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ESTIMATING THE ROUGHNESS OF CITIES AND SHELTERED COUNTRY

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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 -- 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 meteorological 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. About 1990, the wealth of roughness data from boundary-layer experiments in the seventies and eighties was reviewed by Wieringa (1993; for short Wi93) for homogeneous rural terrain, including forests. Effective roughness of realistic landscape types, irrespective of homogeneity, was proved by him to be most reliably described by the 1960 Davenport classification. Wieringa (1992, Wi92) extended that classification to terrain types with low roughness, such as the 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" at best 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, G&O99). Similarly good quality observations well above several very rough rural areas have recently been published, in addition to those of forest. So now we can fully update the rough side of the Davenport classification, and make it a more 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. Many handbooks define roughness only by way of the wind profile parameter z_0 , roughness length, because z_0 is height-independent in the upper surface layer and therefore an excellent working parameter (Wi93). Anyhow, the value of z_0 depends on turbulence intensity and therefore on the 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 the roughness of such terrain can be estimated by visually judging the distribution and properties of its obstacles. Here we will discuss roughness-relevant aspects of obstacle situations in order to identify the terrain features which we should try to observe.

If the 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 ρU^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 amount of flow-confronting obstacle area per unit terrain surface area the frontal area density λ_F .

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The form drag per area will be proportional to λ_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 λ_P, which is the terrain surface fraction covered by obstacles, does not exceed a few percent. If λ_P becomes larger, interference will occur between the wakes of obstacles. When λ_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. the 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 separate flow over the wall reattaches to the surface further downwind, starting a turbulent internal boundary layer, the "far wake" (Bradshaw and Wong 1972).

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 the upwind stagnation and the downwind underpressure are significantly weakened, so 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 documented in Fig.1, and these windtunnel observations are widely supported by field experiments (e.g. Nord 1991, Cleugh et al.1998).

Morphometric models use as input only averages of descriptors z_H, C_R, maybe L, λ_F and λ_P to estimate roughness. The results of this modelling are somewhat disappointing (G&O99). 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 (Rafailidis 1997) 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. When we use eight classes, the resulting error in potential wind speed will not exceed ± 6% (Wi92).

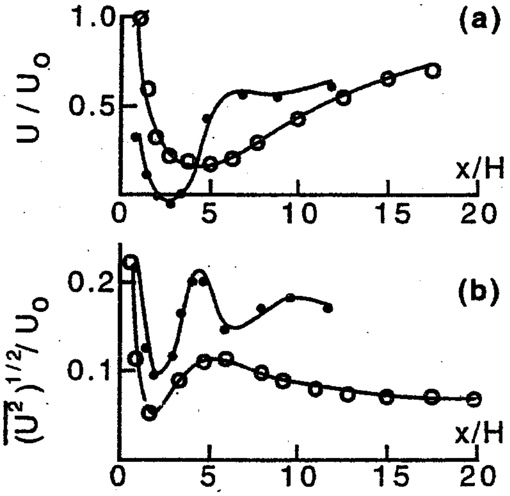

Fig .1 : Flow in the wake of a plate of height H with porosity less (●) and more (o) porous than 20 % ; x = downstream distance. (a) mean velocity; (b) turbulence intensity. (Owen, 1971).

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 published field determinations of homogeneous roughness (Wi93). Since the first three classes refer to open terrain and are dominated by skin drag, revision of these classes is not necessary now. On the other side, the "chaotic" class 8 ($z_o \geq 2.0$ m) is reserved to describe situations as in skyscraper-dotted cities, where it is obviously very, very rough but the surface is such, that wind flow cannot be described by a roughness model which assumes dominance of vertical flux. Revision of this class is not urgent either.

For the classes 4 ($z_o = 0.1$ m) to 7 ($z_o = 1.0$ m) Wi93 furnished part of the material, namely 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 given in Wi92. More recent field data on inhomogeneous rural roughness are listed in Table 1 below, and for updated city roughness data review we refer to lists given in G&O99.

