Spatial variability, mean drag forces, and coefficients in an array of rigid cylinders

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INTRODUCTION, MOTIVATION & OBJECTIVE

Introduction

- Flow-vegetation interaction is important in many ecological and engineering applications
  - River restoration
  - Sediment transport
  - Flood risk management

- Riparian vegetation increases flow resistance resulting in
  - Decreasing conveyance capacity
  - Increasing flood levels

- **Quantitative** understanding of flow-vegetation interaction is of fundamental importance.

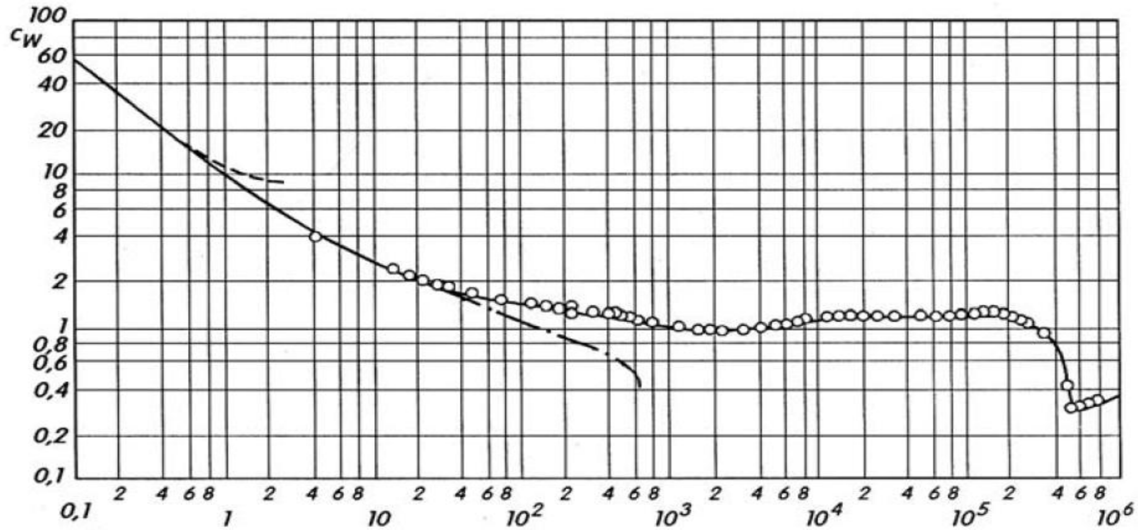
http://www.tennisclub-schwarzau.at/images/hochwasser1.jpg

Introduction

- Flow resistance: $$\rho g h S = \sum F_D / b\Delta l + \tau_0^{'}$$
- Vegetative drag: $$F_D = \frac{1}{2}\rho C_D A_P u_0^{\;2}$$

ρ = fluid density, C_D = drag coefficient,
u_0 = mean flow velocity,
A_P = plant projected area

- Vegetation is in many cases simplified by rigid cylinders
  - $A_P = h \cdot d$ = constant
  - $C_D = f(Re_S)$
  - $u_0 \approx u_{approach}$ for a single, isolated cylinder



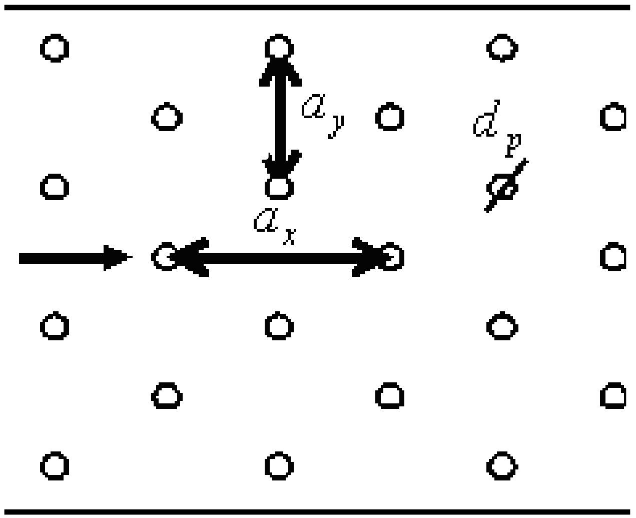
Schlichting&Gersten (2006)

