

## NEW REVISION OF DAVENPORT ROUGHNESS CLASSIFICATION

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### ABSTRACT

The Davenport eight-class description of effective aerodynamic roughness of realistic terrain types is updated, at present summarizing over seventy-five reliable experiments over homogeneous and inhomogeneous terrain. It is used by the WMO and the ASCE, not yet in Europe.

### 1. ROUGHNESS CLASSIFICATION HISTORY.

Obtaining a local working value of roughness for application in a boundary-layer model for wind energy, wind observation exposure correction, diffusion, evaporation or aeronautics may be quite a problem. This is because in Monin-Obukhov-based surface layer models the roughness parameter relates to the turbulence in the layer where the logarithmic wind profile is valid  $\rightarrow$  and the lower limit of this layer is well above the roughness elements. Therefore determination of local roughness parameters requires either wind profile data observed on a sufficiently high mast, or else turbulence or gustiness observations from an anemometer exposed at a level well above the average height of nearby obstacles. Such data are seldom available in working situations.

Practical estimation of terrain roughness at some locality is then often based on published values for roughness of similar terrain elsewhere. The earliest review of roughness parameters covered a rather wide range of terrain types and used only observations made at sufficient height; it was published by Davenport (1960) in an engineering journal. Subsequently in various handbooks many other roughness parameter lists were published, most of which used observations of lesser quality and contained few or no data observed after 1969. The wealth of roughness data from *all* published boundary-layer experiments was reviewed by Wieringa (1993) for homogeneous rural terrain, including forests. Effective roughness of realistic landscape types, irrespective of homogeneity, was proved by him to be most reliably

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described by the 1960 Davenport classification. Wieringa (1992) extended that classification to terrain types with low roughness, such as sea.

At that time, it was rather difficult to update the 1960 classification for high roughness, because most available city roughness determinations could only be rated "acceptable" by objective observation quality criteria. But in the nineties more and better observations of city roughness were obtained by Grimmond et al. (1998) and Grimmond and Oke (1999). Similarly, good quality observations made well above several very rough inhomogeneous rural areas have recently been published, in addition to those for regular forest. Therefore we have updated the rough side of the Davenport classification, making it the most reliable tool for estimating effective aerodynamic roughness over the entire range of real world terrain.

## 2. TURBULENT DRAG DESCRIPTORS.

Roughness parameters describe how effective a surface area is in transforming the energy of the average wind, which flows over it, into turbulent motion in the boundary layer above. Recognizing this fundamental fact helps to understand how we can best estimate roughness. Thermal stratification effects are handled separately. Handbooks define roughness usually in terms of wind profile parameter  $z_0$ , roughness length, because  $z_0$  is height-independent in the upper surface layer and therefore an excellent working parameter (Wieringa 1993). Anyhow, the value of  $z_0$  depends on turbulence intensity and thus on surface drag.

Rough terrain is covered with large obstacles, such as bushes, trees, buildings etcetera. The form drag, which these exert on surface airflow, can soon dominate the skin drag generated by the low cover of the open space in between (e.g. grass, low crops). Therefore roughness of such terrain can be estimated by visually judging distribution and properties of its obstacles. To identify terrain features which we should look at, first consider roughness-relevant aspects of obstacle situations.

If obstacles have height  $z_H$  and cross-flow width  $L$ , the form drag on any isolated obstacle is proportional to its flow-confronting area  $z_H L$  and to the dynamic wind pressure, i.e. to  $\rho U^2$  with the wind speed  $U$  generally taken at  $z_H$ . The proportionality constant  $C_R$ , called drag coefficient, depends on the obstacle shape. We call the total flow-confronting obstacle area per unit terrain surface area the frontal area density  $\lambda_F$ .

Form drag per area will be proportional to  $\lambda_F$  as long as there are so few obstacles that they do not influence each other. This "isolated" flow situation usually applies as long as the plan area density  $\lambda_P$ , which is the terrain surface fraction covered by obstacles, does not exceed a few percent. If  $\lambda_P$  becomes larger, interference will occur between the wakes of obstacles. When  $\lambda_P$  reaches values of the order of 20%, mutual

sheltering of the obstacles becomes dominant. In this situation, called "skimming" flow, interspaces between obstacles below the so-called displacement height  $z_d$  ( $< z_H$ ) have a flow regime rather separate from the boundary layer above. Wind profiles and similarity relations in that boundary layer then are only realistic when related to a "ground" surface located at  $z = z_d$ . In skimming flow, addition of more similar obstacles does not increase any more the form drag per area, i.e. roughness.

For estimating occurrence of wake interference and of the onset of skimming flow we must regard sizes and structure of obstacle wakes. Single buildings have a downwind low-pressure "cavity" zone, in which recirculation occurs, extending to  $\approx 2 z_H$  downwind, and an upwind stagnation zone  $\leq 1 z_H$ ; this implies that wake interference begins at  $\approx 3 z_H$  interspace (Hussain and Lee 1980). Two-dimensionally, for a solid wall of height  $z_H$  its upwind stagnation zone contains a shallow recirculation vortex ("bolster eddy"), and downwind the cavity zone with recirculation, the "near wake", extends to at least  $\approx 5 z_H$ . A separated flow over the wall reattaches to the surface further downwind, starting a turbulent internal boundary layer, the "far wake".

