profiles

- Smooth surface

$$\frac{u}{u_*} = \frac{1}{\kappa}\ln\left(\frac{u_* z}{\nu}\right) + 8.5$$

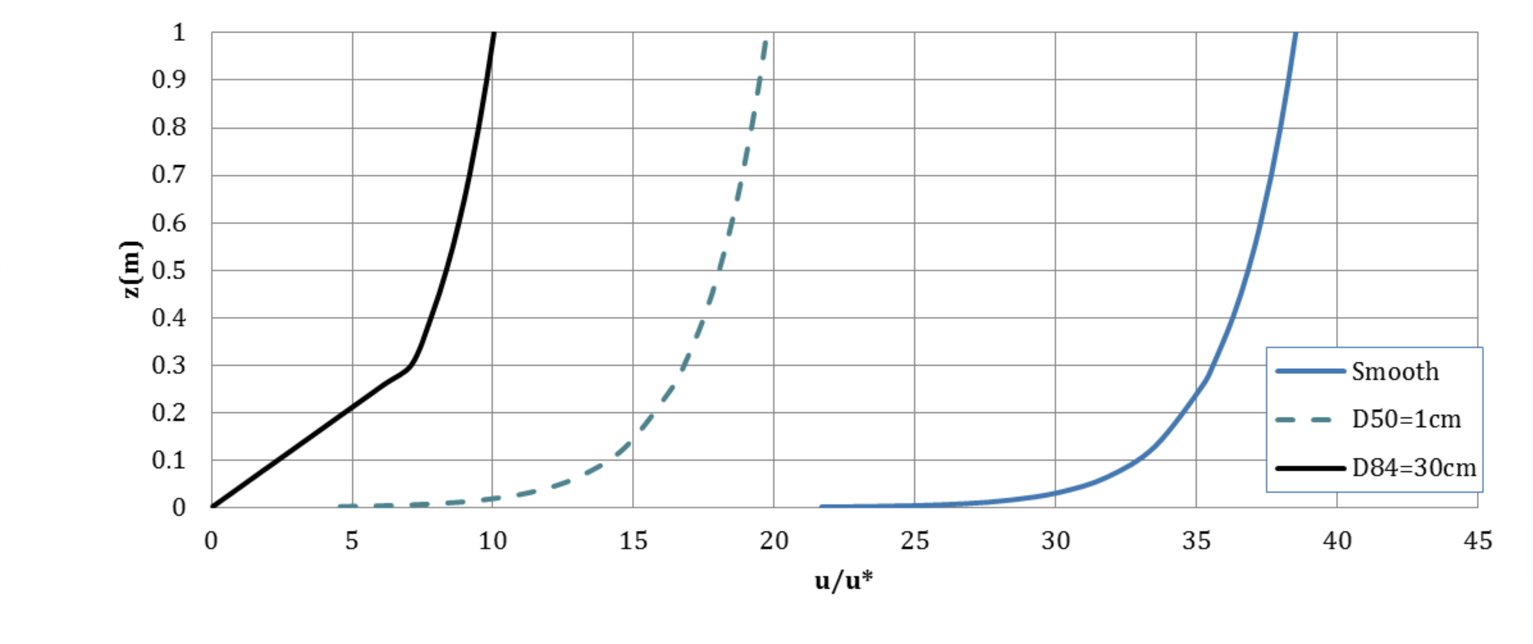
- Rough surface (small scale roughness)

$$\frac{u}{u_*} = \frac{1}{\kappa}\ln\left(\frac{z}{k_s}\right) + B_r = \frac{1}{\kappa}\ln\left(\frac{z}{z_0}\right)$$

$$k_s \sim D_{50} \sim 30z_0\,,\ \ B_r \sim 8.5,$$

$$\frac{U}{u_*} = \frac{1}{\kappa}\ln\left(\frac{h}{ez_0}\right)$$

- U=mean velocity
- Rough surface - Logarithmic linear relationship is maintained, mean velocity is reduced.
- Very rough surface (large scale roughness) - Logarithmic linear relationship is not followed.



z(m)
u/u*
Smooth
D50=1cm
D84=30cm

Manning coefficient

Manning equation

$$U = \frac{1}{n} R_h^{2/3} \sqrt{s_f}$$

$$u_* = \sqrt{g R_h s_f}$$

$$\frac{U}{u*} = \frac{1}{n} \frac{R_h^{1/6}}{\sqrt{g}}$$

Velocity profile

$$\frac{U}{u_*} = \frac{1}{\kappa} \ln\left(\frac{h}{ez_0}\right) = \frac{1}{n} \frac{R_h^{1/6}}{\sqrt{g}}$$

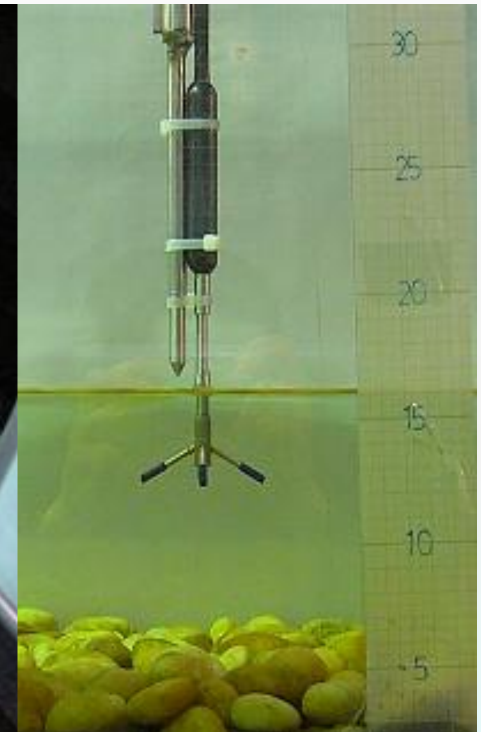
$$R_h \sim h$$

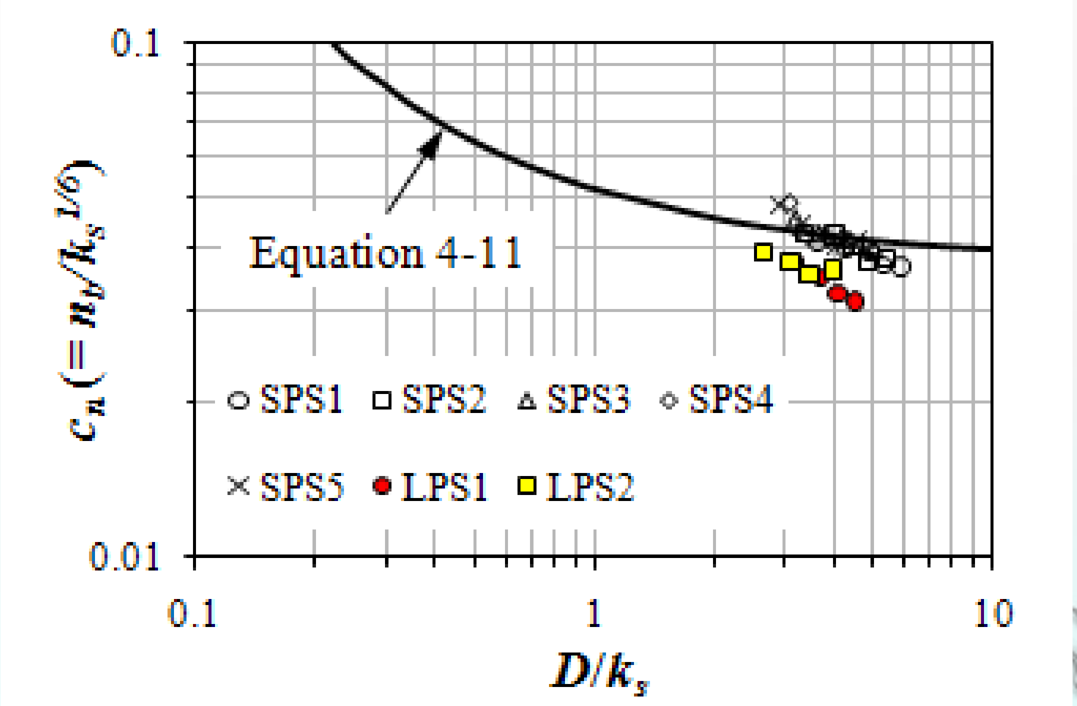
$$n = \frac{\kappa}{\sqrt{g}} \frac{h^{1/6}}{\ln\left(h/ez_0\right)}$$

$$\frac{n}{k_s^{1/6}} = \frac{\kappa}{\sqrt{g}} \frac{(h/k_s)^{1/6}}{\ln\left(11 \frac{h}{k_s}\right)}$$

$$\ln\left(\frac{h}{ez_0}\right) \sim 2.15 \left(\frac{h}{ez_0}\right)^{1/6}$$

$$n = \frac{\kappa}{2.15\sqrt{g}} (ez_0)^{1/6} \sim 0.07 z_0^{1/6}$$


30
25
20
15
10
5


0.1
0.01
0.1
1
10
Equation 4-11
SPS1
SPS2
SPS3
SPS4
SPS5
LPS1
LPS2
$c_n (= n_t / k_s^{1/6})$
D/k_s

