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ARMY RESEARCH LABORATORY

SURFACE ROUGHNESS LENGTHS

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13. ABSTRACT *(Maximum 200 words)*

The surface roughness length is the meteorological equivalent of an aerodynamic drag coefficient. The surface morphology and terrain relief contribute to the roughness, have a large effect upon surface drag, and influence the analysis of wind, temperature, and specific humidity profiles in the surface boundary layer, as well as the examination of the surface energy balance. Roughness lengths effectively determine the vertical wind shear just above the surface with atmospheric stability almost a direct function of shear and roughness. Experimentally, roughness lengths over many natural surfaces have been determined. Many summaries of estimated surface roughness have been prepared, with most listing only a few typical values. One comprehensive study tabulated all values according to the year the data were collected. In this current effort, an attempt has been made to list roughness as a function of five categories, that is, natural surfaces, including seasonal variations, agricultural lands, urban roughness, effective roughness, and land-use categories.

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1. Introduction

The estimation of surface roughness is of primary importance to the development of models that represent atmospheric processes ranging from the microscale to the mesoscale. Modeling efforts directly affected by surface roughness include complex terrain mesometeorological algorithms, subjective and objective stability schemes, the fluxes of sensible and latent neat into the lower atmosphere, the turbulent kinetic energy budget of the surface boundary layer, and the surface energy balance. The topography--that is, the configuration of an area or region of the earth's surface, including its relief and the position of natural and manmade obstacles--is typically described in terms of roughness elements, roughness lengths, zero plane displacements, or land-use categories with respect to mesoscale wind fields, or probable sheltering effects of structures upon anemometers at airports. The lack, or presence, of vegetation on a surface induces a change of the aerodynamic roughness characteristics encountered by the mean wind flow over that surface. Increasing the height or density of roughness elements will increase the surface and Reynolds stresses for the mean wind flow and radically alter the vertical wind shear in both speed and direction. These alterations to the mean flow affect both the vertical and horizontal diffusivities, the mean wind speed and direction predicted by diagnostic or prognostic models, turbulent intensities, and various other atmospheric parameters such as the vertical flux of sensible and latent heat or the evapotranspiration. Consequently, the surface roughness length and the associated zero plane displacement must be considered as an integral part of modeled atmospheric processes.

Land-use categories are a very useful method of estimating surface roughness lengths. These categories (that is, word-picture descriptions of human use of the earth; for example, "abandoned agriculture," "village," "large city," "brush land and scrub growth") can be quite effective in establishing representative roughness lengths. The land-use categories can be expanded to include terrain features such as hills and mountains that result in a form drag contribu to surface roughness. Form (or pressure) drag arises as a result of separation of flow a nd bluff bodies (such as hills or mountains) immersed in a fluid, such as the atmosphere. Usually, a wake region of chaotic flow is where a pressure deficiency exists on the lee of hills and mountains. Roughness lengths for such complex terrains are thus much larger than the typical vegetative canopy would suggest.

Surface roughness lengths can be classified as either a local or a mesoscale effective roughness length. Local or micrometeorological roughnesses are those usually associated with studies conducted by using experimental data obtained with towers and masts. Generally, tower wind and temperature profiles are observed over large homogeneous fetches under stationary conditions. Calculated surface roughness lengths are then assumed to be site calibration parameters.

Effective roughness lengths are those associated with mesoscale diagnostic or prognostic models and reflect the drag and Reynolds stress characteristics that are representative of the model's horizontal grid size and vertical mesh. The individual blocks of the horizontal grid can represent widely varying terrain relief and vegetation. Thus, the effective roughness length will be a composite or aggregate of local values that allow the mean flow predicted by the model to be in equilibrium with a heterogeneous surface at some arbitrary height above ground level.

A compilation of available information on local surface roughness lengths may be used to establish a comprehensive data base of this parameter with respect to geomorphic terrain relief and land-use categories. These micrometeorological roughness lengths can, in turn, be used as an aid in establishing the effective roughness lengths for mesoscale models and other planetary boundary layer applications.

2. Surface Roughness and the Vertical Profiles

Nikaradse (1933), from measurements of fluid flow in pipes uniformly roughened with grains of sand, found that, roughness length, $z_o = h/30$, where h is the roughness element height. In the atmosphere, a good approximation for z_o is

$$z_o \approx 0.08 \text{ } to \text{ } 0.15 \, h \tag{1}$$

which yields fair results in the absence of more precise information. Tanner and Pelton (1960) have noted that the relationship between surface roughness length and vegetation height can be expressed as

$$\log z_o = a + b \log h \tag{2}$$

where z_o and h are in centimeters. Tanner and Pelton found that a = -0.883 and b = 0.997, which is in good agreement with the coefficient of Sellers (1965) (a = -1.385, b = 1.417) and those of Kung (1961, 1963) where a = -1.24 and b = 1.19.

Lettau (1969) suggested that the relationship between roughness and average vegetation height took the form

$$z_o = 0.5h(s/S) \tag{3}$$

where s is the silhouette area (cm^2) of the typical obstacle seen by the wind, and S the specific area measured in the horizontal plane. If n is the total number of roughness elements on a site of area A, then S = A/n. The factor ½ corresponds to an average aerodynamic drag coefficient. Lettau found that equation (3) yields estimates of z_o that are within $\pm$25 percent of values found from a detailed profile analysis.

