HIROSHIMA UNIVERSITY

National University Corporation Shizuoka University

Environmental Flow Physics & Computation Group

EFPCG

Undisturbed Fluid Flow for Improved Macroscopic Estimation of Drag Forces Acting on Circular Cylinders

S. Yokojima[1], T. Uchida[2], Y. Kazehaya[1], and Y. Kawahara[2] ([1]Shizuoka University, Japan; [2]Hiroshima University)

Abstract

A drag-force model is essential in practical predictions of flows around vegetation/urban canopies, since it is too prohibitive to resolve details of the canopy elements and associated fluid motions in practical applications. The model, however, has a serious difficulty inherent in its formulation: how one can specify the representative velocity? In ideal situations such as flows past an isolated obstacle, it is the velocity of the inflow and is easily available. In flows past multiple obstacles, on the other hand, a straightforward extension of the idea behind the ideal situations leads to introduce *undisturbed* flow, which is the flow that would exist at an obstacle location in the absence of that obstacle but with all other obstacles present. Here the undisturbed flow has been evaluated directly in fully resolved computations of a two-dimensional flow past circular cylinders and the fundamental properties of the flow are discussed.

Introduction

- **Macroscopic drag force model**

$$\mathbf{F} = (1/2)C_D \rho A|\mathbf{u}_{rep}|\mathbf{u}_{rep} \quad (1)$$

  - ✓ No standard way to find a proper C_D even for simple array of cylinders – a bottleneck in practical applications
    - $C_{D,global}$ by Yokojima & Kawahara (2015)
    - $C_{D,local}$ by Yokojima & Kawahara (2016)
  - ✓ Here particular attention to representative velocity $\mathbf{u}_{rep}$

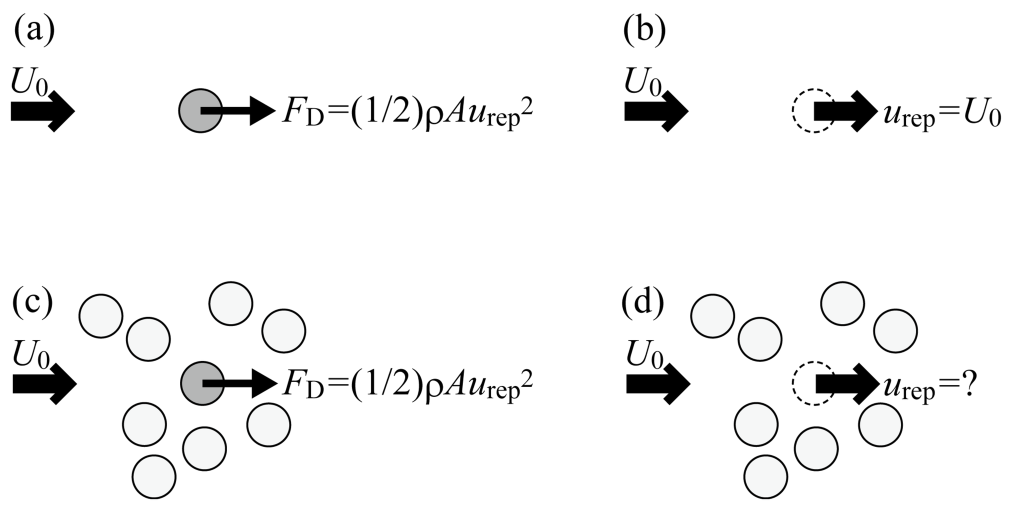
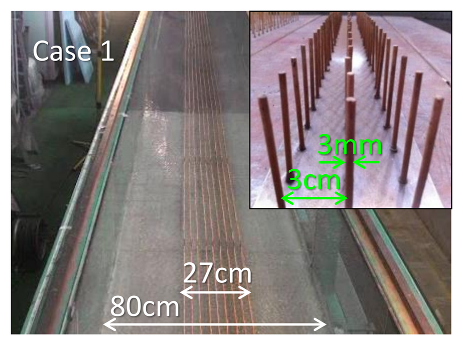


Figure 1. In ideal situations like (a), u_{rep} must be the inflow U_0 (see (b)). In flows past multiple obstacles like (c), a straightforward extension of the idea behind (b) introduces undisturbed flow, which would exist at an obstacle location in the absence of that obstacle but with all other obstacles present. Clearly the undisturbed flow is unavailable in general (see (d)), which causes serious difficulties in application of the model.