Steep rough channels

- Form drag is important
- Empirical formulas are not universal
- Rice (1998)

$$n = 0.029(D_{50}S_0)^{0.147}$$

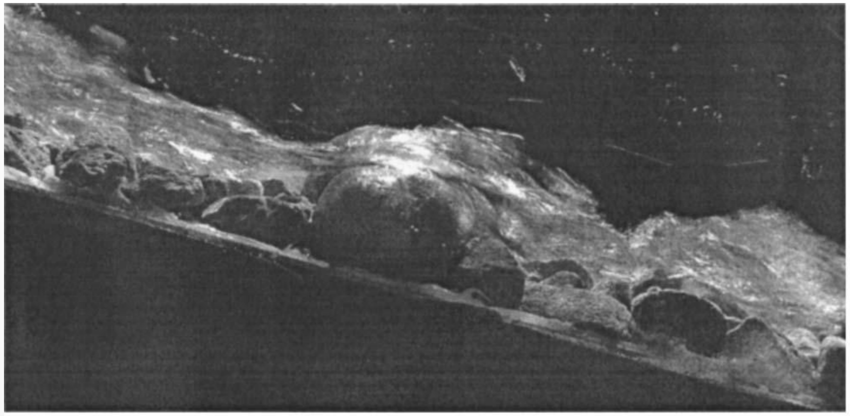
- Zimmerman (2010)

$$n = \frac{\kappa}{2.84\sqrt{g}} \frac{h^{1/6}}{\log\left(8.5h/D_{84}\right)}$$

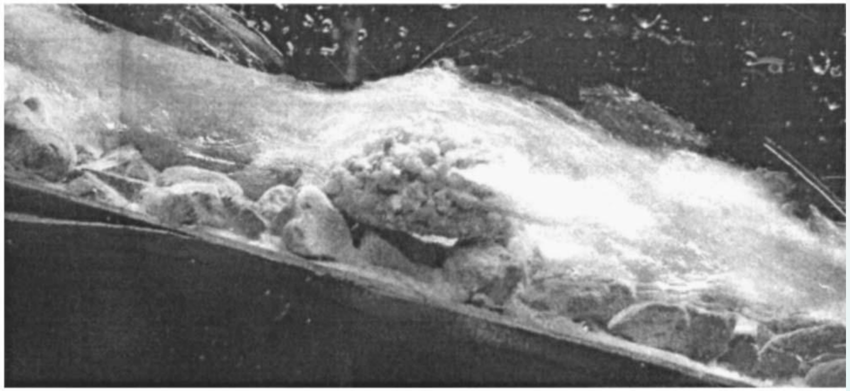
- Many other formulas have been proposed.

Paglliara and Chiavaccini (2006)

- $n=0.064(1+\Gamma)^{c}(D_{50}s_0)^{0.11}$
- Γ=boulder concentration



(a)



(b)

Numerical model using Body force (drag force) method

- Representing the resisting force due to roughness elements by a body force (or drag force)

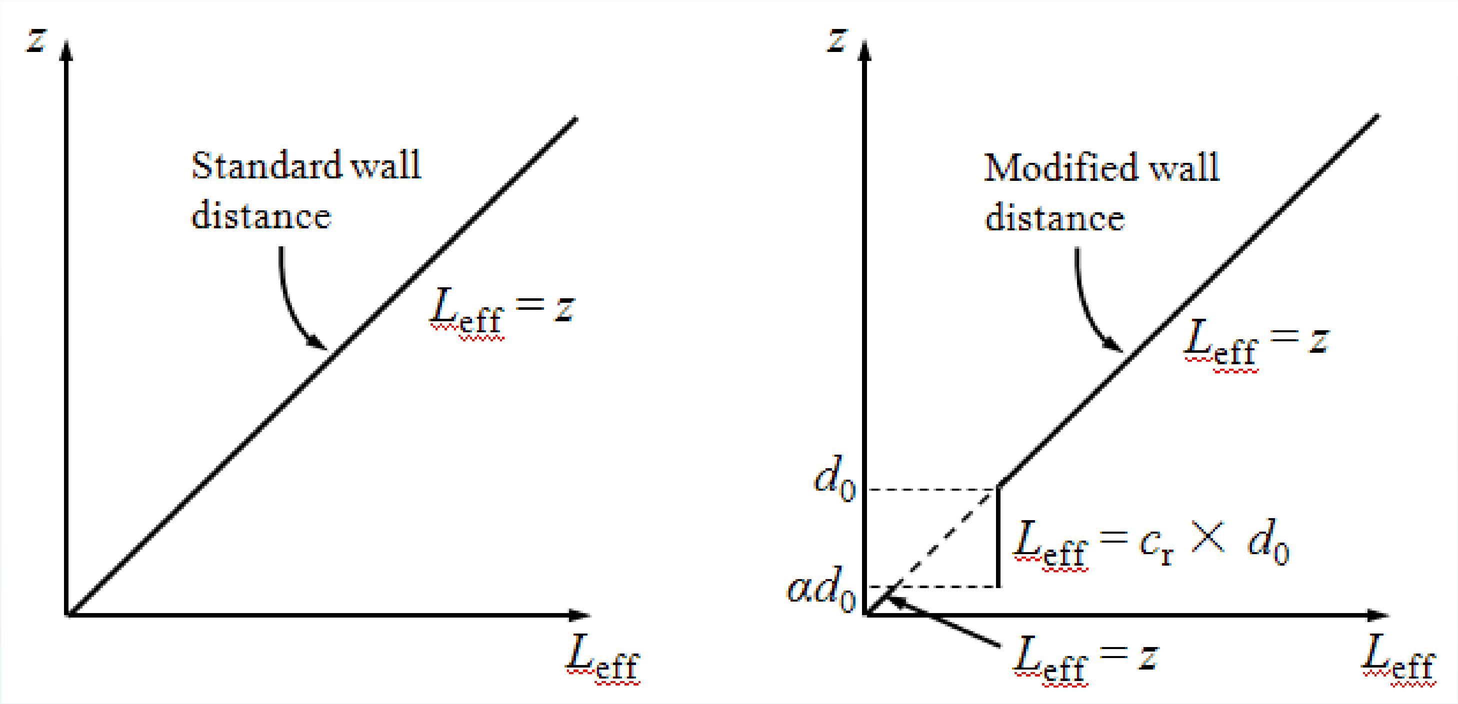
$$\frac{\partial \bar{u}}{\partial t} + v\frac{\partial \bar{u}}{\partial y} + w\frac{\partial \bar{u}}{\partial z} = \frac{1}{1-A_p}\frac{\partial}{\partial z}\left[(1-A_p)\frac{\partial \tau_{xz}}{\partial z}\right] + g_x - \frac{1}{\rho}\frac{F_x}{(1-A_p)}$$

$$\frac{F_x}{1-A_p} = \frac{1}{2(1-A_p)}\rho C_d C_s b_s N \bar{u}_1^2 = \frac{1}{2}\rho f_{rk}\bar{u}_1^2$$

- Spalart-Allmaras turbulence closure is used.

Turbulence length scale $d=d_{eff}$

- Small scale roughness (SWD, standard wall distance model) :
  - $d_{eff} = z$
- Large scale roughness (MWD, modified wall distance model)
  - $d_{eff} = c_r \times d_0$ when $z < d_0$
  - $d_{eff} = z$ when $z > d_0$ or $z < \alpha d_0$

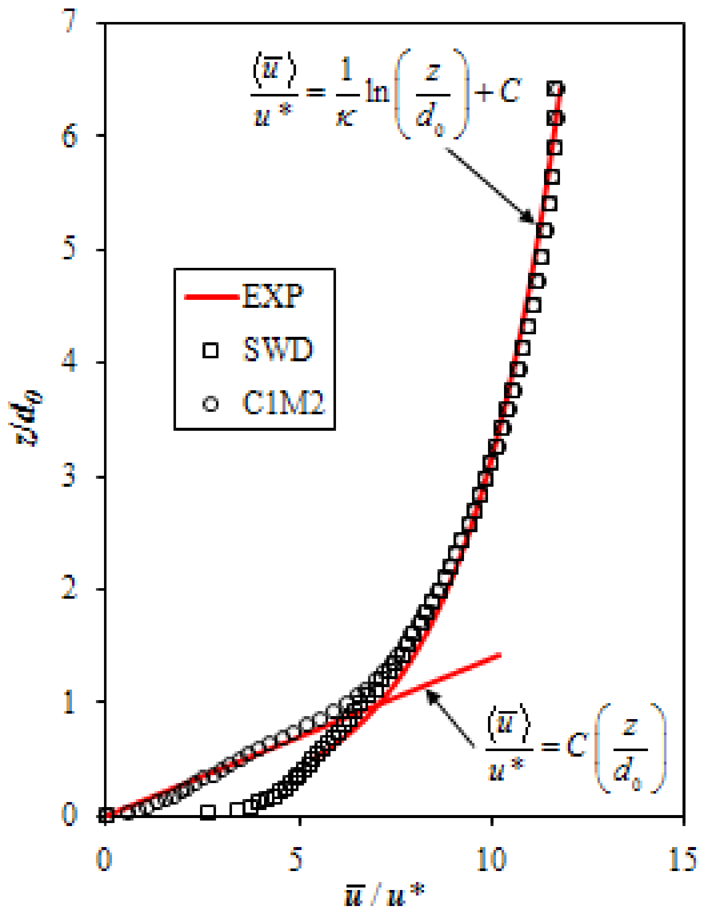


z
Standard wall
distance
$L_{eff} = z$
L_{eff}
z
Modified wall
distance
$L_{eff} = z$
d_0
$L_{eff} = c_r \times d_0$
αd_0
$L_{eff} = z$
L_{eff}