The surface roughness length was initially considered to be a constant of integration for the logarithmic wind profile equation, which is usually written in differential form as

$$\frac{\partial \bar{V}}{\partial z} = \frac{u_*}{kz} \tag{4}$$

and in integrated form as

$$\bar{V} = \frac{u_*}{k} \ln \frac{z}{z_o} \tag{5}$$

where $\bar{V}$ is the mean horizontal wind speed, k is Karman's constant, U_* is the friction velocity and represents the stress term, and z is height above the surface. Equation (5) may also be expressed as

$$\bar{V} = \frac{u_*}{k} \ln \frac{z - d}{z_o} \tag{6}$$

where d is the zero plane displacement and represents a datum height above which normal turbulent exchange occurs.

Equations (5) and (6) represent the neutral or adiabatic wind profile and cannot be used to establish surface roughness in diabatic conditions. For thermally stratified mean flow conditions, the Obukhov (1946) dynamic similarity theory must be invoked where the wind profile is given by

$$\frac{\partial \bar{V}}{\partial z} = \frac{u_*}{kz} \phi_M \quad ; \tag{7}$$

$$\bar{V} = \frac{u_*}{k}\left[\ln\frac{z - d}{z_o} + \psi_M\left(\frac{z}{L}\right)\right] \tag{8}$$

where $\emptyset_M$ is a dimensionless wind shear defined for the unstable regime as

$$\emptyset_M = (1 - 15\ Ri)^{-1/4} \tag{9}$$

and in stable flow as

$$\emptyset_M = 1 + 15\ Ri \tag{10}$$

In equations (6) through (8), z/L is the Monin and Obukhov (1954) scaling ratio, Ri is the gradient form of the Richardson (1920) number, and $\psi_M(z/L)$ is adiabatic influence function. According to Zhang and Anthes (1983), in unstable conditions

$$\psi_M(Z/L) = -\left[0.0954 - 1.86\left(\frac{z}{L}\right) - 1.07\left(\frac{z}{L}\right)^2 - 0.249\left(\frac{z}{L}\right)^3\right]. \tag{11}$$

Hansen (1977) suggests that in stable flow

$$\psi_M\left(\frac{z}{L}\right) = 15\ Ri \tag{12}$$

The associated temperature profile may be written as

$$\frac{\partial\bar{\Theta}}{\partial z} = \frac{T^*}{kz}\emptyset_H \tag{13}$$

$$\bar{\Theta} - \Theta_o = \frac{T^*}{k}\left[\ln\frac{z - d}{z_o} + \psi_H\left(\frac{z}{L}\right)\right] \tag{14}$$

with Ø_H a dimensionless lapse rate, T^* a scaling temperature, $\bar{\Theta}$ potential temperature, and Θ_o the potential temperature at z_o. In the unstable regime

$$\text{Ø}_H = (1 - 15\ Ri)^{-1/2} \tag{15}$$

and

$$\psi_H\left(\frac{z}{L}\right) = -\left[0.201 - 3.23\left(\frac{z}{L}\right) - 1.99\left(\frac{z}{L}\right)^2 - 0.474\left(\frac{z}{L}\right)^3\right] \tag{16}$$

In the thermally stratified stable regime

$$\text{Ø}_H = \text{Ø}_M\ ;\ \psi_H\left(\frac{z}{L}\right) = \psi_M\left(\frac{z}{L}\right) \tag{17}$$

The relationships among the similarity parameters are, by definition,

$$\frac{z}{L} = Ri\,\frac{\text{Ø}_M^{\,2}}{\text{Ø}_H}\ . \tag{18}$$

Therefore,

$$\frac{z}{L} = Ri\ ;\ \text{Ø}_H = \text{Ø}_M^2\quad (unstable) \tag{19}$$

$$\frac{z}{L} = Ri\ \text{Ø}_M\quad (stable) \tag{20}$$

where

$$Ri = \frac{g}{\bar{\Theta}} \frac{\partial \bar{\emptyset}/\partial z}{(\partial \bar{V}/\partial z)^2} \tag{21}$$

$$L = - \frac{u_*^3 \, C_p \rho \, \Theta}{kg \, (H + 0.07 \mathcal{L} E)} \tag{22}$$

with L the Obukhov (1946) scaling length, c_p the specific heat of air at constant pressure, ρ the ambient density, g the gravitational acceleration, and H the sensible heat flux. $\mathcal{L}$ is the latent heat of evaporation and E may be considered as either the evaporation or evapotranspiration rate in millimeters.

Usually, local values of z_o are evaluated by using equation (5) or (6) for the neutral case or equation (8) for adiabatic conditions. Equations (5), (6), and (8) can be solved algebraically for z_o or graphically as suggested by Panofsky (1963). If $\ln z + \psi(z/L)$ is plotted as a function of $\bar{V}$, then z_o is the intercept and k/u_* is the slope. An example is shown in figure 1.* Generally, application of equations (5), (6), and (8) should be restricted to the use of high-quality profile data observed experimentally over homogeneous terrain under stationary conditions.