$Re = \frac{Vd}{\nu}$

Introduction

- Multicylinder array
  - wakes and sheltering effects of upstream cylinders influence the flow field
  - mean flow velocity u_0 differs substantially from individual approach velocity $u_0 \neq u_i$
  - C_D-Re relationship for a cylinder only valid with approach velocity u_i

- C_D- dependencies in a multicylinder array with u_0
  - diameter d
  - spacing a_x, a_y
  - slope S
  - individual approach velocity $u_{0,i}$



➡ Information about the velocity distribution in a multicylinder array is required to estimate C_D-values

Lindner (1982)

- Estimation of C_D in a multicylinder array by using the mean flow velocity u_0
  - wake superposition

blockage ratio (Richter, 1973)

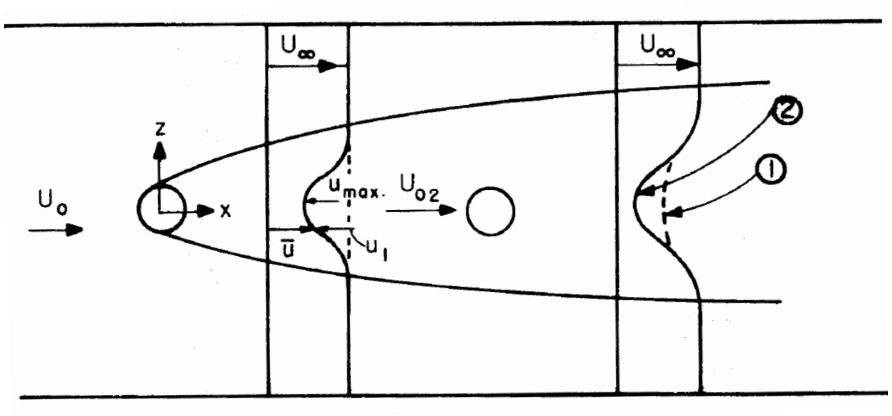
influence of gravity waves

C_D-value of the i-th cylinder in a multicylinder array

$$C_{D,i} = C_D \left(1 + 1.9 \frac{d}{a_y} C_D\right) \left(\frac{u_{0,i}}{u_0}\right)^2 + \Delta C_D$$

single cylinder in undisturbed flow

velocity defect (Li & Shen, 1973)



Lindner (1982)

- Superposition of velocity defects
  - theoretically infinitely long
  - $u_{0,n}/u_0$ roughly constant for n = 20 cylinder
- Qualitative findings
  - increasing $u_{0,20}/u_0$ with increasing a_x/d for $a_x/d < 40$
  - decreasing $u_{0,20}/u_0$ with increasing a_y/d for $a_y/d < 10$
  - $u_{0,20}/u_0$ staggered > in-line
  - $u_{0,20}/u_0$ decreases with increasing u_0
- Verification of the approach in a flume study by measured flow velocities
- Direct drag force measurements on single element in an array showed a spread of ±30% (Li & Shen 1973)

Motivation & Objective

Motivation

- Lindner approach has not been tested using measured drag forces

Objective

- Test of applicability of the Lindner approach by comparing measured and computed drag coefficients
- Direct and multiple drag force measurement in an array of cylinders dependent on
  - flow velocities
  - vegetation arrangement
- Analysis of spatial variability of the drag forces