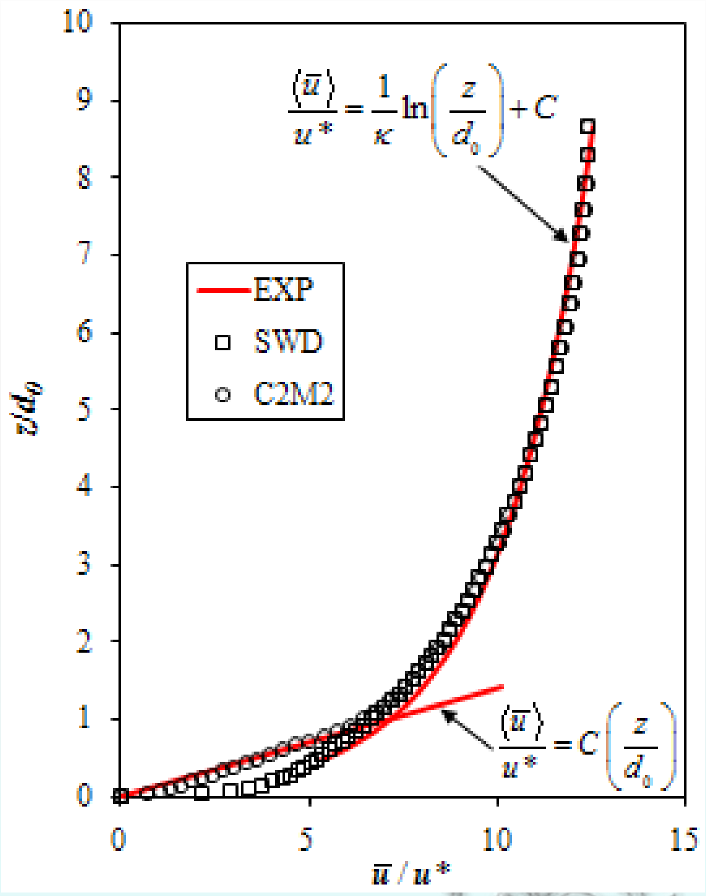
Open-channel flows over large-scale roughness elements

- Expts. by Nikora et al. (2001).

Case	Q (l/s)	S_0	D (cm)	d_0 (cm)	u^* (cm/s)	Re^+ (= u^*k/ν)
1	48.9	0.0032	13.5	2.1	6.5	1,365
2	92.0	0.0031	18.2	2.1	7.7	1,617



$\frac{\langle \overline{u} \rangle}{u^*} = \frac{1}{\kappa} \ln\left(\frac{z}{d_0}\right) + C$
$\frac{\langle \overline{u} \rangle}{u^*} = C\left(\frac{z}{d_0}\right)$
EXP
SWD
C1M2
z/d0
$\overline{u} / u^*$

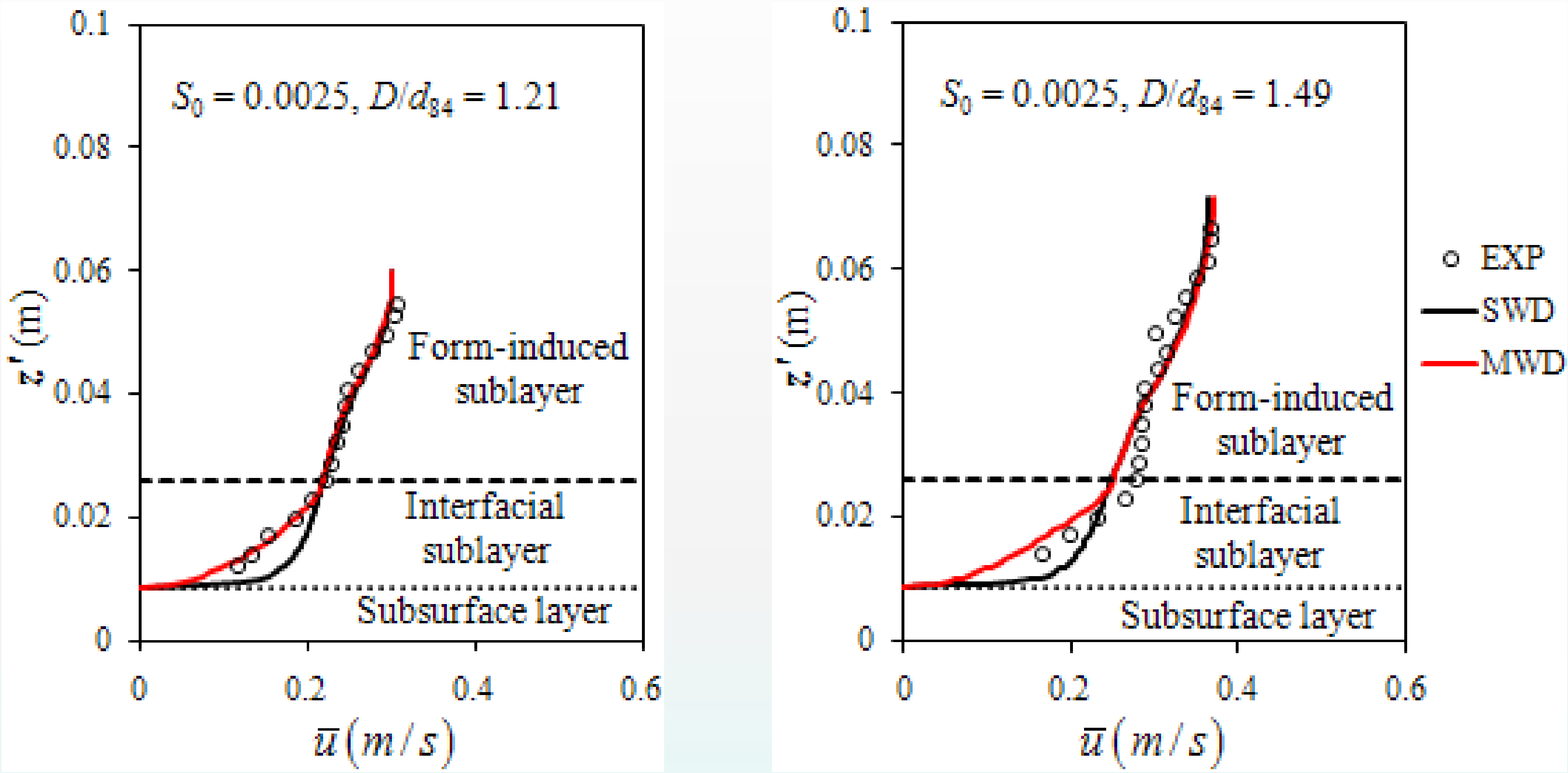


$\frac{\langle \overline{u} \rangle}{u^*} = \frac{1}{\kappa} \ln\left(\frac{z}{d_0}\right) + C$
$\frac{\langle \overline{u} \rangle}{u^*} = C\left(\frac{z}{d_0}\right)$
EXP
SWD
C2M2
z/d0
$\overline{u} / u^*$

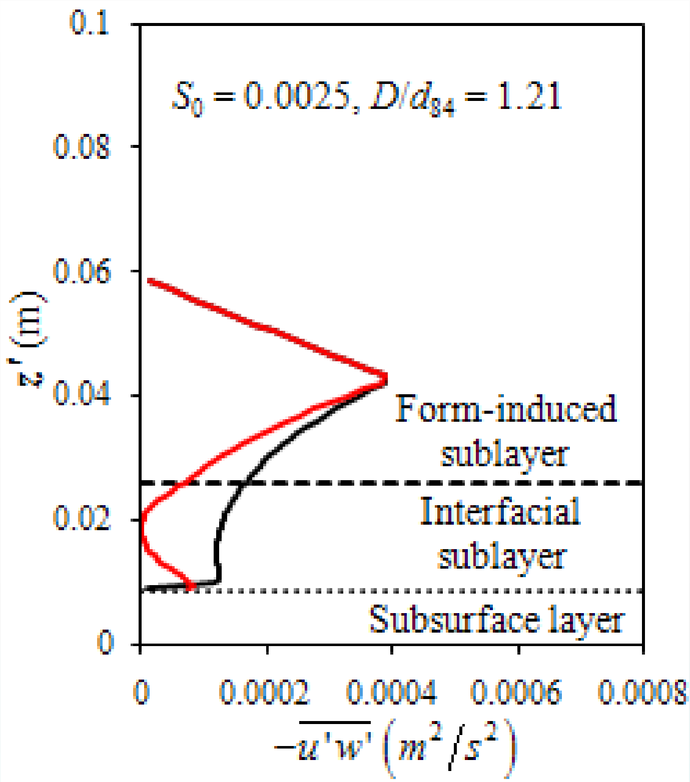
Expts. by Ferro and Baiamonte (1994)

