Large Eddy Simulation of open-channel flow over square bars at different Reynolds numbers

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- Open Channel Flow:

- The water surface features in rivers is correlated to the flow structure underneath it.

- Numerical simulation of the flow reveals the interaction of the bed with the bulk flow and water surface.

- Bar as roughness geometry is rather simple but helpful in studying the flow features over rough surfaces.

[Powerful river flow at Huka falls in Taupo, New Zealand Stock Photo - Alamy]

- Simulation of flow over bars:

- The Navier-Stokes equation:

$$\nabla \cdot \mathbf{u} = 0 \ , \qquad (1)$$

$$\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{u} = -\nabla p + \frac{1}{Re} \nabla^2 \mathbf{u} - \nabla \cdot \tau \ . \qquad (2)$$

- Large Eddy Simulation (LES): Spatial filtering of the governing equations is applied to reduce computational cost

- In- house code: Hydo3D

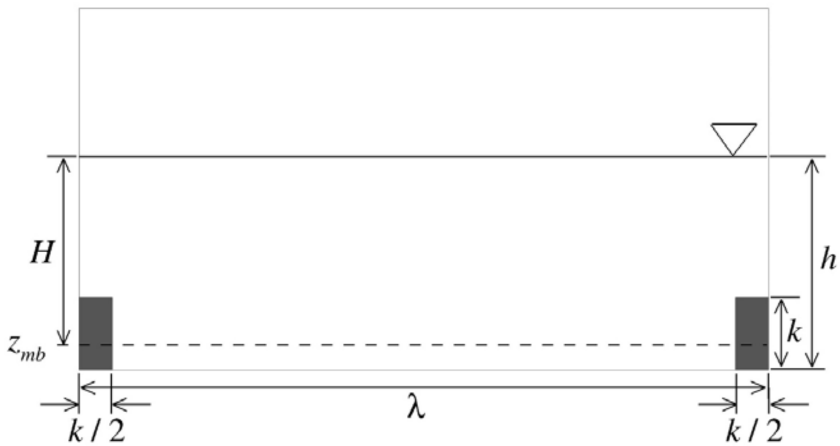
  - Fractional step method

  - Second order central difference scheme for spatial discretization

  - Level set method to capture the free surface:

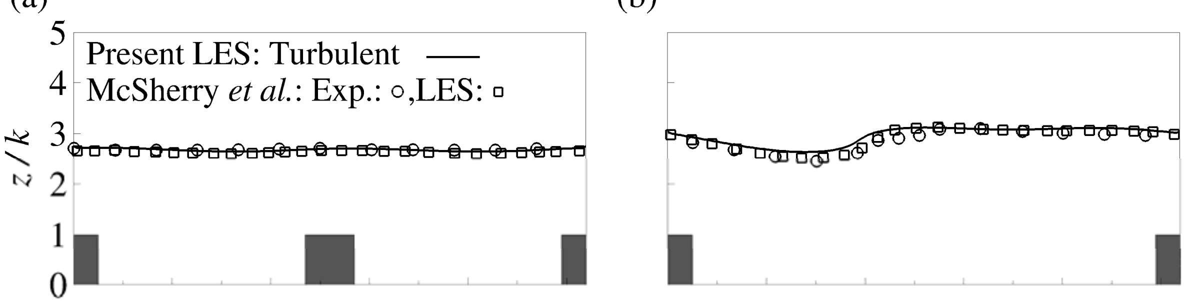
$$\frac{\partial \varphi}{\partial t} + u.\nabla\varphi = 0, \ (\varphi < 0\text{:air}, \varphi = 0\text{:free surface}, \ \varphi > 0 \text{ water})$$

- Flow over bars:



Schematic of the computational domain.

(a) (b)



Time-and spanwise-averaged free-surface elevations for (a) λ / k = 5.2 and (b) λ / k = 10.4.