3. The Zero Plane Displacement

The displacement length d is essentially an empirically determined constant that has been introduced into the logarithmic and diabatic wind speed profiles to extend their usefulness to very rough surfaces. This so-called constant can be regarded as a datum height above which normal turbulent exchange takes place, and is comparable to the depth of an air layer trapped in vegetation. The plane ($z = d + z_o$) can be regarded as the height of an apparent sink of momentum within a canopy, according to Monteith (1965) and Thom (1971). Stanhill (1969) has reviewed a large number of estimates for the displacement length for canopies ranging in height from 0.2 to 20 m. These data are illustrated in figure 2. Stanhill suggests that the following relationship exists between d and h:

*Figures are located at the end of the report.

$$\log d = 0.973 \log h - 0.1536 \quad . \qquad (23)$$

However, Monteith implies that the estimates of d are too scattered to support the precision of equation (23) and that

$$d = 0.63h \qquad (24)$$

fits as well as equation (23).

Generally, the value of d will fall between 0.6 and 0.8 of the height h of the roughness elements. The exact ratio of d to h will exhibit a dependency on the spacing of the plants forming the canopy and the ratio of the cumulative area of each element to the unit area of the underlying surface. Zero plane displacements can also be shown to be a function of wind speed. As wind speed increases, a flexible-stocked canopy will tend to flex in the alongwind direction, flattening and being reduced in height. This is demonstrated in figure 3. Over some surfaces, z_o will tend to increase and d decrease. In figure 3, in region I, z_o increases and d shows a decrease as the wind speed increases from zero to some nominal value ∇_1. Montieth (1965, 1973) attributes this to a transfer of momentum from the canopy top to layers deeper in the canopy. In region II between u_1 and u_2, z_o decreases and d increases. This is attributed to an increase of Reynolds number beyond the critical value, and form drag becomes more important than skin friction. The behavior in region III is characteristic of a substantial lowering of the canopy when the plants bend at high wind speeds.

Thom (1972) has suggested that a good approximation for the roughness length z_o based upon d is

$$z_o = k(h - d) \qquad (25)$$

which is in good agreement with equations (23) and (24) if d varies between 0.6 and 0.8 of canopy heights as a function of wind speed, stock flexibility, and the stalk spacing within the canopy.

An abridged listing of zero plane displacements gleaned from the literature is given in table 1.* Then data are presented in ascending order of height h and displacement length d. All values of d are considered to be estimates and were derived from analyses of wind profiles.

*Tables are located at the end of the report.

4. Roughness of Natural Surfaces

Natural surfaces will be designated as undeveloped hinterlands, that is, nonagricultural and nonurbanized. Included in this category will be water surfaces, snow-covered vegetation and terrain, forests, hills, mountains, and deserts. Roughness lengths obtained from many sources for natural surfaces are compiled in table 2. A large number of the tabulated z_0 values were calculated from the micrometeorological analysis of experimental data observed over each of the particular surfaces. Some of the roughness lengths, however, are averages or generic values summarized from many sources such as those extracted from the Engineering Sciences Data Unit (ESDU) (1972) documentation.*

An item of particular interest in table 2 is the approximate 2.5 orders of magnitude seasonal increase in z_0 for tundra as reported by Lewis and Callaghan (1976). Seasonal variations in surface roughness were also investigated by Luers, MacArthur, and Haines (1981) for a number of surfaces. Their results for the annual regime of nine natural vegetated surfaces are shown in table 3. The five-fold increase in the roughness length of a deciduous forest from winter to summer is an indication of the importance of Leaf Area Index (Monteith 1973) to estimating surface roughness. The influence of the growing season and leafing is reflected in the remainder of table 3 and graphically in figure 4.

5. Roughness of Agricultural Lands

The aerodynamic roughness of fields used for the growing of cash crops is an extremely important parameter to the study of agricultural consumption of water resources. Surface roughness enters into the investigation of evapotranspiration from irrigated acreages in semiarid regions through its effects upon the vertical profiles of wind, temperature, and specific humidity. The profiles are then, of course, utilized in conjunction with the surface radiation balance to estimate evaporation and irrigation requirements.

Uncertainties exist in the roughness lengths for farmland and crops because of the limited fetch across a typical field. These heterogenetics exist since most farm acreages consist of a mixed bag of several crops, fallow fields, possibly a wood lot or two, and roads. Under these circumstances, the mean flow is not in equilibrium with the surface. However, most agronomists do not consider this to be a serious handicap.

Typical agricultural surface roughnesses are tabulated in table 4. Note that a mature corn crop has a surface roughness length equivalent to unforested hills and low mountains (see table 2). This large roughness is due to the density of cornstalks in a field.

*The ESDU is sponsored by the Royal Aeronautical Society, Institution of Chemical Engineers, Institution of Mechanical Engineers, and the Institution of Structural Engineers, London, UK.

6. Roughness of Urban Areas

Urbanization may be thought of as covering the full spectrum of built-up areas from small rural communities to the true megatropolis. Any grouping of a small number of buildings will aid in altering the mean flow near the surface by increasing the roughness length. Circumstances sometimes lead to an accumulation of structures because of geographical features. As an example, two highways have a junction at the only feasible river crossing in miles. At this junction, over the years a service station, café, and mercantile are established. Then a small motel and a bait shop are built since the fishing is good. In time, other businesses and residents are added and the community or settlement acquires a name such as Shagnasty's Corner. This is the lower limit of urbanization.

More properly, urbanization begins with the hamlet and reaches the ultimate in the primary metropolitan statistical area or megatropolis. According to the United States Census Bureau, a hamlet is the smallest urban area recognized. As defined in table 5, a hamlet is unincorporated and lacks nearly all government furnished services except fire protection. Table 5 explains inhabited areas by population ranges. The table is self-explanatory.