Bed shape	*nc*	*Γ* (%)	d_{50} (mm)	d_{84} (mm)	d_{90} (mm)
Ground layer	0	0.0	23.8	26.0	26.5
IV	40	23.5	24.1	42.1	45.0

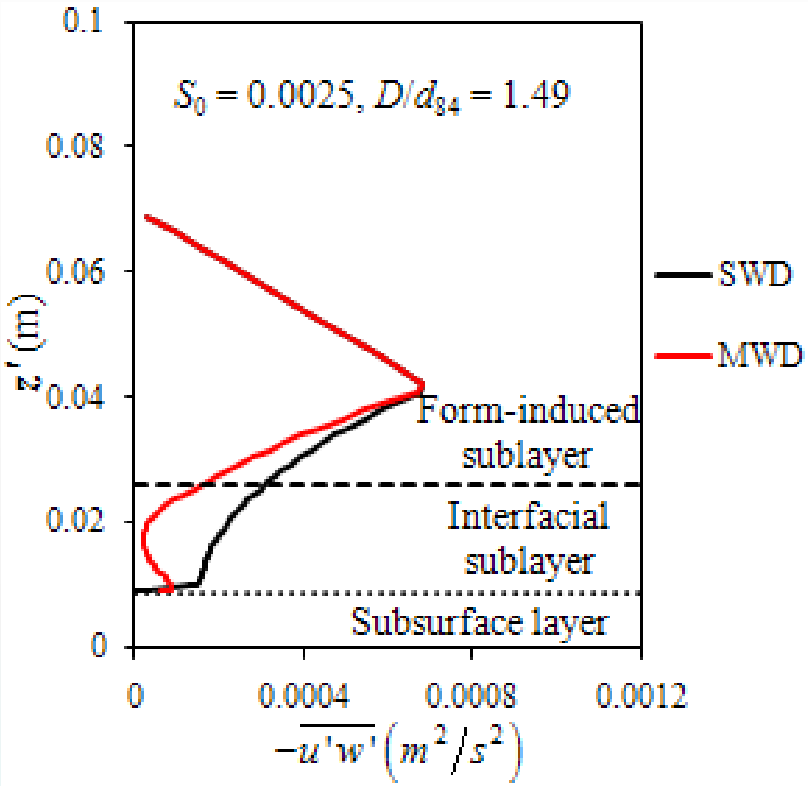
Case	*Q* (L/s)	*D* (m)	D/d_{50}	Fr	Re	*u** (cm/s)
1	4.5	0.051	2.12	0.21	28,421	3.27
2	10.0	0.063	2.61	0.34	61,712	3.57



$S_0 = 0.0025$, $D/d_{84} = 1.21$
Form-induced sublayer
Interfacial sublayer
Subsurface layer
z' (m)
$\bar{u}\,(m/s)$
$S_0 = 0.0025$, $D/d_{84} = 1.49$
Form-induced sublayer
Interfacial sublayer
Subsurface layer
z' (m)
$\bar{u}\,(m/s)$
EXP
SWD
MWD



$S_0 = 0.0025, D/d_{84} = 1.21$
z' (m)
0.1
0.08
0.06
0.04
0.02
0
Form-induced sublayer
Interfacial sublayer
Subsurface layer
0
0.0002
0.0004
0.0006
0.0008
$-\overline{u'w'}\ (m^2/s^2)$

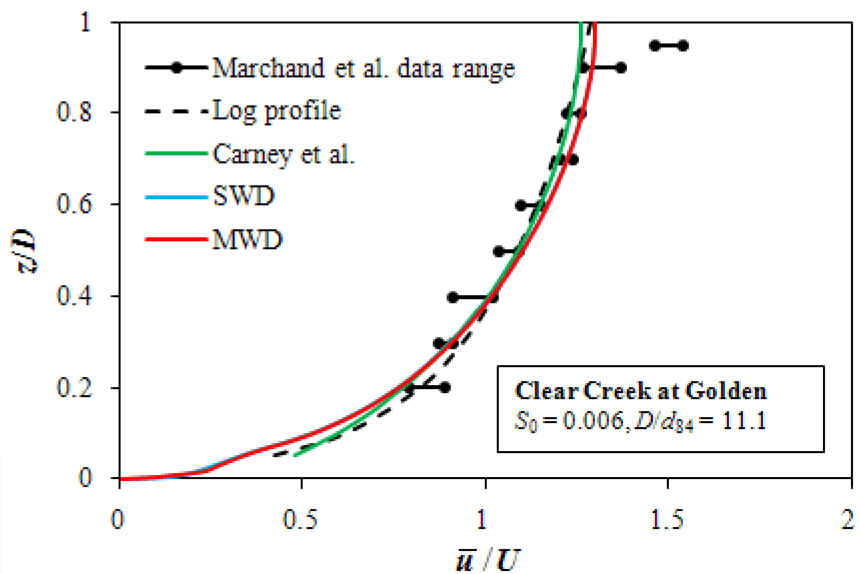


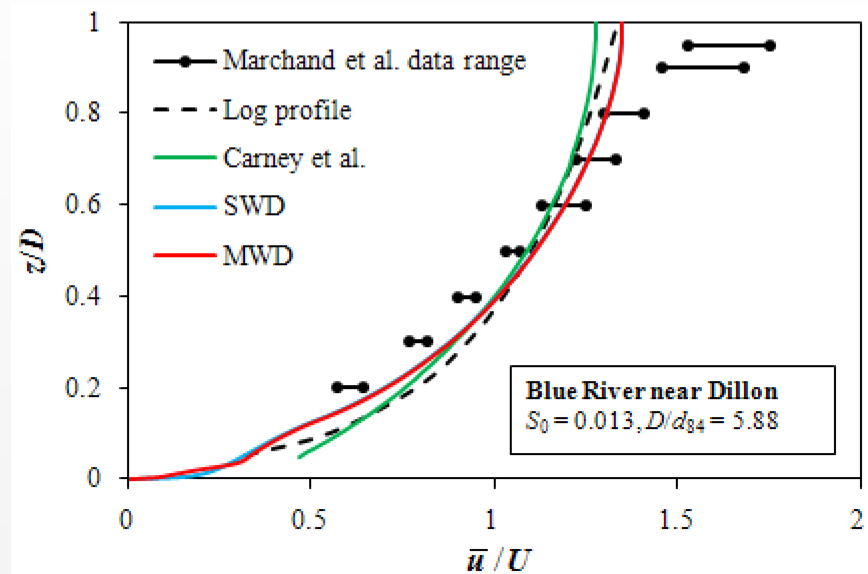
$S_0 = 0.0025, D/d_{84} = 1.49$
z' (m)
0.1
0.08
0.06
0.04
0.02
0
Form-induced sublayer
Interfacial sublayer
Subsurface layer
0
0.0004
0.0008
0.0012
$-\overline{u'w'}\ (m^2/s^2)$
SWD
MWD

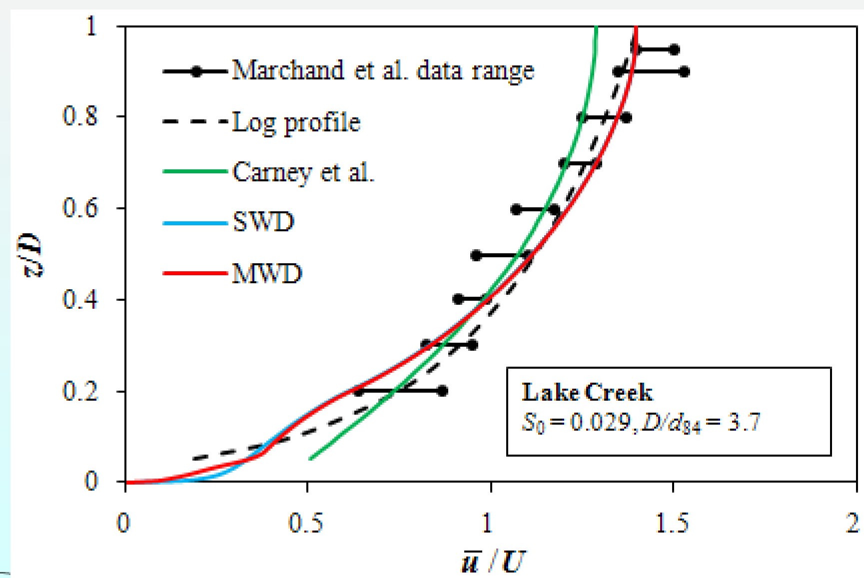
Steep-slope gravel-bed river flows

Characteristic parameters and average velocities for three simulations of river flows