  - ✓ Objective – to examine fundamental properties of undisturbed flow in a two-dimensional flow past circular cylinders

Physical and numerical details



- **Physical details** (see figure 2 and Yokojima et al. (2015))
  - ✓ Fully-developed open-channel flow through emergent vegetation
  - ✓ Vegetation model consists of circular cylinders of diameter 3 mm with in-line arrangement of center-to-center distance 3 cm
  - ✓ Flow discharge is 9000 cm^3/s, and resulting water depth H and bulk Reynolds number $Re_b = U_b H/\nu$ are about 4.7 cm and 11250, respectively, in both cases

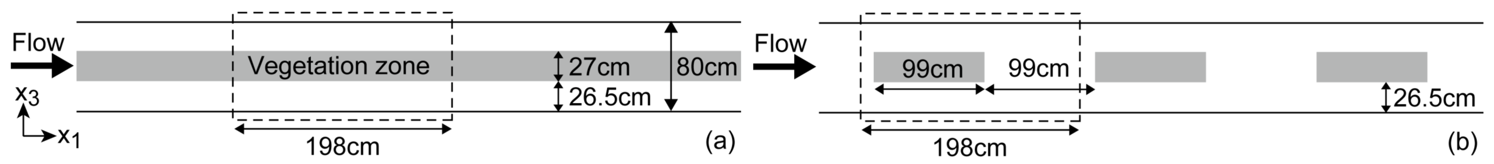


Figure 2. (a) Case 1; (b) Case 2. Dashed rectangle indicates the computational domain for the present, microscopic, fully resolved numerical simulations (see figure 3).

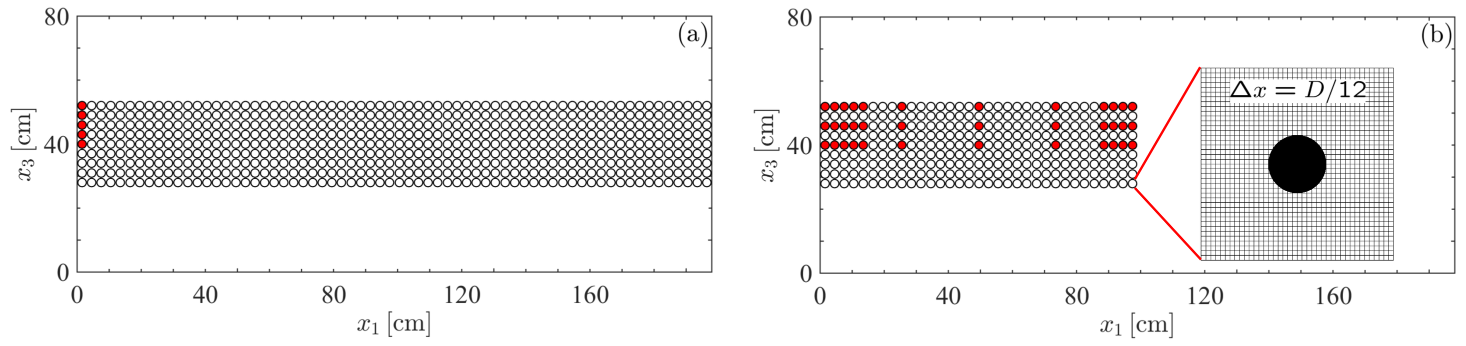


Figure 3. Computational domain and arrangement of circular cylinders: (a) Case 1; (b) Case 2. Periodicity is imposed in x_1 direction. Each of the cylinders colored with red is removed to compute the undisturbed flow u_{un} at the cylinder location. For clarity, the cylinders are depicted larger than the actual size.

- **Numerical details**
  - ✓ Introduce horizontally two-dimensional system, as zeroth approximation to target flow
  - ✓ Stem Reynolds number Re_D = 700
  - ✓ Immersed boundary method, $\Delta x = D/12$
- **Undisturbed flow u_{un} & drag coefficient $C_{D,un}$**
  - ✓ Direct calculation of undisturbed flow u_{un}
    - Refer cylinder i-th from the top (row) and j-th from the left (column) to as 'ricj'
    - Remove a cylinder, simulate the new system, and calculate u_{un} at the cylinder location
    - Calculate u_{un} at five different locations (r1c1, r2c1, r3c1, r4c1, r5c1) in Case 1 and at 36 locations (r1, r3, r5 in the transverse direction, and c1, c2, c3, c4, c5, c9, c17, c25, c30, c31, c32, c33) in Case 2 (see figure 3)
    - Number of cylinders that are statistically independent is five in Case 1, and 165 (= 5*33) in Case 2
    - Obtain u_{un} by both spatial averaging over entire volume occupied by the target cylinder and temporal averaging
  - ✓ Evaluation of drag coefficient $C_{D,un}$ based on eq. (1)
    - Assume that eq. (1) holds at time-averaged flow level
    - Obtain drag to the target cylinder F_D from simulation results of the original system where no cylinders are removed
    - Calculate $C_{D,un} = 2F_D/(\rho D u_{un}^2)$