EXPERIMENTS

Experiments – Flume characteristics

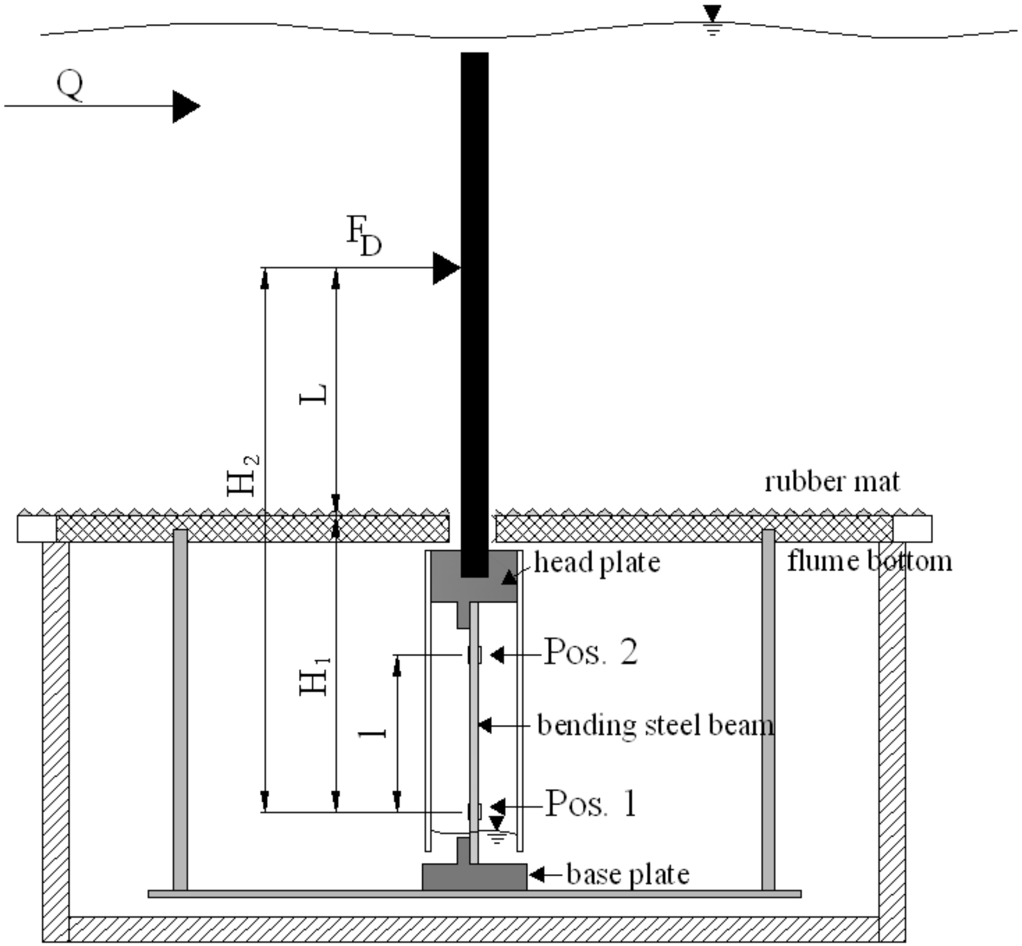
- Tilting flume
  - 32 m long, 0.6 m wide, 0.4 m deep
  - Pyramid shaped rubber mat, k = 3 mm
- Measurement section
  - 1.5 m long, 15.1 m downstream from flume inlet
  - 10 DFS
- Vegetation elements
  - 18.5 m long, 6 m downstream from flume inlet
  - Cylinders, Ø = 1 cm, height = 23 cm
- Flow conditions
  - steady uniform flow conditions
  - constant water depth h = 0.25 m (just submerged)
  - flow velocities $\mathbf{u_0}$ **= 0.20 – 0.70 m/s**

Experiments – Drag Force Measurement System

- Drag Force Measurement System (DFS)