	Case 1	Case 2	Case 3
Parameters	Clear Creek at Golden	Blue River near Dillon	Lake Creek
Bed slope	0.006	0.013	0.029
d_{50} (cm)	4.5	4.9	11.9
d_{84} (cm)	10.08	10.71	23.76
D (cm)	112	63	88
Range of U measured by Marchand et al. (1984) (cm/s)	193-250	161-213	140-285
U computed by Carney et al. (2006) (cm/s)	200	191	285
U for simulation with SWD model (cm/s)	214	188	261
U for simulation with MWD model (cm/s)	217	190	263


Marchand et al. data range
Log profile
Carney et al.
SWD
MWD
Clear Creek at Golden
$S_0 = 0.006, D/d_{84} = 11.1$
z/D
0
0.2
0.4
0.6
0.8
1
0
0.5
1
1.5
2
$\bar{u}/U$


Marchand et al. data range
Log profile
Carney et al.
SWD
MWD
Blue River near Dillon
$S_0 = 0.013, D/d_{84} = 5.88$
z/D
0
0.2
0.4
0.6
0.8
1
0
0.5
1
1.5
2
$\bar{u}/U$


Marchand et al. data range
Log profile
Carney et al.
SWD
MWD
Lake Creek
$S_0 = 0.029, D/d_{84} = 3.7$
z/D
0
0.2
0.4
0.6
0.8
1
0
0.5
1
1.5
2
$\bar{u}/U$

Conclusions I

- A RANS model incorporating the drag force method (DFM) and a modified S-A turbulence closure has been developed for open channel flows over gravel beds.
- Extensive tests show that the model is able to simulate the velocity variations in the interfacial sublayer, form-induced sublayer and logarithmic layer. Particularly, the S-shape velocity profile for sparsely distributed or unsorted large size roughness elements can be reproduced.
- The modification of the turbulence length scale within the interfacial sublayer increases the viscous force and reduces the drag force in balancing the gravitational force component, as well as generates a quasi-linear velocity distribution.

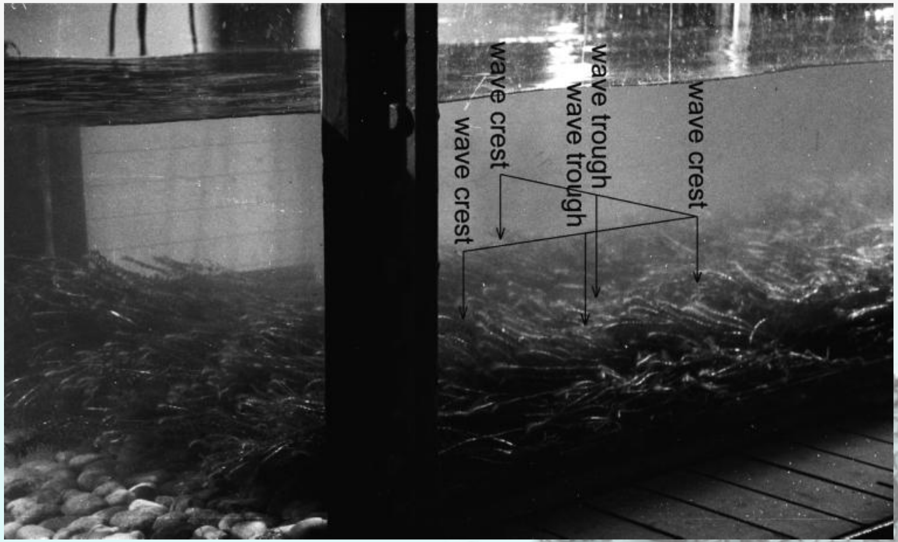
Vegetation roughness

Rigid vegetation

- Similar to gravel roughness

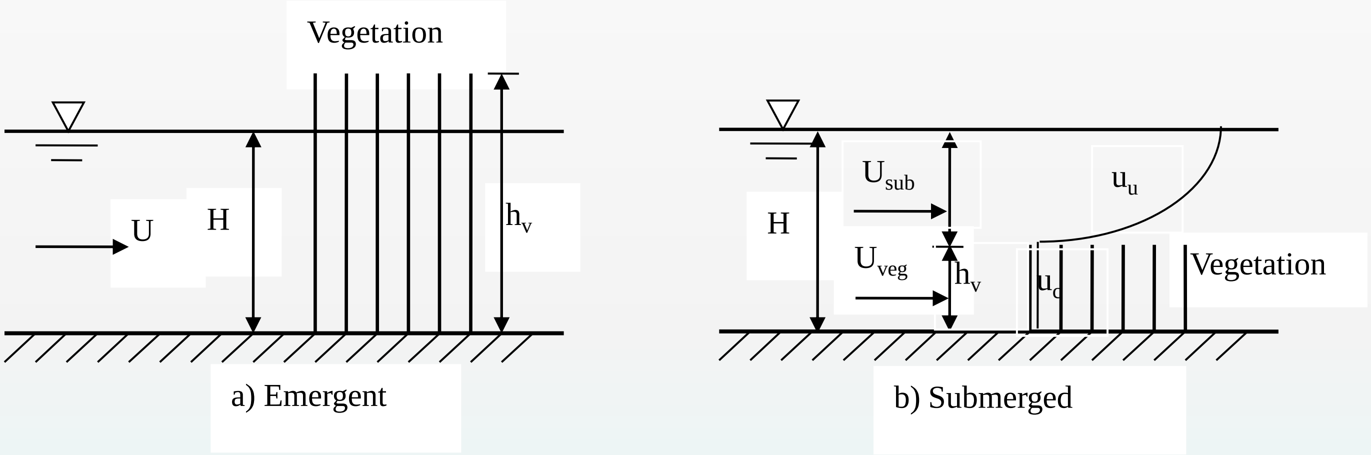
Flexible vegetation

- Vegetation height and drag coefficient are flow dependent
- Occurrence of 'Honami' phenomenon



Stephan and Gutknecht (2002)

Equivalent Manning Roughness



n_v=equivalent Manning roughness

n_b=Manning roughness for bed

C_D=drag coefficient for stems

m= number density

D=diameter of stems

Empirical equations

- Emergent Vegetation
- Force balance analysis gives

$$n_v = \sqrt{n_b^2 + \frac{C_D m D H^{4/3}}{2g}}$$

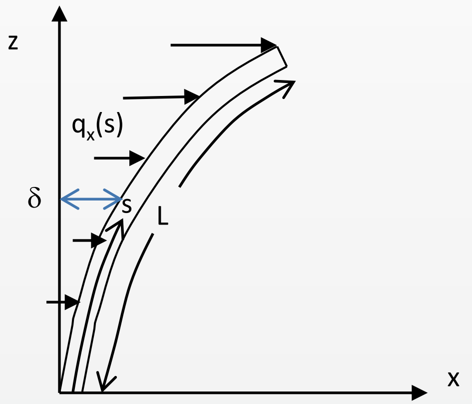
- Submerged vegetation
- Force balance analysis and assumption of a velocity profile shape

$$n_r = \left\{ \sqrt{\frac{1}{n_b^2 + (C_D m D h_v H^{1/3})/2g}} \left[1 + (\alpha - 1)\left(1 - \frac{h_v}{H}\right) \right] + \frac{1}{H^{1/6}} \frac{\sqrt{g}}{\kappa} \left[\ln\left(\frac{H}{h_v}\right) - \left(1 - \frac{h_v}{H}\right) \right] \right\}^{-1}$$

Flexible vegetation

- Large deflection of a plant stem.

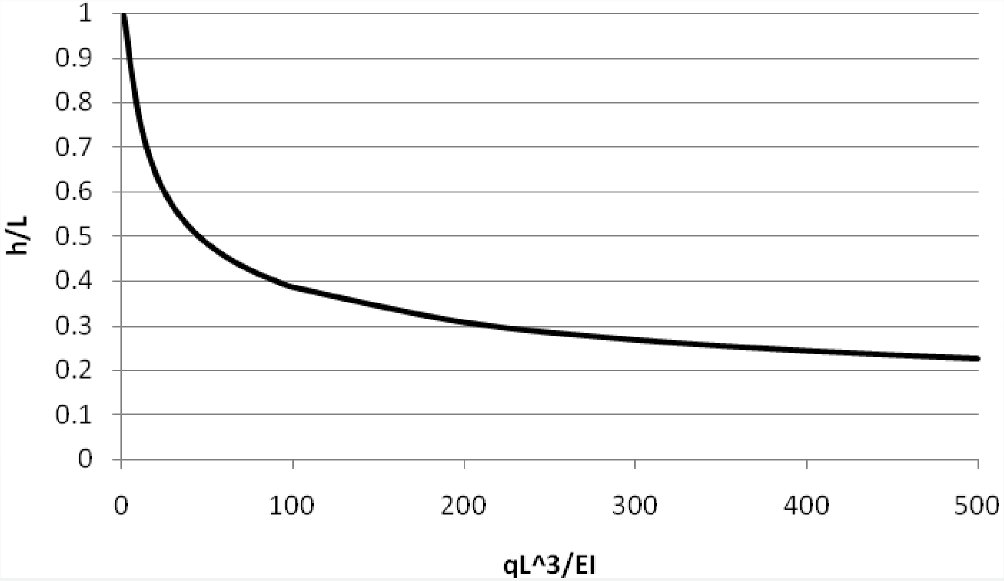
$$\frac{d^2}{ds^2}\left[EI(s)\frac{\frac{d^2\delta}{ds^2}}{\left[1-\left(\frac{d\delta}{ds}\right)^2\right]}\right]+\frac{d}{ds}\left[EI(s)\frac{\frac{d^2\delta}{ds^2}}{\left[1-\left(\frac{d\delta}{ds}\right)^2\right]}\right]\frac{\frac{d\delta}{ds}\frac{d^2\delta}{ds^2}}{\left[1-\left(\frac{d\delta}{ds}\right)^2\right]}=-q_x(s)\frac{d\delta}{ds}$$