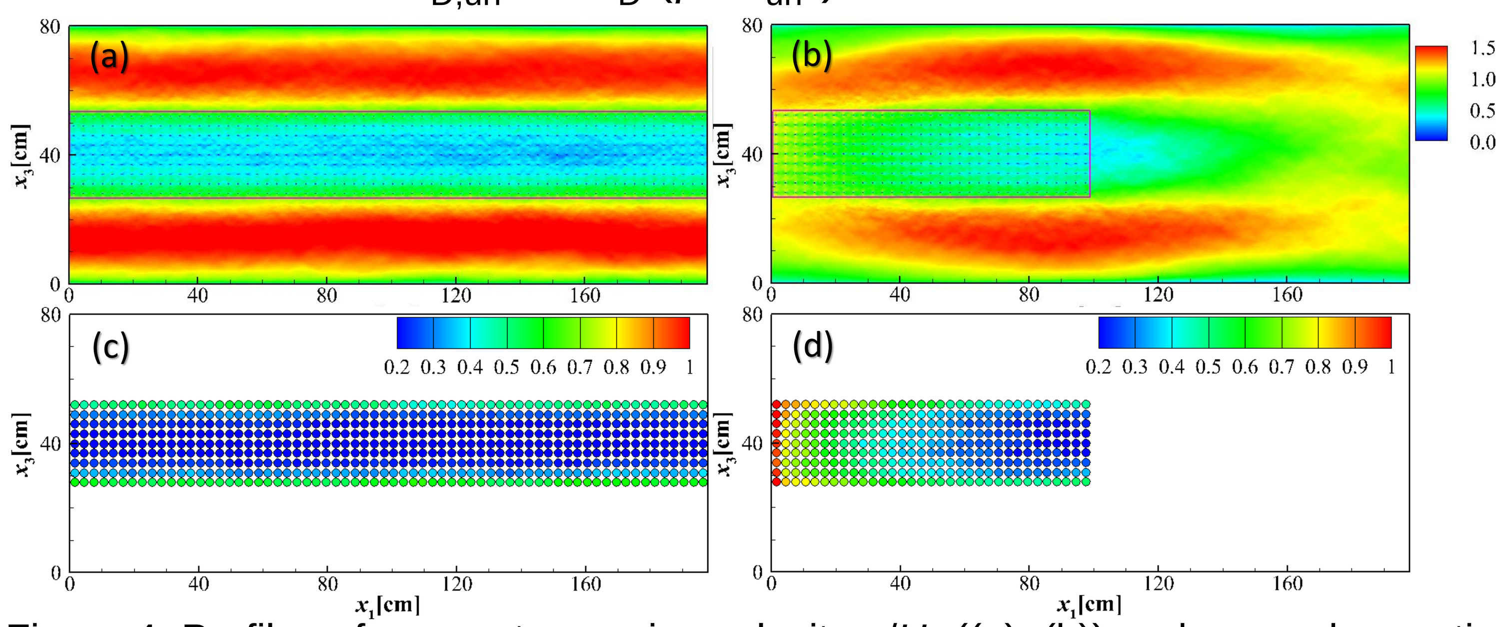


Figure 4. Profiles of mean streamwise velocity u/U_b ((a), (b)) and mean drag acting on each cylinder $F_D/(\rho U_b^2 D)$ ((c), (d)), obtained from the original system (i.e., no cylinders are removed).