$$F_d = \frac{M_1 - M_2}{l}$$

where
M_1, M_2 = moments at Pos. 1 and 2
l = distance between Pos. 1 and 2



- Standard error ±0.02 N
- Sampling frequency 200 Hz

- Simultaneous measurement of 10 DFS

Experimental procedure

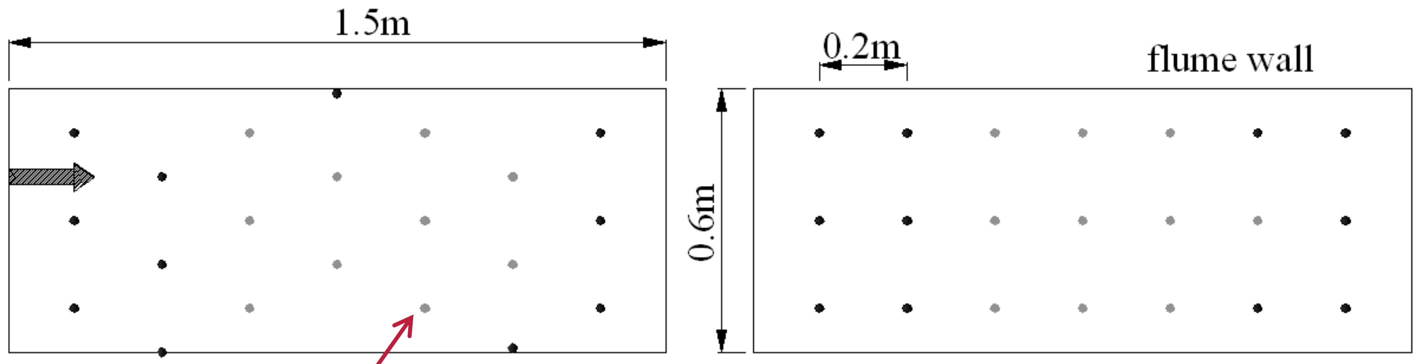
staggered

20S

in-line

20L

a_x/a_y = 20/20 cm



Measurement section

drag force measurements

RESULTS

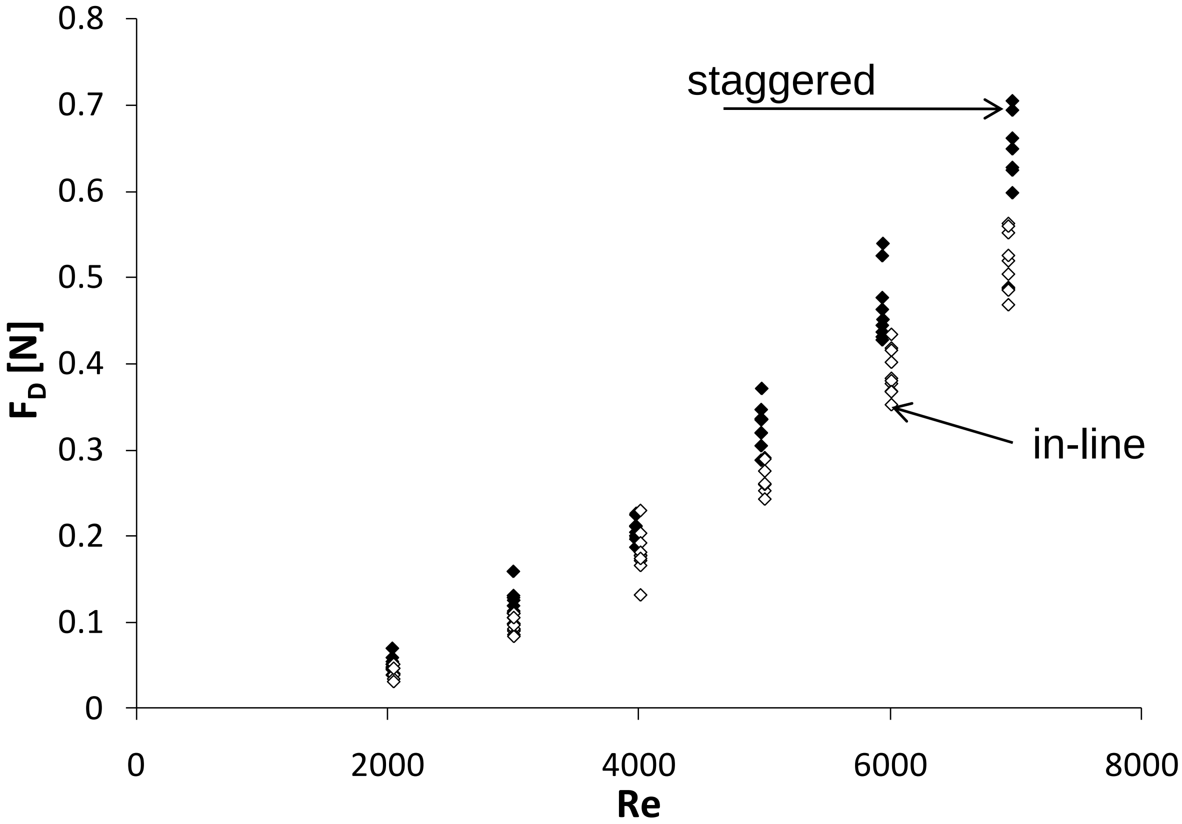