$$z_i=\sum_{j=1}^{i}\sqrt{\Delta s^2-(\delta_i-\delta_{i-1})^2}$$

Large deflection of a cantilever beam under combined loading

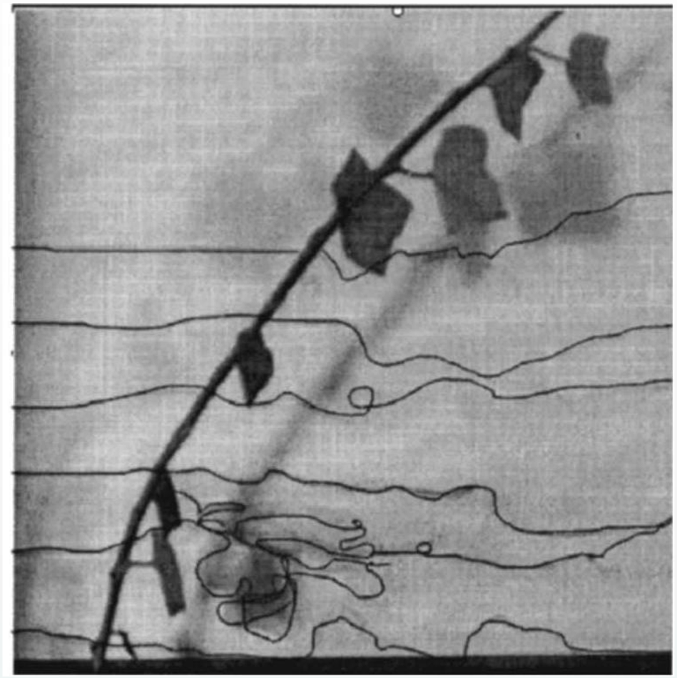
F(N)	δ(m) Experimental (Belendez et al. 2005)	δ(m) computed	Difference (%)
0.000	0.089	0.0895	0.6
0.098	0.149	0.1501	0.7
0.196	0.195	0.1940	0.5
0.294	0.227	0.2251	0.8
0.392	0.251	0.2475	1.4
0.490	0.268	0.2641	1.5
0.588	0.281	0.2767	1.5



Non-dimensional plot of deflection against distributed load

Effect of foliage

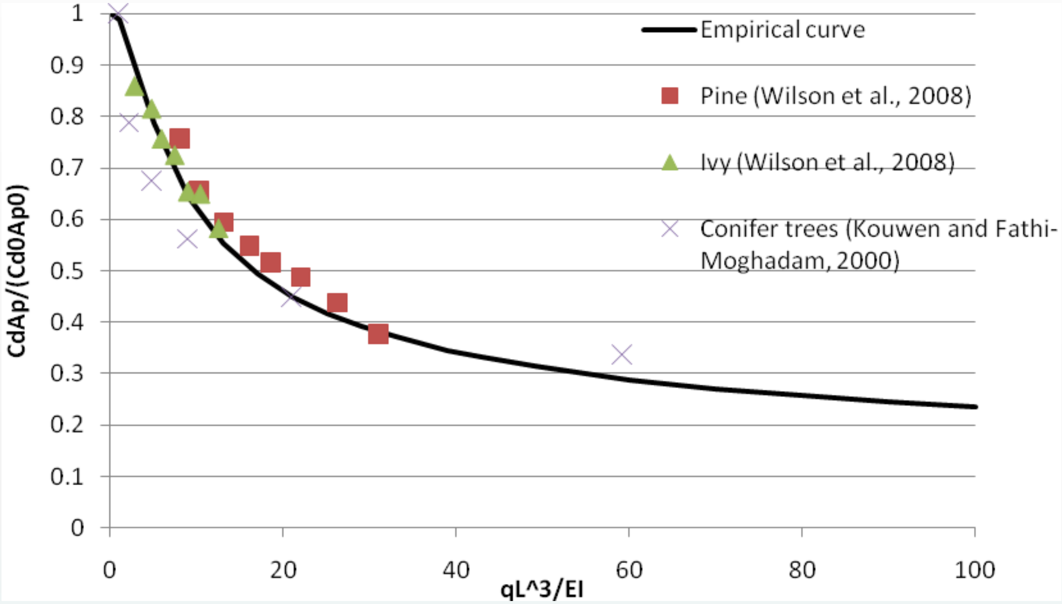
- When the plants are subjected to water flow, their stems will deflect and the foliage will streamline along the flow. This will cause the decrease of the projected area and also the decrease of the drag coefficient.



Wilson et al. (2008)

Variation of drag coefficient and projected area with angle of inclination for a plate (Holmes, 2007)

Angle of inclination θ (deg)	C_d/C_{d0}	$A_p/A_{p0}=\sin\theta$
10	0.55	0.17
30	0.6	0.5
45	0.75	0.71
90	1.0	1



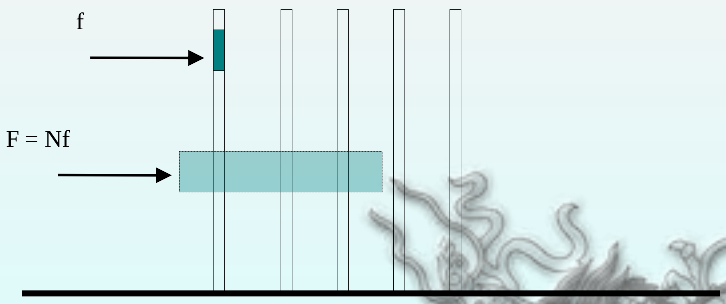
Non-dimensional plot of C_dA_p against distributed load