Table 6 is a listing of generic urban roughness lengths. Included in the compilation are such urban features as large expanses of deserted parking lots (blacktop and concrete) well-manicured lawns, airports, plus highway and railway roadbeds and rights-of-way. The final six listings in table 6 define the typical surface roughness of large cities and metropolitan areas.

The surface roughness length of cities is of worldwide interest and has applications to air pollution, the surface energy balance and the all-encompassing urban heat island effect. Roughness lengths for 46 cities are given in tables 7, 9, and 10 for North America, the British Isles plus the Continent, and Japan, respectively. North American cities for which data are available extend from Canada to Texas and from the midwest to the eastern seaboard. Saint Louis, Missouri, has been the subject of an intensive investigation by Clarke, Ching, and Godowitch (1982) who found that the roughness of Saint Louis ranged from about 30 cm in the suburbs to approximately 170 cm in the central core. A second, less extensive urban experiment was reported on by Yersel and Goble (1986) for Worchester, Massachussetts. For one site in the city, surface roughness was estimated by using two approaches and tabulated for 30- to 40-degree sectors of azimuth about the observation site. These data are reproduced in table 8. For a neutral atmosphere, the logarithmic profile assumption was used to establish z_0 and compared with values calculated from the height of the roughness elements divided by a constant, a method attributed to Brutsaert (1975). The agreement is considered to be only fair. However, the dependence of surface roughness on wind direction is obvious in both methods.

The United Kingdom and Continental urban roughness data are in good agreement with their North American counterparts with the exception of roughness listed for Kiev and Copenhagen. Hanna (1969), in an examination of urban micrometeorology, points out that

Ariel and Kliwchnikova (1960) failed to include a zero plane displacement in their analysis. As a consequence, Hanna found $z_o = 150$ cm for Kiev. Hanna's reanalysis is shown in figure 5. Jensen's (1958) surface roughness length for Copenhagen is abnormally high, also. The zero plane displacement may not have been considered.

Japanese investigators have assembled what is probably the only national survey of urban roughness. Table 10 shows estimates of surface roughness lengths for 25 towns and cities, including a comprehensive study of Tokyo. These estimates were determined for various sections of the city from the suburbs to the central core. The general trend of surface roughness for Tokyo parallels that of Saint Louis, increasing towards the inner city. It would appear that urban roughness is about the same worldwide, that is, a general increase in z_o as a function of population and city area.

Yersel and Goble (1986) and Ayer (1978) have pointed out that in a typical metropolitan area, only about 17 percent of the area consists of structures and 21 percent trees. The remainder or 62 percent of the area is water surfaces, grassy areas, residential streets, parking lots, and street canyons in the city core. This suggests that the large roughness lengths for urban areas are the result of pressure or form drag rather than the aerodynamic roughness of a surface.

Structures in an urban area may be considered to be bluff bodies and are characterized by having a relatively large proportion of form drag. Flat plates normal to the mean flow are examples of pure form drag. Aerodynamically speaking, the various types of drag are form drag and viscous drag or skin friction. Combining these yields profile or parasite drag and the numerical difference between the two types of drag is labeled residual drag. Typically, form drag in unseparated flow is small, but large if flow separation or cavitation has occurred. Viscous drag can be directly related to vertical shear or the Reynolds stresses. The drag on two bodies placed close together is generally quite different from the sum of the separate drag, is usually defined as interference, and becomes important when one body is affected by the wake of another.

This is the case in an urban area where the roughness elements (buildings) are always downwind of one another and not of uniform height, distribution, and cross-sectional areas.

7. The Effective Roughness Length

Fiedler and Panofsky (1972) have defined the effective roughness as the roughness length which homogeneous terrain would have in order to produce the space-average downward flux of momentum near the ground with a given wind near the surface. Expanding upon this concept the effective roughness can be expressed as a function of the geostrophic drag coefficient, the surface Rossby number and a suitable buoyancy parameter. The concept of an effective surface roughness is necessary to properly scale the surface and Reynolds stresses for inclusion in large-scale atmospheric models. In most complex terrain-mesoscale models the friction velocity u_* is used to represent the stress terms.

Several numerical approaches exit for determining the effective surface roughness length over some arbitrary area or region. The most common is to utilize the adiabatic wind profile, that is, equation (5) and Rossby number similarity,

$$\ln(Ro) = A - \ln Cg + \left\{ \left(\frac{k}{Cg}\right)^2 - B^2 \right\}^{1/2} \tag{26}$$

where Ro = $G/(fz_o)$, the surface Rossby number, Cg = U_*/G the geostrophic drag coefficient, f the Coriolis parameter, and A and B constants. For indifferent thermal stratification

$$A = 1.5, B = 4.0 .$$

A second approach is to assume that the effective roughness length is mostly determined by the roughest elements within the averaging domain.

Thirdly, Taylor (1987) advocates that the effective roughness length may be implied from a grid-square average of local or micrometeorological roughness lengths from

$$z_{o(eff)} = z_o m \tag{27}$$

where

$$\ln z_o m = \langle \ln z_o \rangle \tag{28}$$

and $\langle\,\rangle$ may be construed as an ensemble average over the averaging domain.

A fourth approach utilizes weighting functions for a series of diminishing values of z_o in each grid of the mesoscale area. Smith and Carson (1977) used two weights of ⅔ and ⅓ for the major and minor roughness elements; van Dop (1983) initially weighted the largest fraction as 0.67, the second 0.22, and the least prominent at 0.11. Van Dop then modified his initial weights to obtain optimum agreement between calculated and observed values, resulting in weights of 0.85, 0.125, and 0.025.