Results – Drag forces

- Large F_D-variability for both arrangements

  -28% to +27% in-line

  -23% to +19% staggered

- Significantly larger drag forces for staggered than for the in-line pattern



Results – Drag coefficients

- Large C_D-variability for both arrangements

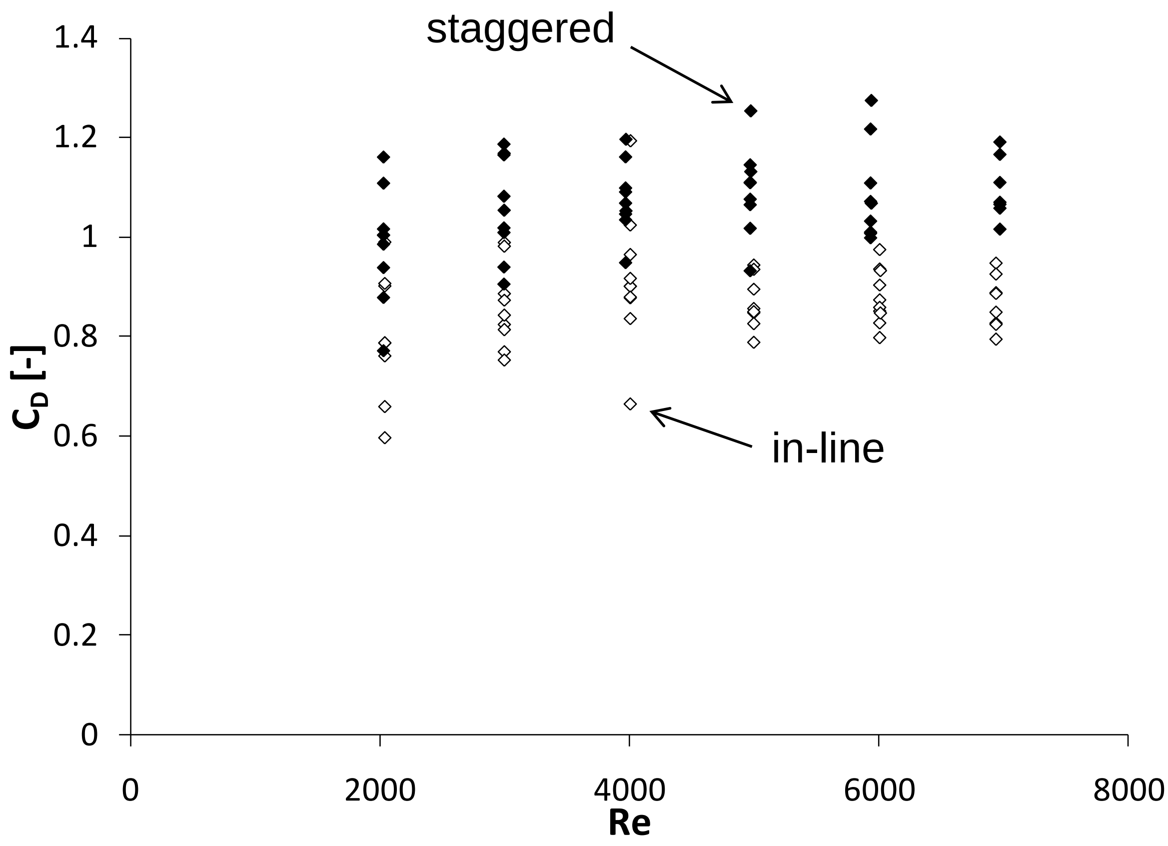
  -30% to +28% in-line

  -18% to +22% staggered

  (in accordance with measurements of Petryk, 1969)