$\lambda/k = 5.2,\ H/k = 2.5$

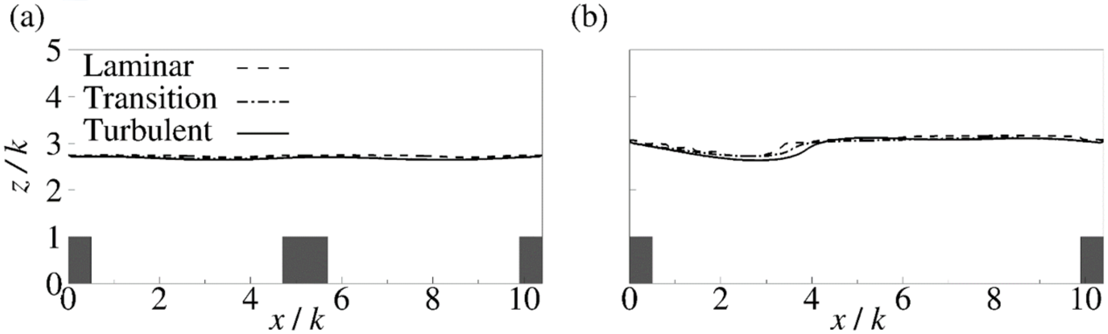
Case	U_b	U_τ	Re	Fr	Δx^+	Δy^+	Δz^+
Turbulent	0.24	0.073	7.2×10^3	0.44	58.3	68.3	36.4
$\text{Turbulent}_{\text{fine}}$	0.25	0.073	7.5×10^3	0.46	29.5	34.8	18.1
$\text{Turbulent}_{\text{double domain}}$	0.25	0.073	7.5×10^3	0.46	59.3	68.7	36.0
Transitional	0.23	0.073	6.9×10^2	0.42	5.8	6.8	3.6
Laminar	0.24	0.081	7.2×10^1	0.44	1.0	1.5	0.8
McSherry et al. (2018)	0.28	0.077	8.3×10^3	0.51	75.1	71.8	38.8

$\lambda/k = 10.4,\ H/k = 2.9$

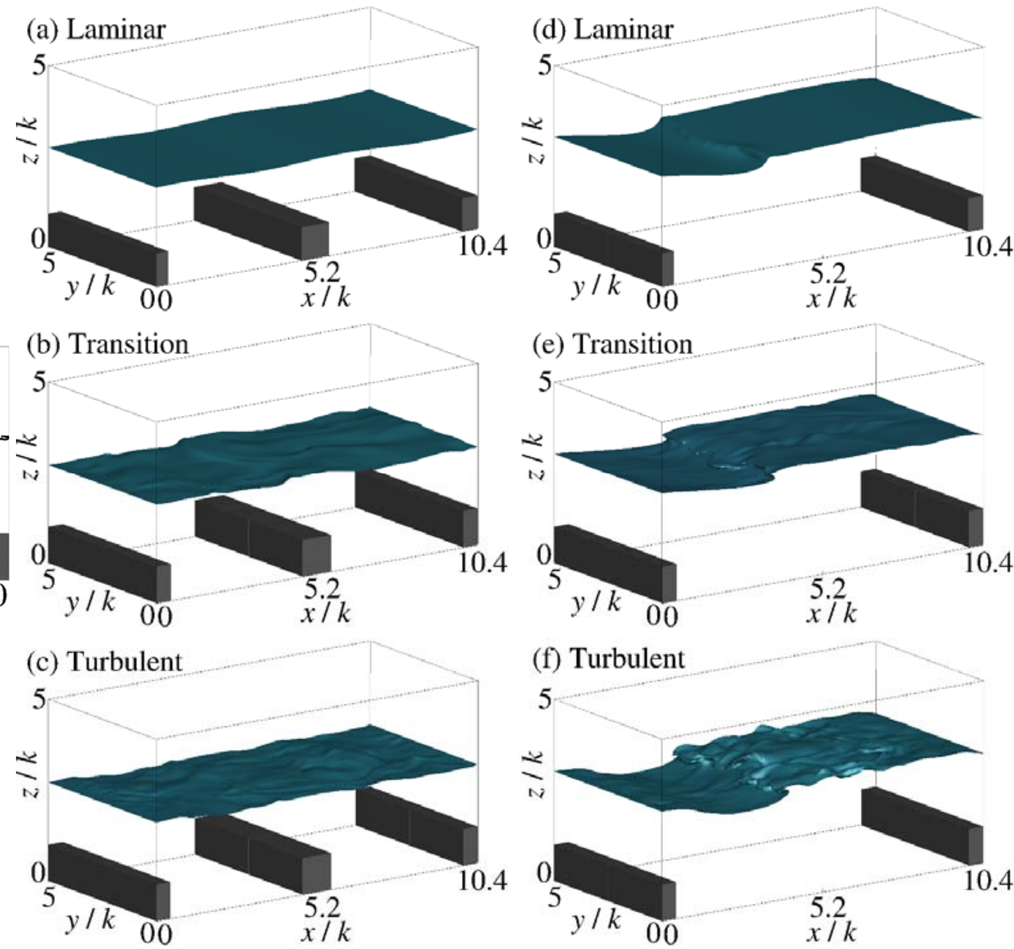
Case	U_b	U_τ	Re	Fr	Δx^+	Δy^+	Δz^+
Turbulent	0.23	0.074	8.0×10^3	0.39	59.5	69.7	37.2
$\text{Turbulent}_{\text{fine}}$	0.24	0.075	8.3×10^3	0.41	30.2	35.4	18.9
$\text{urbulent}_{\text{double domain}}$	0.24	0.075	8.3×10^3	0.41	60.4	70.7	37.7
Transitional	0.22	0.075	7.7×10^2	0.38	5.9	7.0	3.7
Laminar	0.23	0.11	8.0×10^1	0.39	1.3	2.0	1.1
cSherry et al. (2018)	0.24	0.083	8.3×10^3	0.42	80.3	76.9	41.0