3D LES model for flow through flexible vegetation

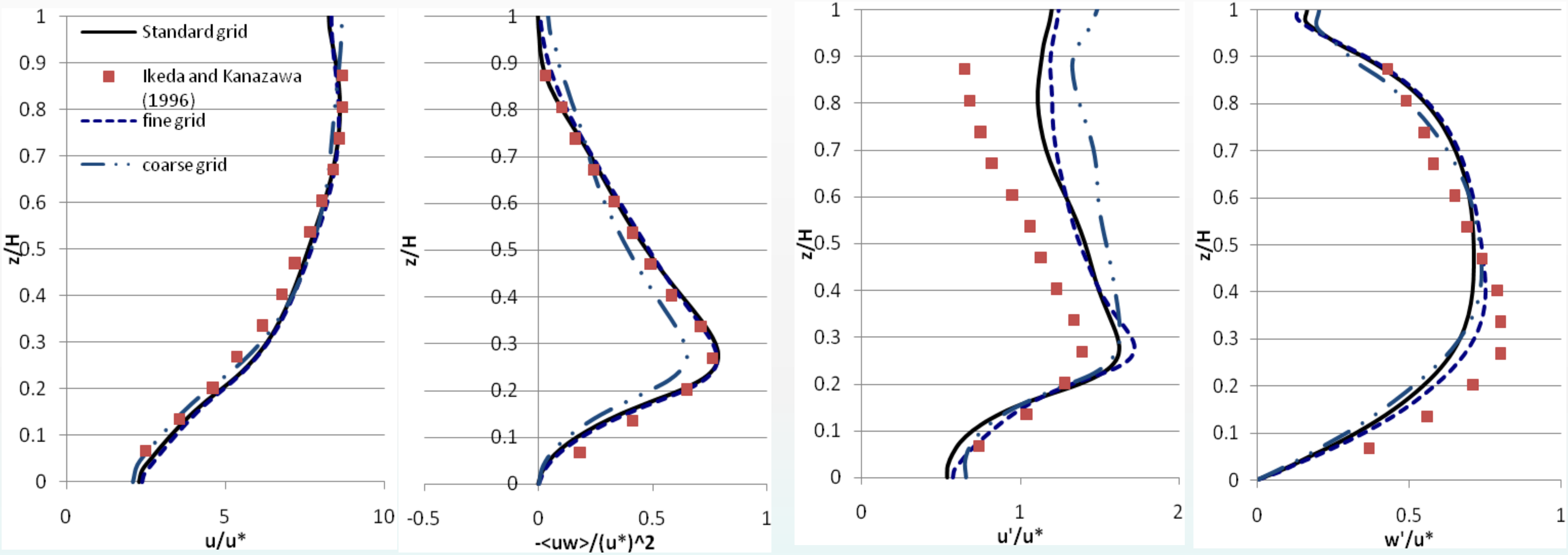
- source terms

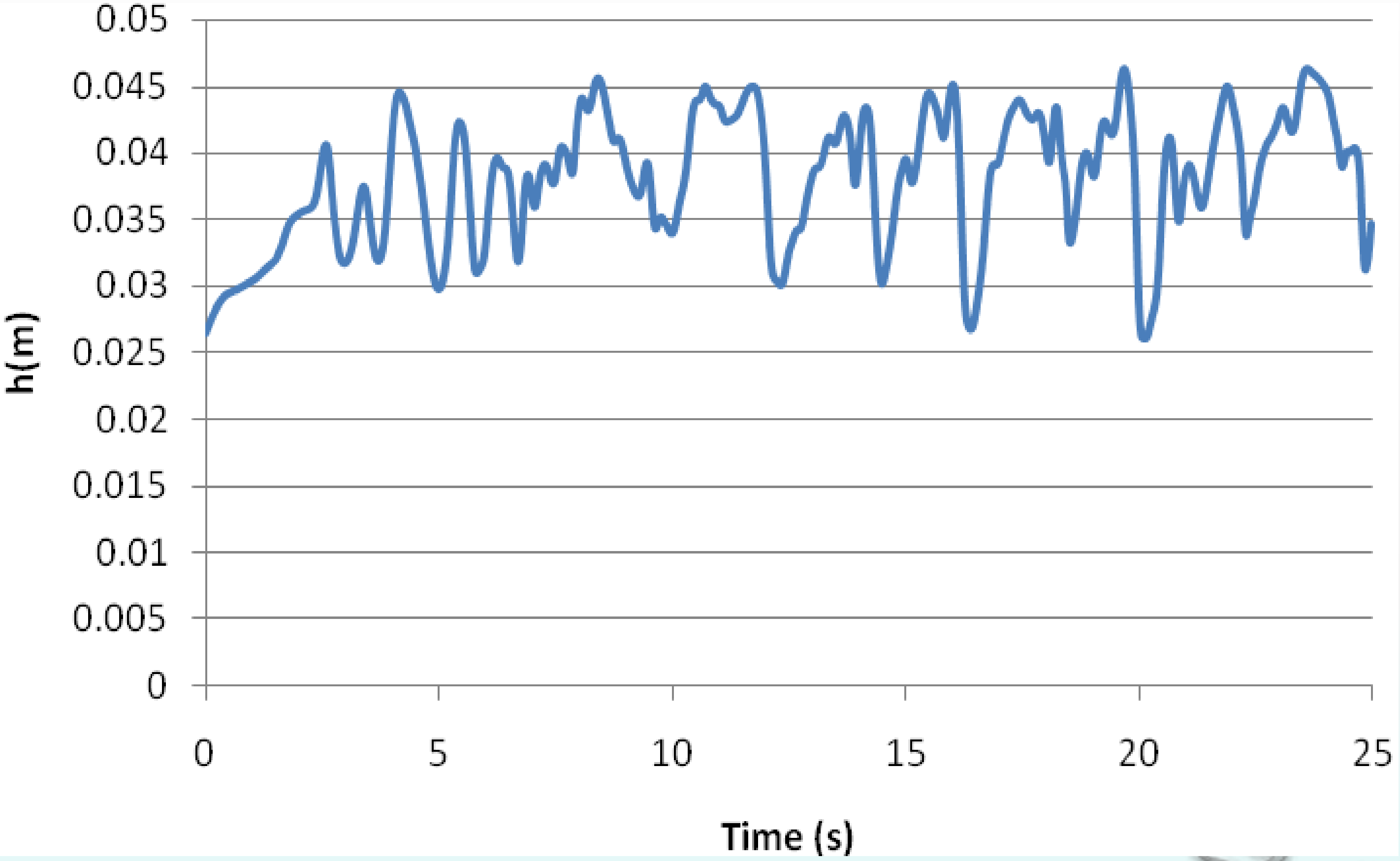
$$f_i = \frac{1}{2}\rho C_D b \tilde{u}_i \sqrt{\tilde{u}_j \tilde{u}_j} \qquad i=1,2$$

$$F_i = N f_i = \frac{1}{2}\rho C_{D0} b \frac{C_D A_p}{C_{D0} A_{p0}} \frac{L}{h} N \tilde{u}_i \sqrt{\tilde{u}_j \tilde{u}_j} \qquad i=1,2$$

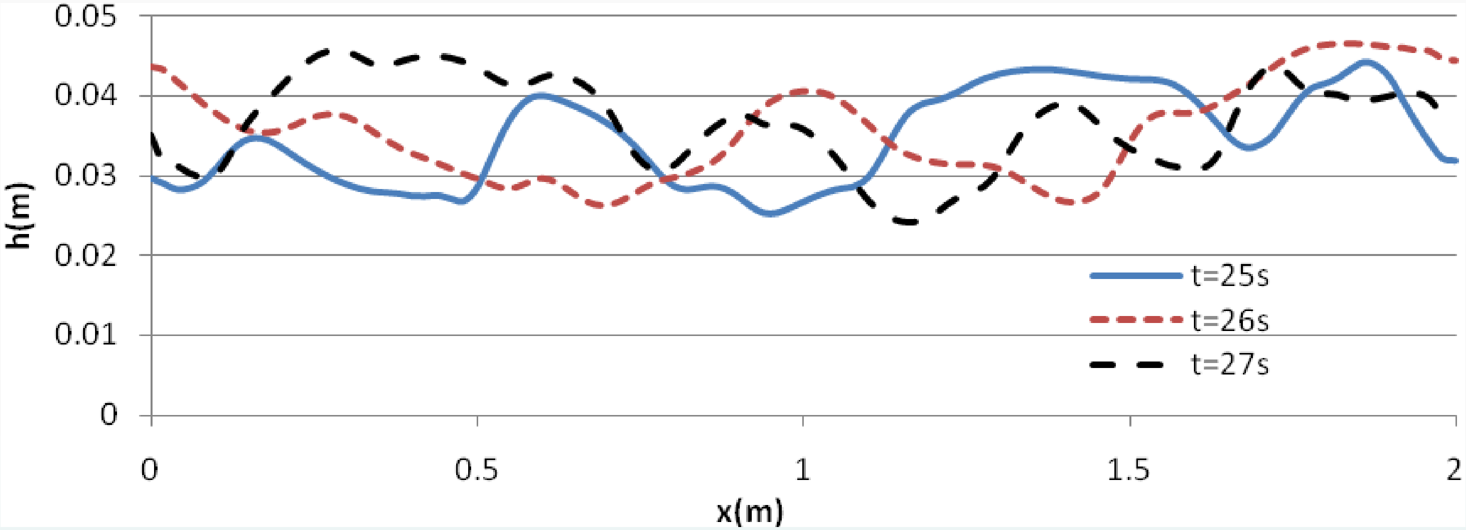


Vertical profiles of velocity and Reynolds stress and turbulence intensity for the case of Ikeda and Kanazawa (1996)