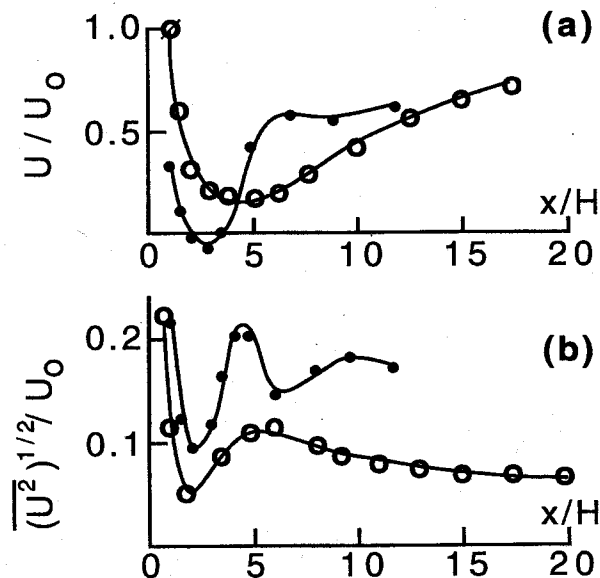


Figure 1 : Flow in the wake of a plate of height  $H$  with porosity less (●) and more (○) porous than 20 % ;  $x$  = downstream distance. (a) mean velocity; (b) turbulence intensity. (Owen, 1971).

Rural wakes are longer and differently structured because the obstacles are flexible and porous. A 2-dimensional barrier with at least 20% porosity, say a shelterbelt, allows enough flow to "bleed" through it that both upwind stagnation and downwind underpressure are so much

weakened, that recirculation does not occur on either side. Instead there is a "quiet zone", extending at the surface to  $\approx 8 z_H$  downwind. This implies that, e.g. for shelterbelts, wake interference begins at  $\approx 10 z_H$  interspace. This difference of wind speed and turbulence regimes behind bluff and porous barriers (or perhaps behind buildings and trees) is illustrated in windtunnel observations given in Figure 1, and these are widely supported by field experiments (e.g. Cleugh et al.1998).

Morphometric models use as input only averages of descriptors  $z_H$ ,  $C_R$ , maybe  $L$ ,  $\lambda_F$  and  $\lambda_P$  to estimate roughness. The results of this modelling are somewhat disappointing (Grimmond and Oke 1999). Variances of the descriptors have not yet been included in these models, though it is known that inhomogeneity or patchiness of obstacle distributions generally increases form drag (Claussen and Klaassen 1992, Schmid and Bünzli 1995, Goode and Belcher 1999). Including other factors such as orientation, or roof shape, or the presence of trees in cities, will complicate modelling and increase input requirements further.

Therefore we should not disregard the option of estimating average roughness visually, using the eye as integrator of (maybe aerial) photographs or land-use maps. We can judge sizes, shapes, distances and densities of obstacles and, when we are supported by a clearly-worded classification, our error will not be more than a single roughness class width. As shown elsewhere (Wieringa 1992), for eight classes the resulting error in potential wind speed will not exceed  $\pm 6\%$ .

### 3. AVAILABLE FULL-SCALE OBSERVATIONS.

The basic material for the 1992 update of the 1960 Davenport roughness classification was primarily a quality-screened review of *all* well-published field determinations of homogeneous roughness (Wieringa 1993). Since the first three classes refer to open terrain and have not much form drag, revision of these classes is not necessary now. On the other side, the "chaotic" class 8 ( $z_0 \geq 2.0$  m) is reserved to describe situations such as skyscraper-dotted cities, where it is obviously very, very rough but the surface is such, that wind flow cannot be described by a 1-dimensional roughness model, assuming dominance of vertical flux. Revision of this class is not urgent either.

For the classes 4 ( $z_0 = 0.1$  m) to 7 ( $z_0 = 1.0$  m) this review furnished part of the material, namely for homogeneous but rather high surface cover. For example, regular forests of sufficiently large area are rather homogeneous in this context, so forest roughness could be confidently located in class 7. But also terrain with partial cover of high obstacles belongs in classes 4 - 7, and for these inhomogeneous terrain situations an additional review list was also published (Wieringa 1992). More reliable recent field data on inhomogeneous rural roughness were

obtained in recent years, among others from tethered-balloon observations, by e.g. Parlange and Brutsaert (1989), Grant (1991), Dolman et al.(1992), Lloyd et al.(1992), Hopwood (1996) and Bottema et al.(1998). A complete review table of 11 of these recent good experiments in rough country is given in Davenport et al. (2000). For updated city roughness data of 14 well-observed townscape sites we refer to similar review lists given by Grimmond and Oke (1999).