Table 1: Hydraulic conditions and computational details.

- Water surface at different Re:



Time-and spanwise-averaged water surface profiles in turbulent, transitional and laminar flow for (a) λ / k = 5.2 and (b) λ / k = 10.4.

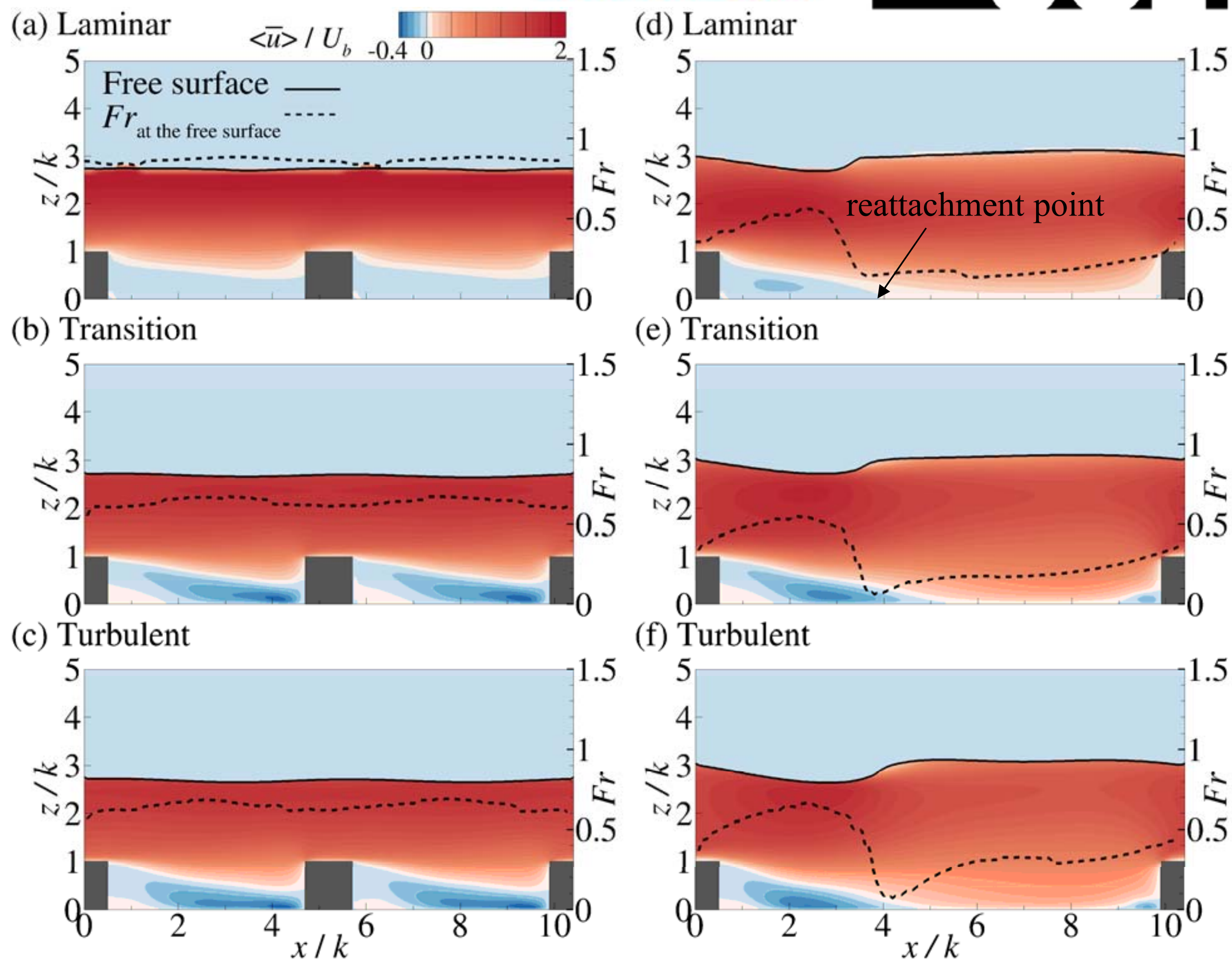


Instantaneous water surface in turbulent, transitional and laminar flow for (a-c) λ / k = 5.2 and (d-f) λ / k = 10.4.