All four methods produce fair approximations of effective roughness lengths, but are laborious to apply. A fifth approach suggested by Yamazawa and Kondo (1989) is an elaborate regression scheme based upon four land utilization divisions shown in table 11, with z_o calculated from

$$z_o = 40a + 125b + 200c + 110d - 30 \text{ for } 20\ cm < z_o < 150\ cm \tag{29}$$

where a, b, c, and d are the ratios of each utilization area to total fetch area. Fetch areas are fan-shaped with a 45-degree central angle with a radius of 100 z_a where z_a is anemometer height. Again, the use of equation (29) would be extremely time-consuming.

Establishing an effective roughness length is necessary if adequate solutions are required for mesoscale analysis, reliable estimates of atmospheric stability using either objective or subjective schemes, and for solutions pertaining to the diffusion of windborne material.

8. Land-Use Categories

Kung's (1963) climatological effective surface roughness lengths for the northern hemisphere successfully utilized land-use categories to classify regional roughness. Surface roughness associated with land-use categories obviously is well within the realm of effective roughness lengths. Land-use categories are simply general, or common, verbal descriptions of the world around us. It is relatively simple to define the association between surface roughness lengths and a subjective description of the terrain for which z_o was determined. Figure 6 consists of an abridged listing of effective roughness lengths with respect to land-use categories. Figure 6 is in the ESDU (1972) format. Included are both rural and urban information that may be used to estimate aerodynamic roughness for areas and regions where no actual micrometeorological measurements are available or practical.

9. Discussion

Counihan (1975) summarized a large number of roughness lengths obtained either by direct measurement or by inference. Unfortunately, these data are tabulated by the year the observations were reported and alphabetically by author rather than by land-use category or by numerically ascending order. Site descriptions are also vague, being in terms of city names or simply urban; by terrain descriptions such as trees, rural, grass, sea, woods, coastline, or snow. Sorting out these data in an orderly array would be an onerous chore. Overall, however, this very complete history of the surface roughness length provided many clues to sources of information for this study.

An attempt was made to include only roughness length values that were determined by using good scientific and engineering practice. Several suspect studies were excluded after an independent evaluation of the data was made.

Throughout the roughness length literature, there are indications that sufficient accuracy for profile applications is obtained with surface roughness estimates within a factor of 2 or so. Rachele et al. (1991) found that for surface energy balance evaluations an error in estimating z_o of only 30 percent led to rather alarming errors in both the sensible and latent heat fluxes as well as a 30- to 42-percent error in the Obukhov (1946) length.

Apparently the sensitivity of micrometeorological data to variations in the roughness length is quite critical.

10. Conclusions

Surface roughness length data has been examined with respect to several categories of land use and terrain relief. Additionally, the role of the surface roughness with respect to wind and temperature profile analysis has been discussed, as well as the areal effective roughness length. Urban roughness was scrutinized with respect to the effects of form drag of buildings and interference drag components of upwind structures. A general rule regarding surface roughness lengths can be tentatively expressed that $z_o \approx 0.1$ the height of the roughness elements, and for mesoscale areal estimates that z_o is numerically the equivalent of the largest upwind roughness elements. A reasonable upwind fetch for applying this crude estimate would be about 3 km.

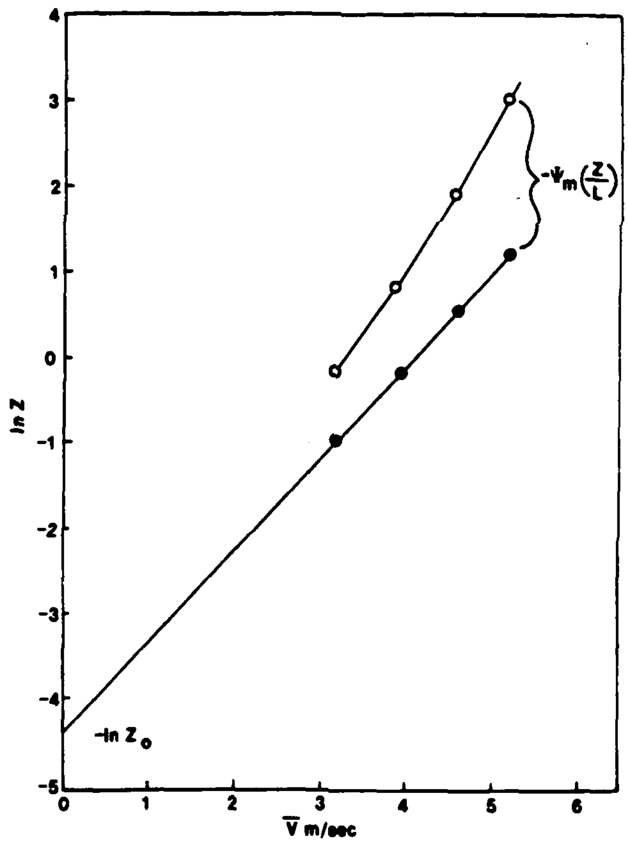

Figure 1. Example of windspeed $\overline{V}$ (m/s) plotted against ln z, where z_o is the intercept and k/u_* is the slope.