For our purpose of class description and validation, observation quality criteria of Wieringa and Bottema (Grimmond and Oke 1999) were used. These stipulate that observations must be well-exposed and stability-corrected, and it is especially necessary to require sufficient height of the measurements, for two reasons. First, to determine roughness parameters without a roughness sublayer bias it is necessary that observations are taken above the blending height — or maybe diffusion height (Grant 1991). Second, roughness remains an area-integral parameter and we require an upwind footprint of sufficient size.

This requirement of sufficient observation height implies, that  $z_d$  must be determined from the curvature of a logarithmic wind profile at a height where that curvature is still small. So scatter in  $z_d$ -data is uncomfortably large (Grimmond and Oke 1999), but the elusiveness of precise  $z_d$  knowledge may not be a pretext to omit its use. As soon as wake interference occurs, some inclusion of  $z_d$  in analysis is needed for handling wind information around the  $z_H$ -level (Bottema et al.1998). However, in practice  $z_d \approx 0.7 z_H$  is an adequately useful estimate for skimming flow.

#### 4. UPDATE AND DISCUSSION.

Considering the recent information available from Grimmond and Oke (1999) for cities and from Davenport et al. (2000) for rough country, the roughest five classes of the 1992-updated original 1960 Davenport classification have been reformulated in Table 1. In particular, it seems necessary to revise the indicated height-normalized interspaces for classes 5 and 6 by assigning separate interspace values to bluff and porous obstacles. The update by Wieringa (1992) presented the wide rural interspace values for classes 5 and 6, but for class 7 the narrow value for cities and regular forests, resulting in an interspace jump between classes 6 and 7. This will not have done much harm in practice because the class descriptions were quite clear.

An earlier zero-draft update of the classes by Wieringa (1980) — with very short class descriptions — already assigned overall the right level of roughness, and the present update does not show that it was significantly biased. However, the Davenport et al. (2000) update of Davenport's effective roughness classification takes more account of differences in obstacle type and therefore allows more precision. Moreover, its reliability on the side of high roughnesses is increased

because the classification now summarizes more than forty experiments over homogeneous terrain and thirty-five experiments at sufficient height over inhomogeneous terrain and over cities — nearly all existing well-published useful experiments. The 1980 and 1992 updates were already adopted by major users such as WMO (1996) and ASCE (1999), and handbooks such as Stull (1995).

This commentary is actual, because presently a Wind Action Eurocode (1991) is proposed, which describes roughness by only four classes instead of eight. That results in a significant class assignment error of around  $\pm 12\%$ . Moreover, that Code's roughness length assignment to open water is about a factor 50 too high, and for forest areas it's  $z_0$  is unrealistically low, only 0.3 m. Some reassessment of the Eurocode roughness descriptions seems necessary to bring it into line with the ASCE and WMO usage, and with nature. Alternatively, an explicit reference to an eight-class code could be given in the Eurocode.

## 5. CONCLUSION

Two dozen good recent publications on the roughness of inhomogeneous rural landscapes and of cityscapes were used to update the Davenport classification into a full-range, optimally reliable description of effective terrain roughness of non-complex terrain. Its eight-class setup places its accuracy well within the uncertainty range, which is operationally necessary for judging and handling terrain roughness in wind engineering models. So use it.

## 6. REFERENCES

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Table 1: Davenport classification of effective terrain roughness

$z_0$ (m)	Landscape description
1: 0.0002 "Sea"	Open sea or lake (irrespective of wave size), tidal flat, snow-covered flat plain, featureless desert, tarmac and concrete, with a free fetch of several kilometers.
2: 0.005 "Smooth"	Featureless land surface without any noticeable obstacles and with negligible vegetation; e.g. beaches, pack ice without large ridges, marsh and snow-covered or fallow open country
3: 0.03 "Open"	Level country with low vegetation (e.g. grass) and isolated obstacles with separations of at least 50 obstacle heights; e.g. grazing land without windbreaks, heather, moor and tundra, runway area of airports. Ice with ridges across-wind.
4: 0.10 "Roughly open"	Cultivated or natural area with low crops or plant covers, or moderately open country with occasional obstacles (e.g. low hedges, isolated low buildings or trees) at relative horizontal distances of at least 20 obstacle heights.
5: 0.25 "Rough"	Cultivated or natural area with high crops or crops of varying height, and scattered obstacles at relative distances of 12 to 15 obstacle heights for porous objects (e.g. shelterbelts) or 8 to 12 obstacle heights for low solid objects (e.g. buildings). (Analysis may need $z_d$ .)
6: 0.5 "Very rough"	Intensively cultivated landscape with many rather large obstacle groups (large farms, clumps of forest) separated by open spaces of about 8 obstacle heights. Low densely-planted major vegetation like bushland, orchards, young forest. Also, area moderately covered by low buildings with interspaces of 3 to 7 building heights and no high trees. (Analysis requires $z_d$ .)
7: 1.0 "Skimming"	Landscape regularly covered with similar-size large obstacles, with open spaces of the same order of magnitude as obstacle heights; e.g. mature regular forests, densely built-up area without much building height variation. (Analysis requires $z_d$ .)
8: $\geq 2$ "Chaotic"	City centres with mixture of low-rise and high-rise buildings, or large forests of irregular height with many clearings. (Analysis by windtunnel advised.)