- Larger drag coefficients for staggered than for the in-line pattern

- Estimation of <F_D> or <C_D> might result in large degree of uncertainty if only one vegetation element is considered



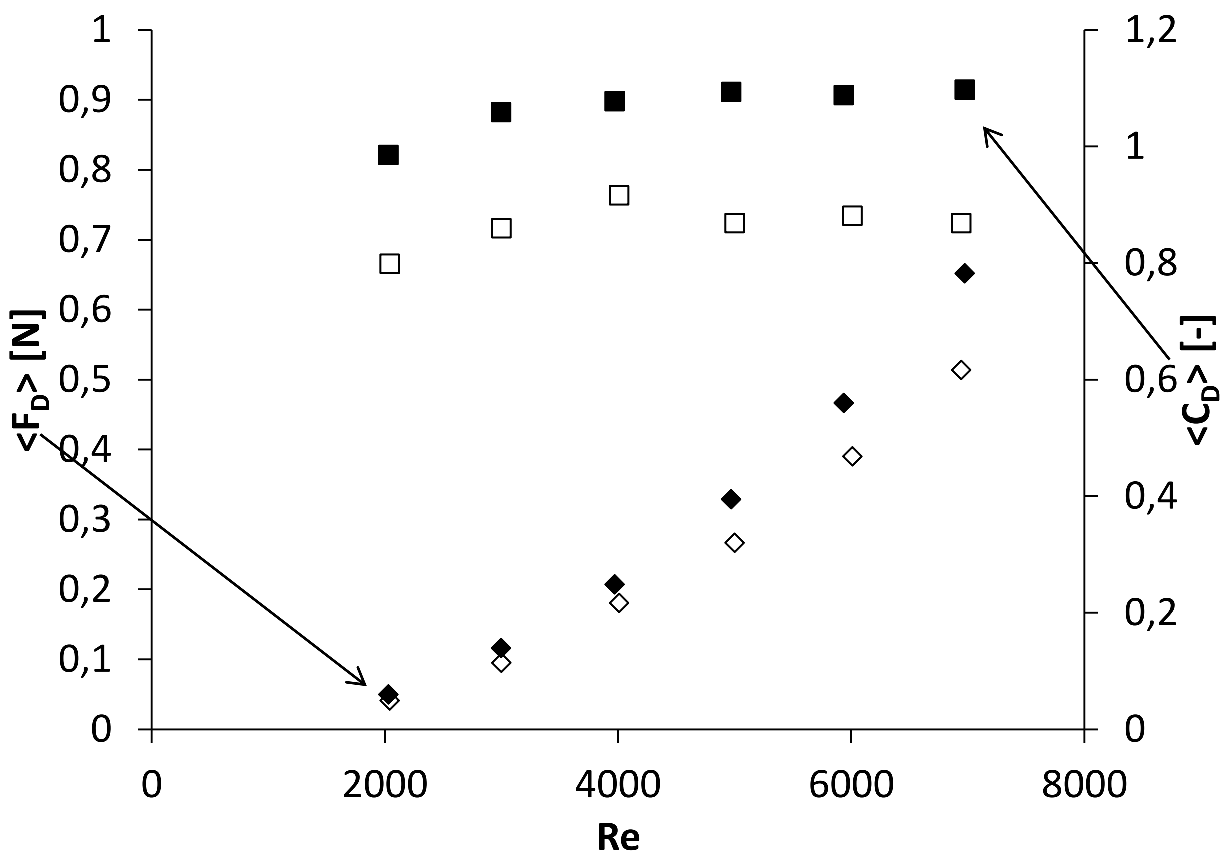
Results – Spatially averaged drag forces and coefficients

- Consistently larger $\langle F_D \rangle$ and $\langle C_D \rangle$ for staggered than for the in-line pattern

  $\langle F_D \rangle \approx 1.42\, u_0^2$ (staggered)