- Streamwise velocity:

- The longest recirculation zone is in the transitional flow as the shear stress and the disturbances are not the strongest as they are in the laminar and turbulent flows respectively.

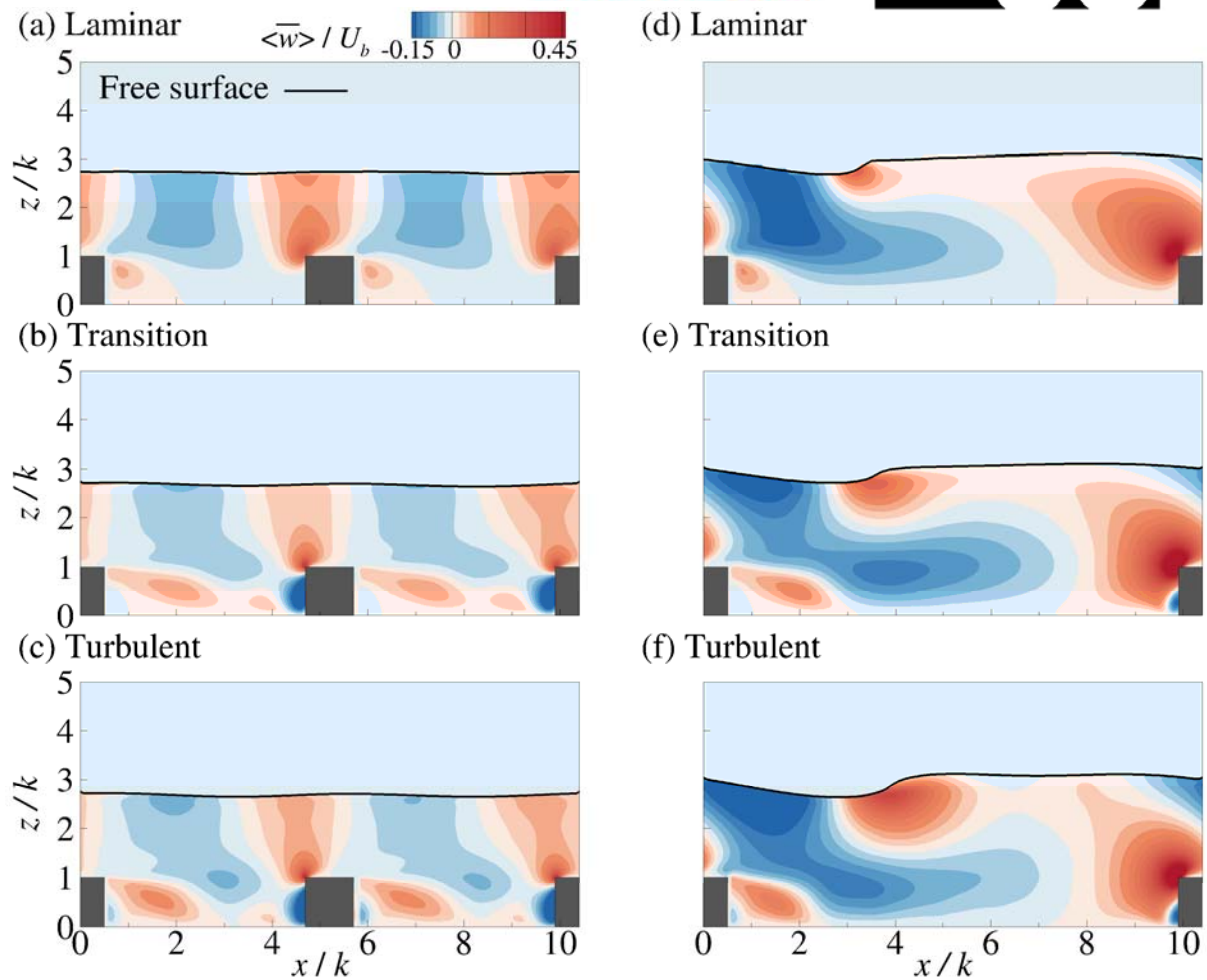
- The flow accelerates at the upstream of the standing wave and decelerate at its downstream so leads to large variation of *Fr* in larger bar spacing.