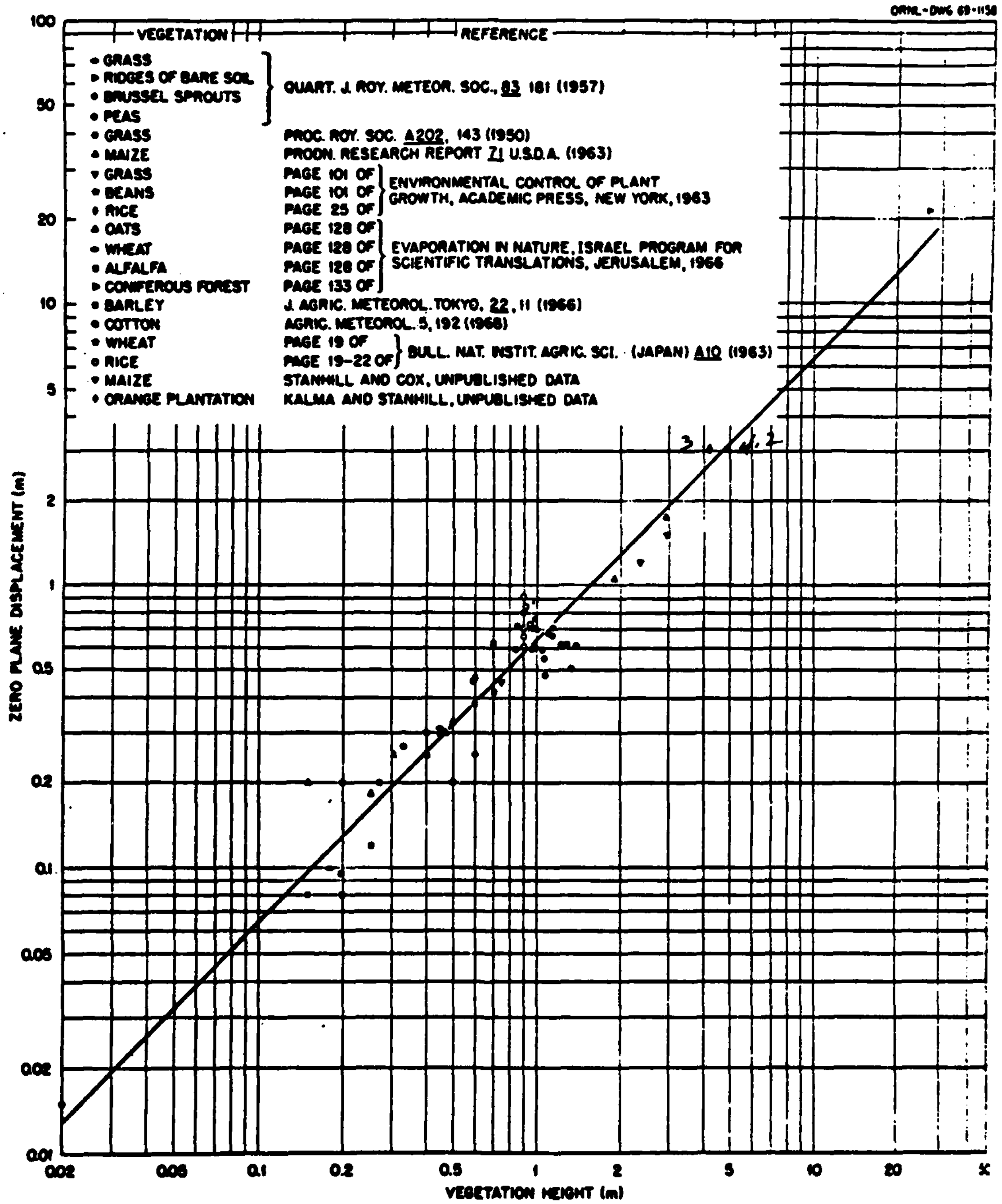

Figure 2. Estimates for the displacement length for canopies (after Stanhill 1969).

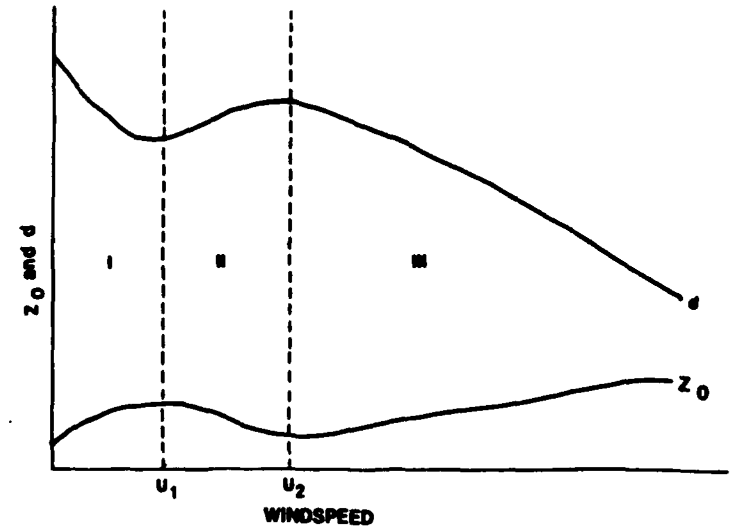

Figure 3. Zero plane displacement shown as a function of wind speed (see text for details of regions I, II, and III).

Figure 4. Annual cycle of surface roughness lengths for selected surfaces.