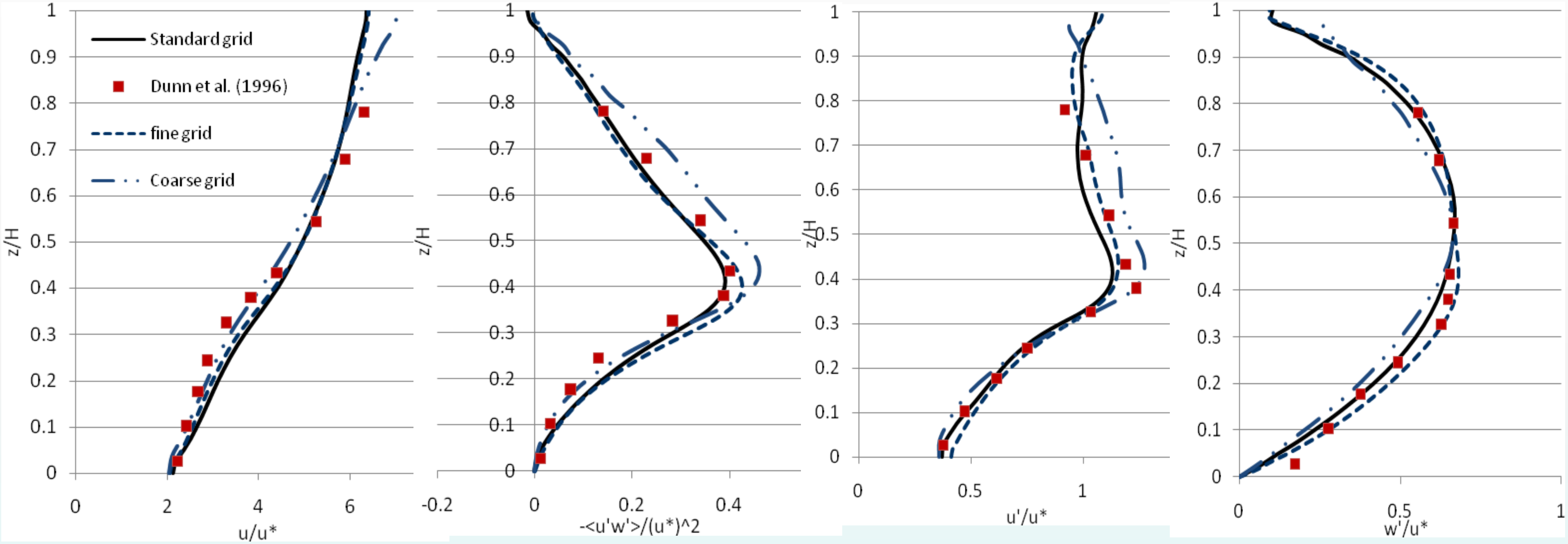


Time history of deflected height of a stem

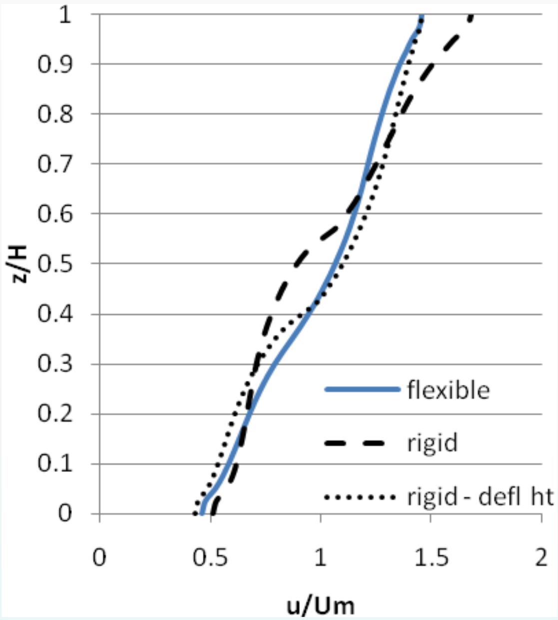


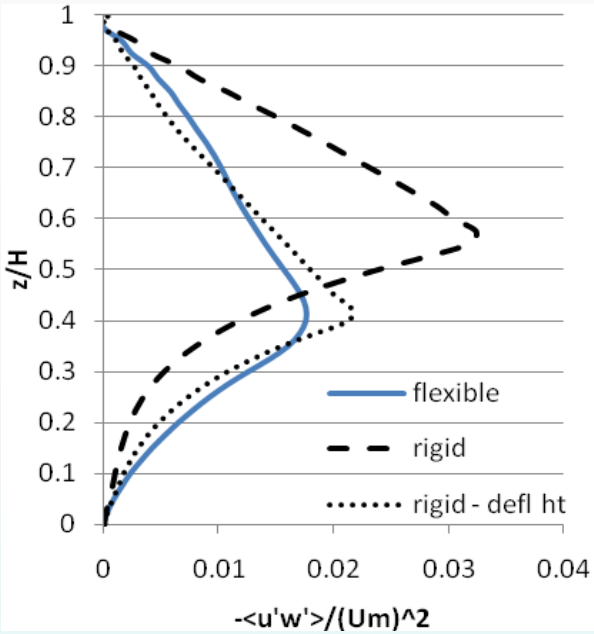
Spatial variation of deflected height at different instants

Vertical profiles of velocity, Reynolds stress and turbulent intensity for the case of Dunn et al. (1996)

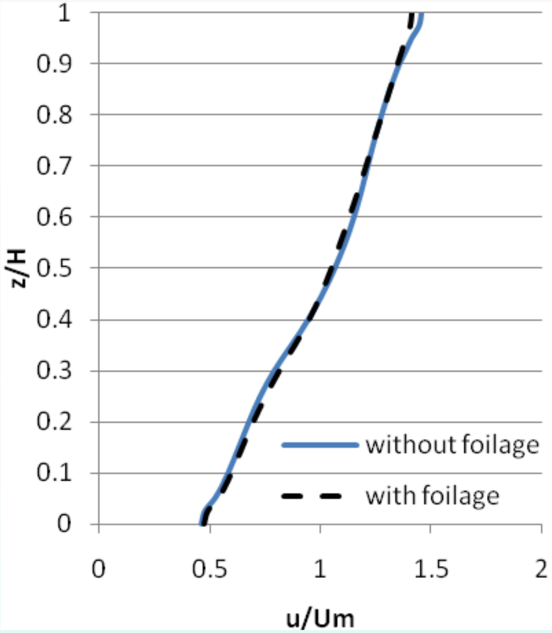


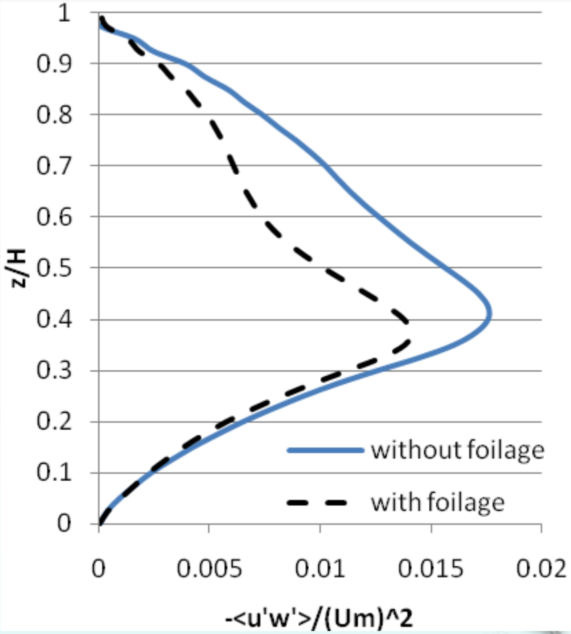
Effects of flexibility on vertical profiles of velocity and Reynolds stress (constant discharge)



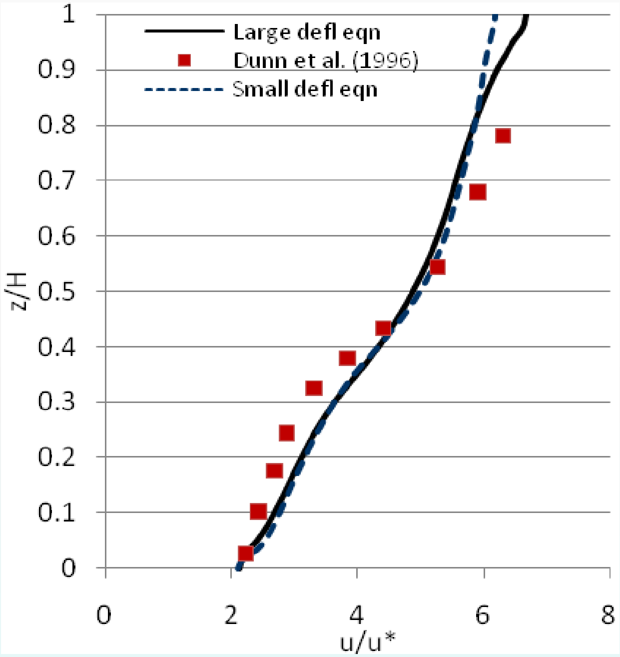


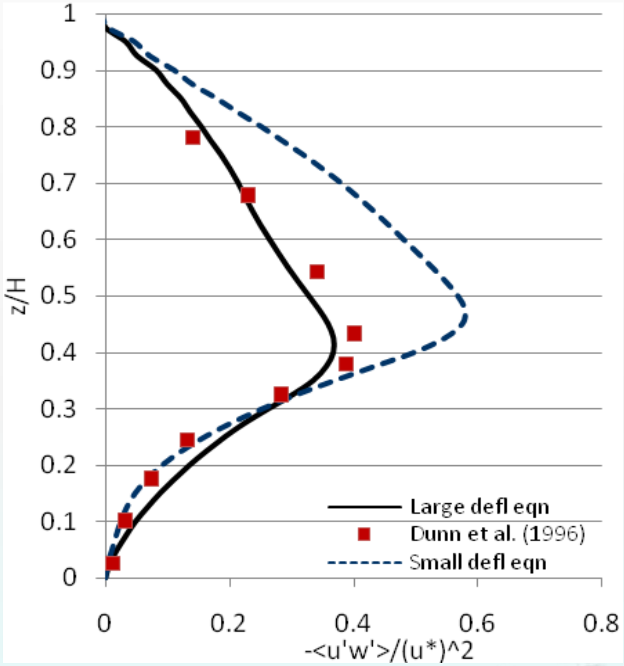
Effects of foilage on vertical profiles of velocity and Reynold stress (constant discharge)





Effects of small deflection analysis and large deflection analysis on flow characteristics.





CONCLUSIONS II

- Flexible vegetation roughness is flow dependent.
- A 3D numerical model has been developed and validated for the simulation of flow through flexible vegetation.
- The model generates the spatial and temporal variation of the deflection of stems which resembles the field observed 'Honami' phenomenon.
- The effects of flexibility and foliage on flow resistance are assessed and the results show that the flexibility of vegetation decreases both the vegetation-induced flow resistance force and the vertical Reynolds shear stress. The presence of foliage further enhances these reduction effects.