Contours of the time- and spanwise-averaged streamwise velocity together with the local Froude number at the water surface for turbulent, transitional and laminar flow for (a-c) $\lambda / k = 5.2$ and (d-f) $\lambda / k = 10.4$.

- Wall-normal velocity:

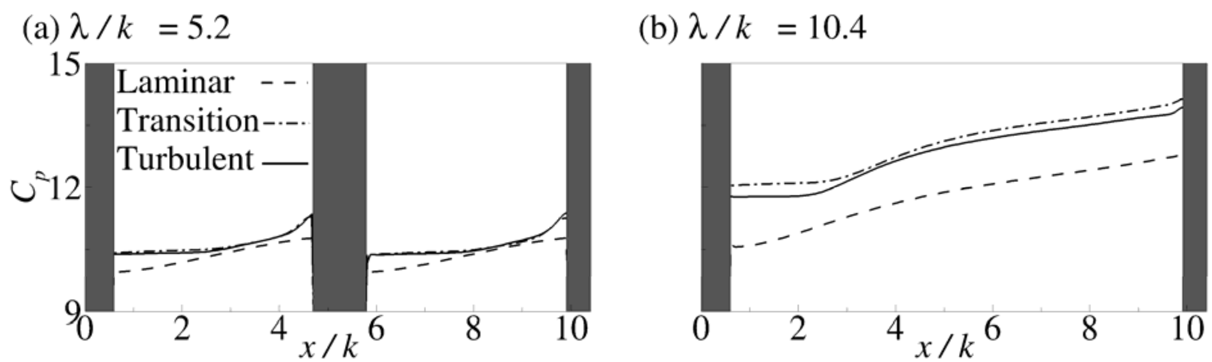
- Significant interaction of the near bed flow with the flow near the water surface in terms of the variations of mean wall-normal velocity.



Contours of the time- and spanwise-averaged wall-normal velocity for turbulent, transitional and laminar flow for (a-c) $\lambda / k = 5.2$ and (d-f) $\lambda / k = 10.4$.

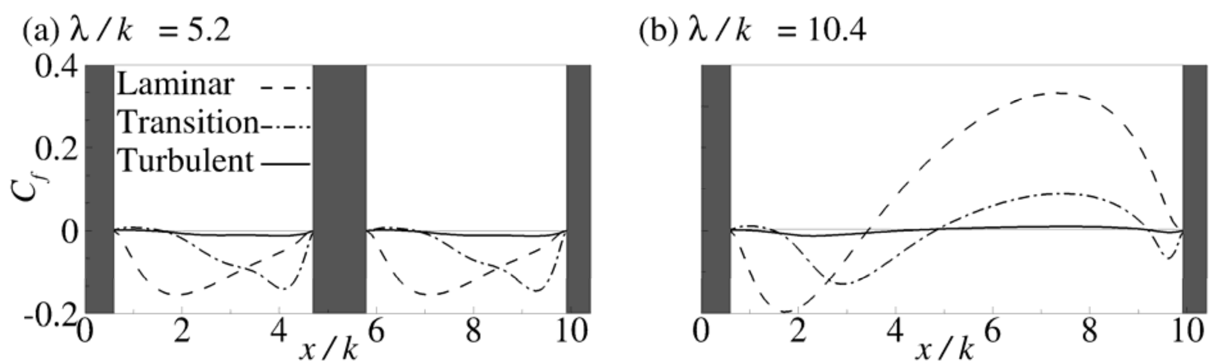
- Friction and pressure coefficients:

- C_p:
  - Largest in the transitional flows



Pressure coefficient in turbulent, transitional and laminar flow for (a) λ / k = 5.2 and (b) λ / k = 10.4.