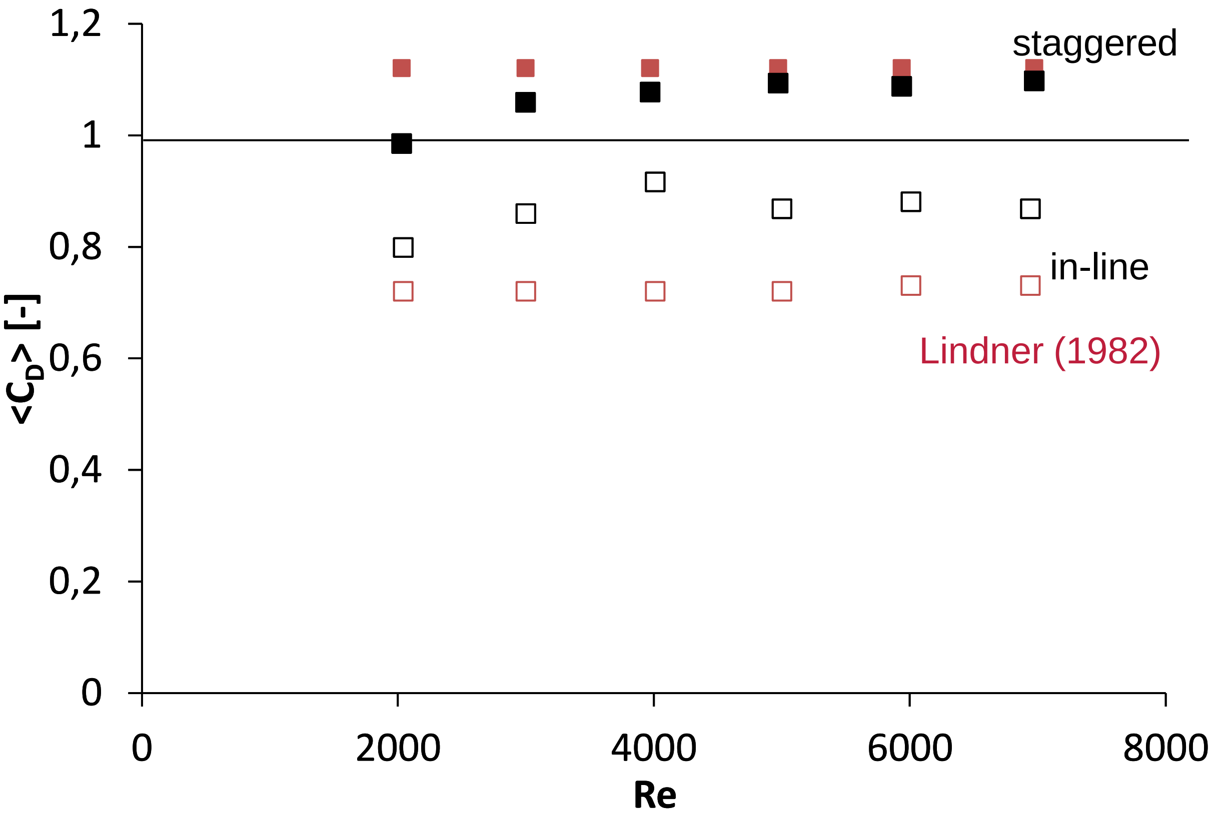
  $\langle F_D \rangle \approx 1.14\, u_0^2$ (in-line)

- Agrees well with findings of Li & Shen (1972) and Lindner (1982)



Results – Lindner (1982) approach in comparison with measured C_D-values

- Neglecting array arrangement results in error related to $\langle C_D \rangle$
- in-line: measured values underestimated by ~16%
- staggered: measured values overestimated by ~5%
- small deviations indicate applicability of Lindner (1982) approach



Summary & Conclusions

- Measured drag forces and coefficients
  - spatial variability significant, deviation from spatial mean ±30%
  - values larger for staggered setup than for in-line

- Good agreement between measured and predicted values by Lindner (1982)
  - deviations -16% for in-line and +5% for staggered

➡ Estimation of C_D in a multicylinder array based on single, isolated cylinder analogy is a crude approximation

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Thank you for your attention!

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