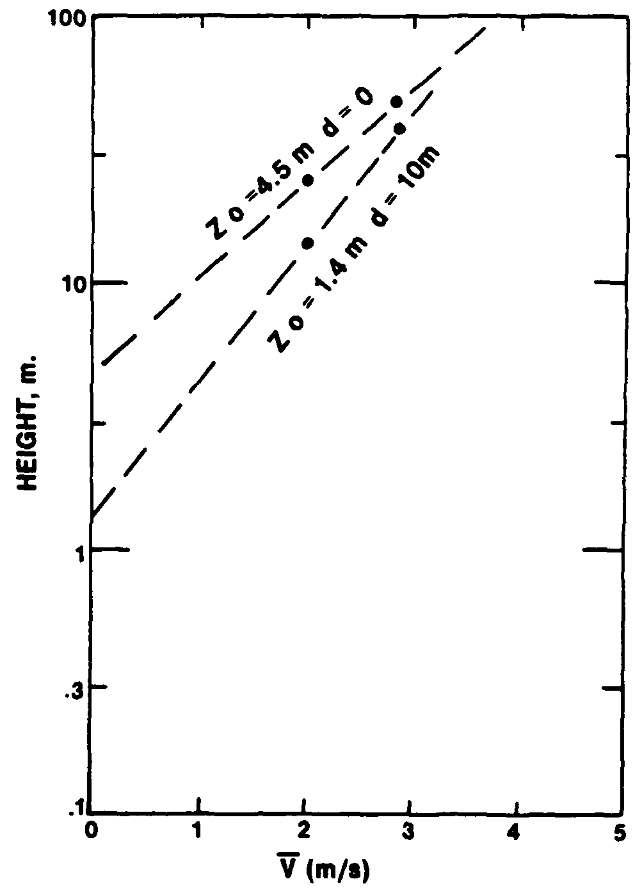

Figure 5. Illustration of the consequence of failing to include a zero plane displacement in surface roughness analyses (after Hanna (1969) and Ariel and Kliwchnikova (1960)).

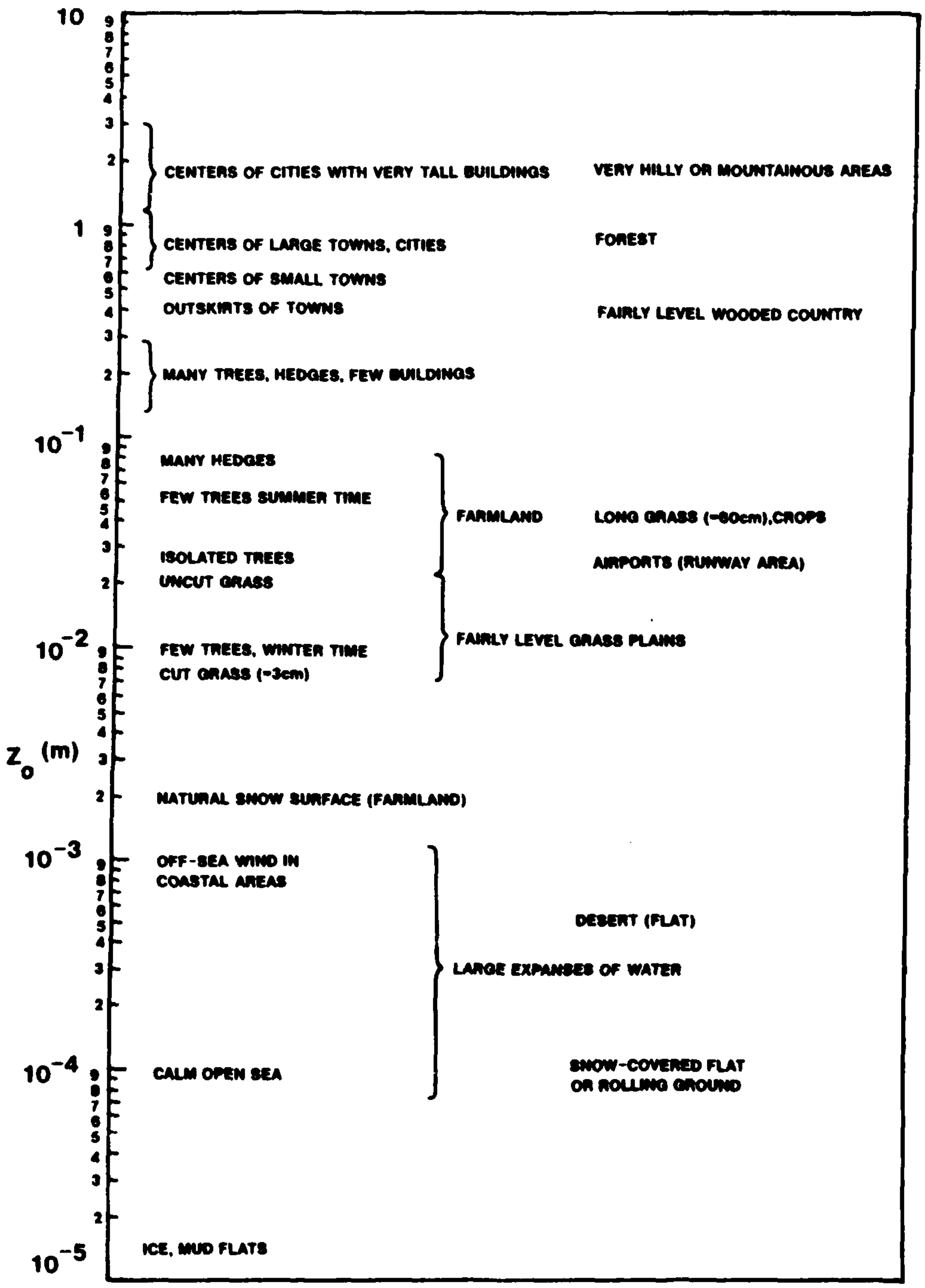

Figure 6. Abridged listing of effective roughness lengths with respect to land-use categories (after ESDU, 1972).