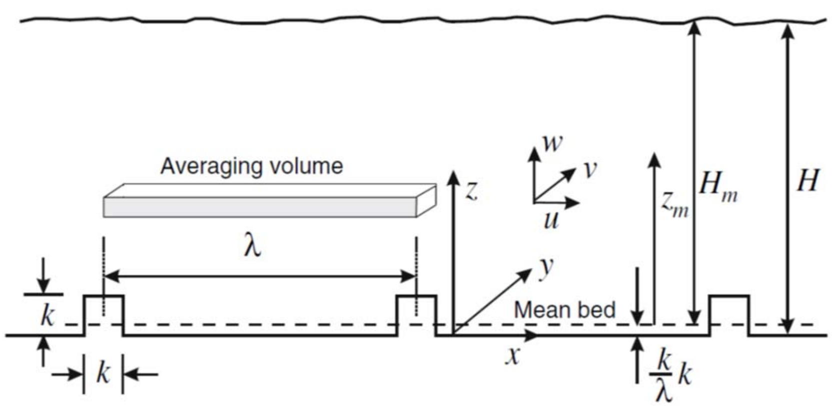
- C_f:
  - Largest in the laminar flows due to the larger viscosity.



Friction coefficient in turbulent, transitional and laminar flow for (a) λ / k = 5.2 and (b) λ / k = 10.4.

- # Fluctuations:

- Instantaneous variable in turbulent flow over a homogeneous geometry: $u_i = \overline{u_i} + u_i{}'$
- Instantaneous variable in turbulent flow over roughness (spatial inhomogeneity): $u_i = <\overline{u_i}> + u_i{}' + \widetilde{u_i}$
  - Double-averaged component $<\overline{u_i}>$: temporally and spatially averaged
  - Dispersive component $\widetilde{u_i}$: spatial variations in time-averaged velocity field caused by roughness

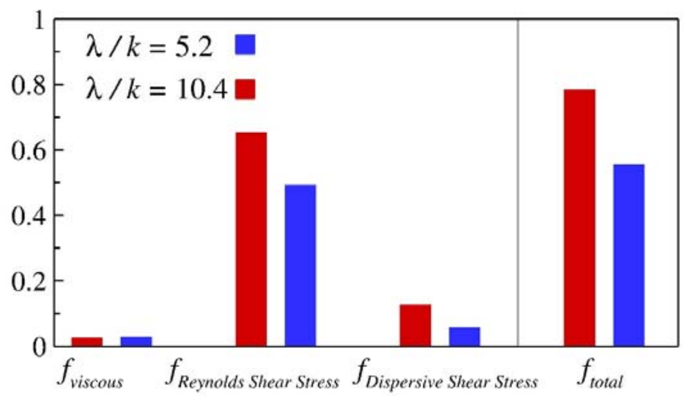


Averaging volume in space and time in flow over bars (Pokrajac *et al.*, 2007).

- Fluctuations:

TABLE II. Contributions to the friction factor f.

λ/k	f	$f_{viscous}$	$f_{ReynoldsShearStress}$	$f_{DispersiveShearStress}$
5.2	0.62	1.0%	88.7%	10.3%
10.4	0.84	0.6%	83.0%	16.4%