Results and discussion

- **Approaching velocity u_a** (see Yokojima & Kawahara (2016))
  - ✓ u_a to the cylinder j-th from the left (upstream) is defined by the maximum value of u_1 between the (j-1)-th and j-th cylinders.
  - ✓ u_{un} is generally unavailable (as can be seen in figure 1(d)), and hence u_a can be an alternative to u_{un} in practical applications

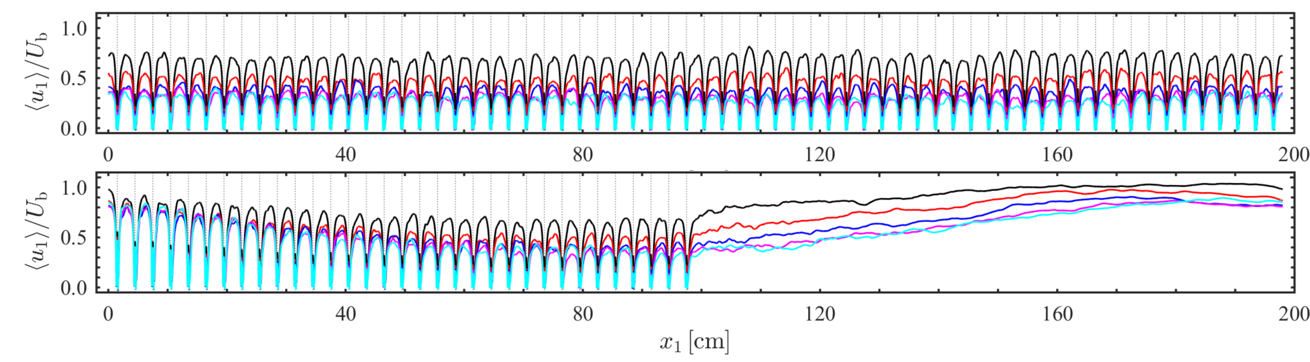


Figure 5. Mean streamwise velocity profiles along streamwise rows passing center of each cylinder. The curve colored by black, red, blue, magenta, and cyan represent velocity profiles along r1, r2, r3, r4, and r5.

- **Profiles of u_{un} and u_a, and the drag coefficient $C_{D,un}$**

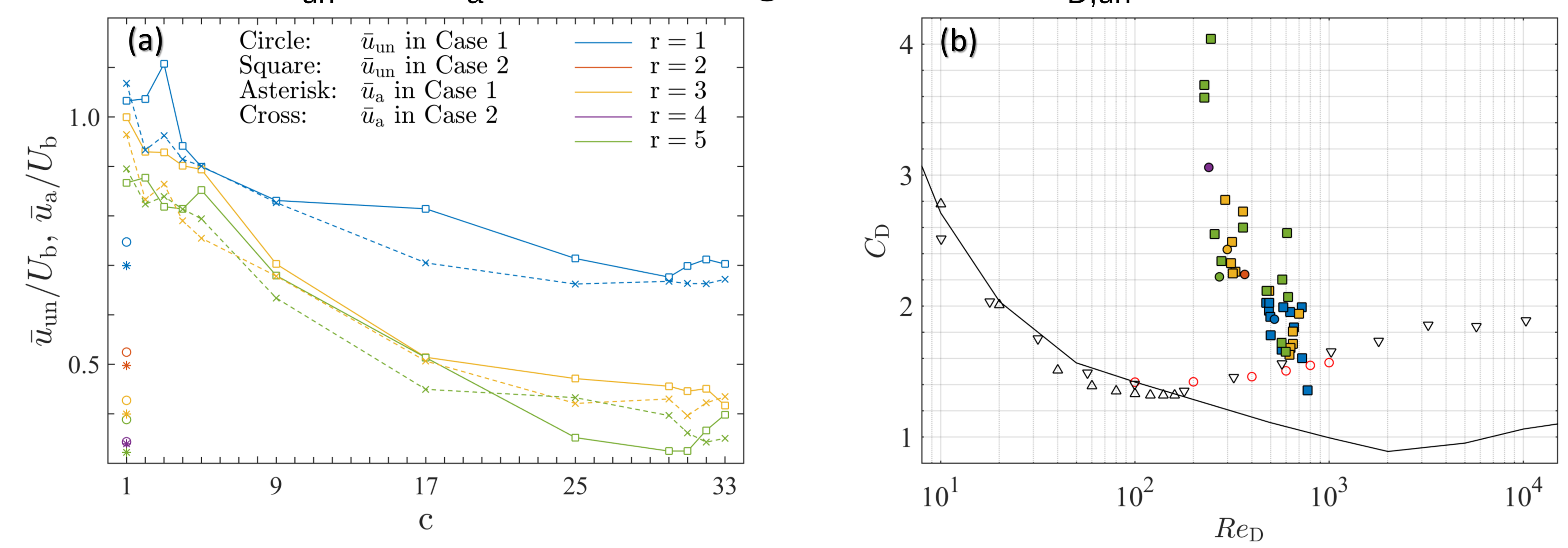


Figure 6. (a) Distributions of undisturbed velocity u_{un} and approaching velocity u_a. (b) C_D-Re_D relation based on u_{un}. In (b), solid line - an isolated circular cylinder in 3-D space (Finnemore and Franzini (2001)); open symbols - an isolated circular cylinder in 2-D space (realized by CFD simulations); filled symbols - array of circular cylinders.