For our purpose of class description and validation, observation quality criteria of Wieringa and Bottema (G&O99) were used. In particular it was 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 sufficent 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 (G&O99), 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 (Shaw and Pereira 1982, 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 G&O99 for cities and from Table 1 for rough country, the roughest five classes of the Wi92-updated original 1960 Davenport classification have been reformulated in Table 2. In particular, it seems necessary to re-evaluate the indicated height-normalized interspaces for these classes, by assigning separate interspace values to bluff and porous obstacles.

The Wi92-update presented the rural interspace values for classes 5 and 6, but for class 7 the urban value, resulting in a jump between classes 6 and 7. This may not have done much harm in practice. In fact, the earlier zero-draft update of the classes by Wieringa (1980), adopted by users such as WMO (1996), is still not unrealistic because its class descriptions are extremely short. However, the description as updated here is more complete — and a new short version will be given in a planned follow-up study on the comparison of city and country roughness.

Such a study seems necessary, because we should explain why in classes 5 and 6 the same effective toposcale roughness requires less obstacle density in a rural setting than in suburban situations (according to our listed data that are the best available). One hypothetical explanation is, that the roughness-parameterized vertical exchange of horizontal motion is less effective for bluff-body than for porous-body wakes, because bluff sharp-edged bodies tend to generate vortices (e.g. in city streets) which are relatively closed systems with respect to turbulent vertical exchange of kinetic energy. Then the boundary layer "sees" a less rough surface than is presented by a more messy wake behind, say, trees. To increase our understanding of such matters, new field data in rough terrain should include observations made well above the major obstacles.

In the meantime, this updated effective roughness classification gives us a field-validated working tool for application in wind engineering and boundary layer modelling over non-complex terrain, well within the uncertainty range which is operationally unavoidable when judging and handling roughness parameters. Our thanks go to all those who made and published the measurements in urban and rural conditions.

TABLE 1 : **Recent field-data on effective roughness of inhomogeneous terrain.**

Surface type	z_o (m) z_d (m)	z_H (m) λ_p (%)	Instruments Obs.heights	Reference Location
many fields ≈ 200 m wide, separated	0.09	4	teth. balloon	Hopwood 1996
by thin porous hedges	0.5	2 %	35 - 225	Oxfordshire, U.K.
sparse bush area (≈ 500 m radius)	0.17	2.3	2 turb.flux	Lloyd et al. 1992
surrounded by fallow savannah	0.9	20 %	3 - 10; 13	Sadoré, Niger
pasture and some narrow woods	0.25	20	teth. balloon	Bottema et al. 1998
(local azimuth WSW)	7	30 %	85 - 150	Sherwood, U.K.
some narrow woods in open fields	0.3 - 0.4	10	teth. balloon	Grant 1991
(local azimuths ESE and ≈ N)	≈ 5	15 - 40 %	40 - 130	Reading, U.K.
scrawny 1.5 m wide trees	0.4	8	5 U + turb.flux	Garratt 1980
on savannah (≈ 20 m spacing)	5	0.4 %	11 - 48; 17	Koorin, Australia
tigerbushes ≈ 20 m wide	0.5	≈ 3	sonde + turb.flux	Dolman et al. 1992
with ≈ 50 m bare interspaces	≈ 2	33 %	10 - 80; 16	Fandou Beri, Niger
regular bushland	0.43	2.3	4 U + turb.flux	Chen Fazu 1989
	1.8	32 %	7 - 21; 8.4	Australia
woods and some pasture fields	0.85	20	teth. balloon	Bottema et al. 1998
(local azimuths W and S)	12	70 %	85 - 150	Sherwood, U.K.
scrawny 2 m wide trees	0.9	9.5	5 U + turb.flux	Garratt 1980
on savannah (≈ 10 m spacing)	7	3 %	10 - 28; 17	Koorin, Australia
woods with some large clearings	1.3	10	teth. balloon	Grant 1991
(local azimuth SSW)	≈ 5	65 %	40 - 130	Reading, U.K.
broken forest	1.2	20	radiosonde	Parlange & Brutsaert 1993
	6	65 %	80 - 160	Landes, France

TABLE 2 : **Davenport classification of effective terrain roughness** (revision 2000).

z_o (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: ≥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.)

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