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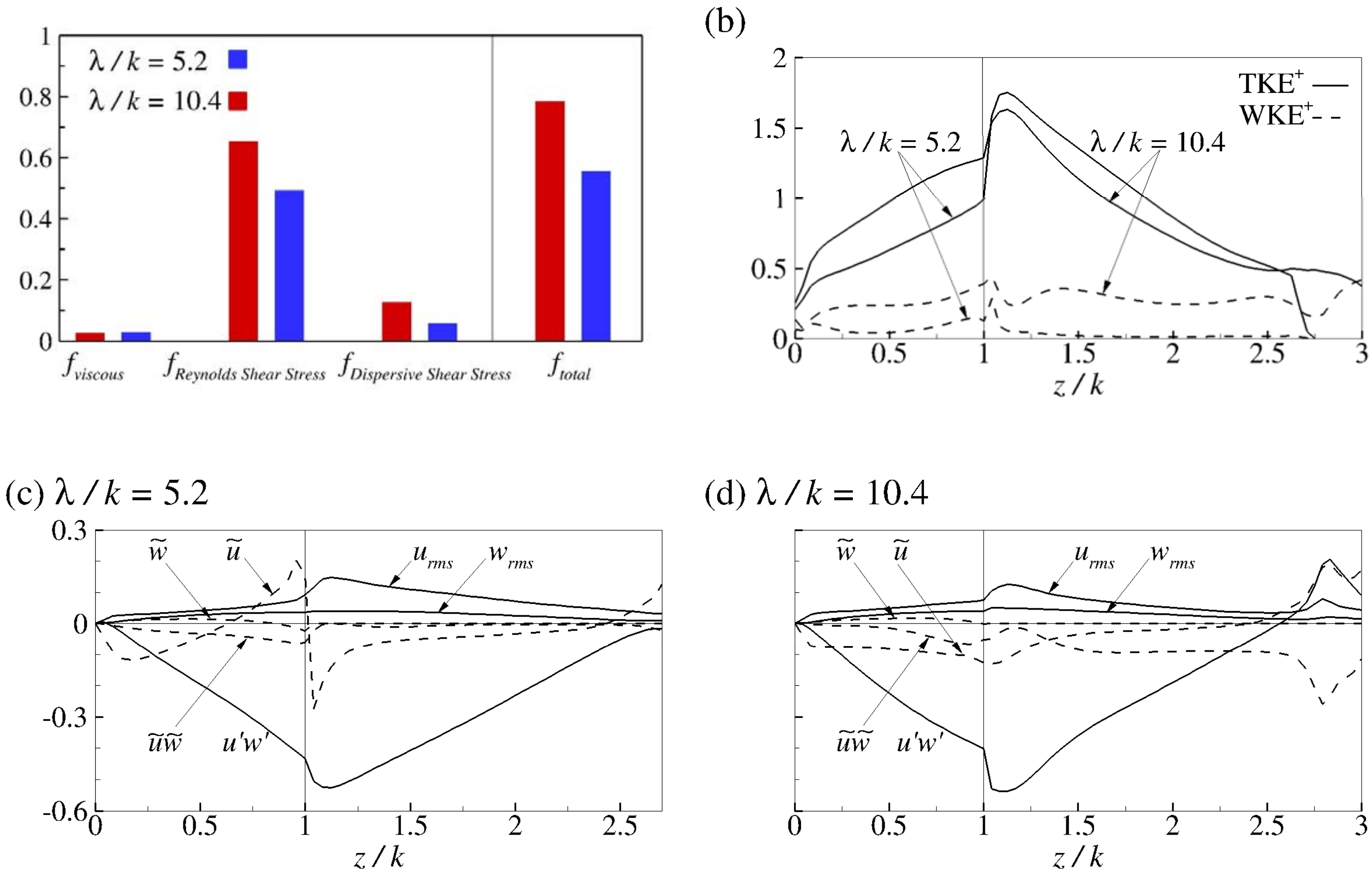

- Summary and conclusion:

- No considerable difference in the mean water surface between the three flow cases over the $\lambda / k = 5.2$. There is a standing wave at the water surface for all flow cases over the $\lambda / k = 10.4$ which becomes steeper by increasing *Re*.

- The instantaneous water surface is more disturbed for the higher *Re* in both cases.

- *Fr* at the water surface is relatively constant for $\lambda / k = 5.2$ but it has abrupt changes due to the standing wave for $\lambda / k = 10.4$ for all *Re* considered.

- The standing wave in $\lambda / k = 10.4$ leads to the large interaction of the near bed flow with the flow near the water surface in terms of the variations of $<\overline{w}>$.

- Increasing the bar spacing, the friction coefficient increased and the contribution of the dispersive shear stress to this coefficient increased as well.

Thank you.