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Using illumination and shadow to model aerodynamic resistance and flow separation: An isotropic study

Adrian Chappell*, George L. Heritage

School of Environment and Life Sciences, University of Salford, Manchester M5 4WT, UK

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Abstract

The momentum extracted from fluid flow by the underlying surface roughness is important for understanding processes of entrainment, transportation and deposition of sediments. The parameter z_0 is a length scale that characterizes the loss of wind momentum attributable to the roughness elements. However, it is very difficult to estimate accurately and precisely even under carefully controlled conditions in wind tunnels. This limits the use of the parameter over large areas and in particular across scales of roughness, e.g., grain to form scale. This is problematic for studies of wind erosion and dust dispersion which require estimates of aerodynamic resistance over very large areas.

A new concept is proposed with the potential to unify the estimates of fluid flow resistance along the continuum of sparse to tightly packed object spacing and across multiple scales. It is based on the creation of shadows by the illumination of roughness elements and the assumption that flow separation is created behind roughness elements on a plane surface as a function of free-stream wind velocity and obstacle height. The concept was implemented using a computer program and validated against a wind tunnel study that estimated z_0 for configurations of spheroids. Various spheroid coverages used in the wind tunnel study were reconstructed using a digital elevation model of the surface simulated by the computer. A strong relationship was established ($R^2 = 0.91$) over two orders of magnitude between the shadow area ratio (SAR) and z_0.

Fluid drag was shown to be dependent on the arrangement of roughness elements at the surface. The configurations of spheroids were replaced by cylinders of the same basal area and computer simulations of shadow area were repeated. Object shape was evidently important to the overlap of shadow with downstream adjacent obstacles and hence aerodynamic resistance was dependent on object shape. These findings appear to contradict empirical evidence of previous studies.

Illumination and shadow of objects on a plane surface appears to adequately represent z_0. Shadow appears to approximate the flow separation behind an obstacle and to represent a wake. The overlap on to downstream adjacent objects of the shadow cast from an upstream object appears to mimic the interference of wakes caused by fluid flow moving around stationary objects with close spacing. There is a compelling argument for the use of SAR as a unifying measure of aerodynamic resistance over the continuum between isolated and tightly packed objects. Furthermore, given elevation data of objects on a plane surface the results show that shadow length is a point-based measure that may be integrated for all points evaluated to provide SAR. The demonstrated angular relationship between illumination and drag (shadow and flow separation) has considerable potential for estimating aerodynamic resistance over multiple scales and for significant

*Corresponding author.
E-mail address: a.chappell@salford.ac.uk (A. Chappell).

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investigations of (i) the anisotropic nature of aerodynamic resistance and (ii) its estimation using directional measurements of reflectance and bidirectional reflectance models.

Keywords: Flow separation; Drag; Wake; Aerodynamic resistance; Boundary layer; Roughness length; Shadow; Illumination; Ray casting; Digital elevation model

1. Introduction

Fundamental to the behaviour of fluid flows and the processes of entrainment, transportation and deposition of sediments is the turbulent transfer of momentum from the fluid to the bed. The fluid velocity depth profile is a manifestation of this downward flux of momentum and the construction of a boundary layer (BL). Horizontal fluid velocities are at a maximum in the free-stream immediately outside the BL and decrease towards the bed because bed roughness imparts resistance to fluid flow over the bed. The parameter z_0 is a length scale that characterizes the loss of wind momentum attributable to the roughness elements. In neutral conditions, the roughness length can be derived from the vertical logarithmic profile of the wind velocity

$$U(z) = \left(\frac{u^*}{\kappa}\right) \ln\left(\frac{z-d}{z_0}\right), \quad (1)$$

where $U(z)$ is the mean velocity at height z, u^* the friction velocity, κ (ca. 0.4) is the von Karman constant and d is height of the displacement plane above ground. According to Arya (1975) a region of separated flow, a distance B, occurs behind each obstacle and at the end of that region, after re-attachment of flow to the surface occurs, a BL develops and the wind profile in that region would also follow the logarithmic law (Fig. 1).

Elliot (1958) believed it reasonable to assume that the flow would not immediately adjust to the array of obstacles and therefore the height of the BL (δ), would increase with distance downwind from the point of discontinuity in roughness. Marticorena and Bergametti (1995) used this concept to suggest that a mean efficient shear stress should integrate the variation in δ between the roughness elements. They argued that for large-scale applications the distance between the roughness elements would be variable and could not be precisely determined. Instead, they demonstrated that a mean value of δ could be defined to estimate the efficient ratio over a range of roughness lengths (between 0.001 and 0.2) for roughness elements between 2.2 to 20 cm.

The roughness length is believed (Elliot, 1958) to depend only on the geometric properties of the surface provided the flow is dynamically fully rough. The momentum extracted by the roughness elements is primarily controlled by their frontal surface and this explains the description of drag partition (Marshall, 1971) involving a roughness density λ, defined as the mean frontal area of the roughness elements (Raupach, 1992). For a plane

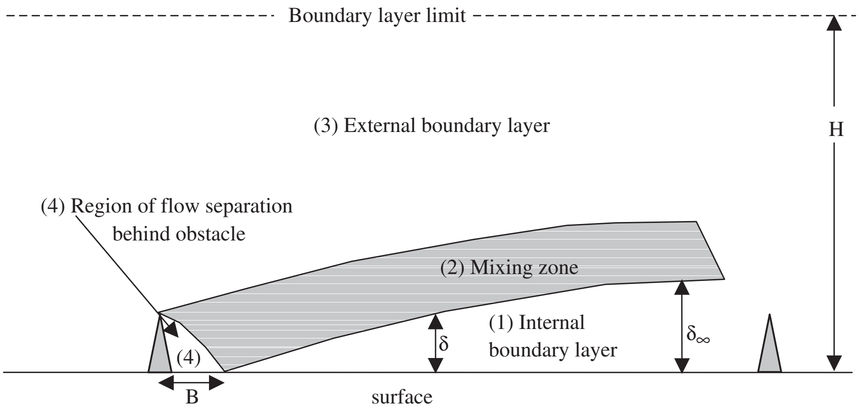

Fig. 1. Schematic representation of boundary layer flow over obstacles and showing four distinct zones (after Arya, 1975).