- **Comparison of $C_{D,global}$, $C_{D,local}$, and $C_{D,un}$**

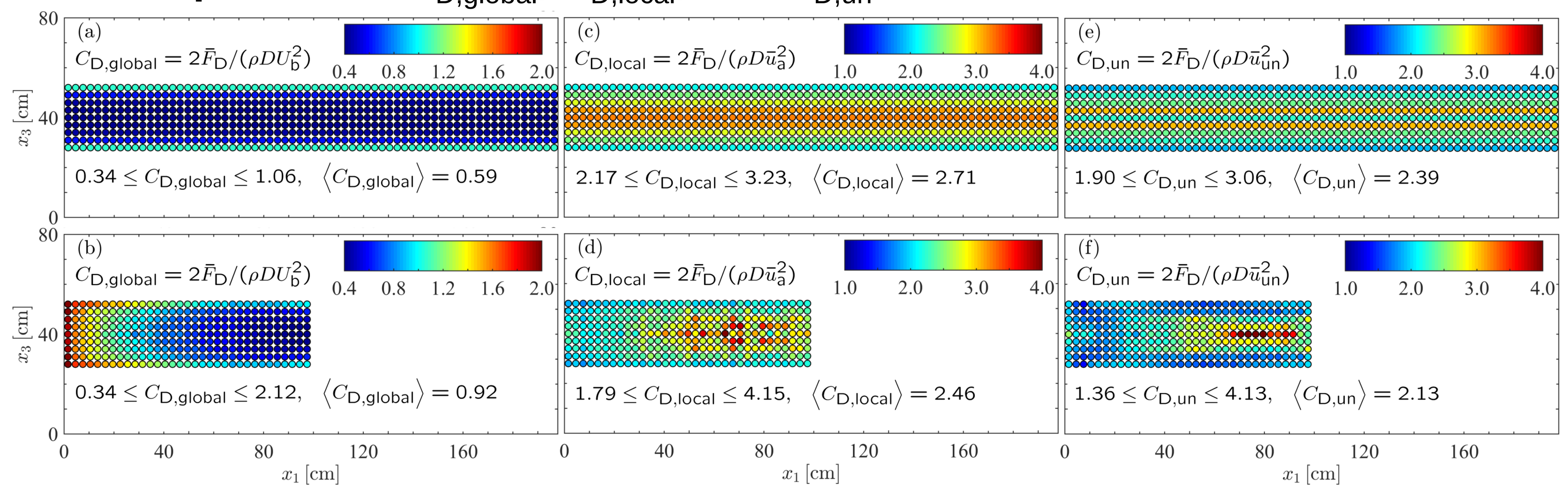


Figure 7. Estimated drag coefficient profiles. Since u_{un} is available only at 36 locations in Case 2, a linear interpolation was used to obtain u_{un} elsewhere.

- **Discussion**
  - ✓ C_D-Re_D relation for each cylinder in array of cylinders is deviated from that for an isolated cylinder even when C_D and Re_D are evaluated based on u_{un}.
  - ✓ Most $C_{D,un}$ are in between 1.5 and 2.5.
  - ✓ u_a captures basic characteristics of u_{un} qualitatively but not quantitatively.
  - ✓ $C_{D,global}$ tends to underpredict vegetation drag (Yokojima & Kawahara (2015)), and $C_{D,local}$ basically overestimate flow resistance (Yokojima & Kawahara (2016)). Since $C_{D,un}$ falls between $C_{D,global}$ and $C_{D,local}$, $C_{D,un}$ is expected to provide a proper resistance to the flow.

References

- Yokojima et al. (2015) "Impacts of vegetation configuration on flow structure and resistance in a rectangular open channel" JHER 9(2) 295.
- Yokojima and Kawahara (2015) "Influence of model drag coefficient on LES prediction accuracy of vegetated open-channel flows" 36th IAHR World Congress.
- Yokojima and Kawahara (2016) "Drag coefficient distribution in LES of vegetated open channel flows" River Flow.