Table 1. Zero Plane Displacements as a Function of Canopy Heights

Canopy	Vegetation Height, h, meters	Displacement length, d, meters	Source	
Lawn	0.01	0.007	Monteith	1973
*Alfalfa	0.24	0.13	Stanhill	1969
Rice	0.90	0.85	Stanhill	1969
*Corn	1.09	1.00	Stanhill	1969
Corn	2.30	0.95	Monteith	1973
Corn	2.90	1.80	Stanhill	1969
Orange grove	4.20	3.00	Stanhill	1969
**Scattered trees, shrubs	8.00	5.30	Garratt	1978
†Scattered trees, shrubs	9.50	6.10	Garratt	1978
Pine forest	20.00	13.10	Thom	1971
Coniferous forest	25.00	22.00	Stanhill	1969

*immature crops
**roughness element spacing about 20 m
†roughness element spacing about 10 m

Table 2. Roughness Lengths of Natural Surfaces

Type of Surface	z_0 cm	Source	
Ice	0.001	Deacon	1953
Smooth mud flats	0.001	Deacon	1953
Dry lake bed	0.003	ESDU	1972
Tundra		Lewis and Callaghan	1976
Snow-covered	0.01		
Patchy snow	0.03		
Water-covered, after melt	0.40		
Midsummer	2.40		
Snow cover (Antarctic)	0.01	Jackson and Carroll	1978
Calm open sea	0.01	ESDU	1972
Snow-covered rolling ground	0.01	ESDU	1972
Smooth desert	0.03	Deacon	1953
Flat desert	0.05	ESDU	1972
Normal sea	0.10	ESDU	1972
Closely mown grass	0.10	Deacon	1953
Short grass	0.14	Rider et al.	1963
Snow-covered farmland	0.20	ESDU	1972
Caspian Sea	0.20	Goptarev	1957
Snow (Sastruga) crosswind	0.70	Jackson and Carroll	1978
Sparse grass, 10 cm high	0.70	Deacon	1953
Nebraska prairie	0.70	Barad	1959
Thick grass, 5 to 6 cm high	0.75	Lovey	1958
Fairly level grassy plains	1.0	ESDU	1972
Salisbury Plain, UK	1.0	Scrase	1930
Kansas prairie	1.0	Businger et al.	1971
Level terrain, low shrubs	2.6	Cramer	1952
Grasslands, ≈ 18 cm high	2.7	Ripley and Redmann	1976
Uncut grass, isolated trees	3.0	ESDU	1972
Grass and trees, mixed	3.5	Shiotani	1962
Semiarid, sparse brush	5.0	Blackadar	1965

Table 2. Roughness Lengths of Natural Surfaces (continued)

Type of Surface	z_0 cm	Source	
Sparse grass, 50 cm high	5.0	Deacon	1953
Thick grass, 50 cm high	9.0	Deacon	1953
Thick grass, 60 to 70 cm high	8 - 15	Deacon	1953
Brush, scrub growth, open	16	Luers et al.	1981
Field, scattered trees, hedges	25	ESDU	1972
Brush, scrub growth, dense	25	Leurs et al.	1981
India, trees, 13 m high	29 - 34	Panchal and Chandrasekharan	1983
Fairly level wooded country	40	ESDU	1972
Forest clearings, cutover areas	40	Leurs et al.	1981
Subtropical savannah, grass, scattered trees, 8 m high	31 - 41	Garratt	1978
Subtropical savannah, shrubs, grass, 8 m; ≈ 10 m spacing	51 - 61	Garratt	1978
Low mountains, hills, unforested	75	Leurs et al.	1981
Fairly level forested plateau	70 - 120	Ming et al.	1983
Tropical rainforest, 40 m high	100	Allen and Lemon	1976
Smooth, open forest	100 - 500	Ming et al.	1983
Coniferous forest	110	Leurs et al.	1981
Pine forest ≈ 20 m trees	110 - 170	Thom	1972
Pine forest ≈ 20 m trees	128	DeBruin and Moore	1985
Forested plateau, rolling	120 - 130	Ming et al.	1983
Rolling terrain, forested scattered structures	200 - 250	Ming et al.	1983
Fir forest	283	Baumgartner	1957
Forested ridges, 150 to 200 m	350	Nappo	1977
Irregularly forested hills 100 to 200 m high	600-1100	Ming et al.	1983

Table 3. Annual Cycle of Surface Roughness Lengths for Selected Surfaces

Surface	J	F	M	A	M	J	J	A	S	O	N	D
	Month											
Semiarid, widely spaced low vegetation	0.02	0.02	0.02	0.02	0.05	0.07	0.1	0.1	0.1	0.1	0.06	0.02
Semiarid, closely spaced low vegetation	0.17	0.17	0.17	0.17	0.43	0.69	0.95	0.95	0.95	0.95	0.56	0.17
Wetlands	0.5	0.5	0.5	0.5	1.25	2.0	2.75	2.75	2.75	2.75	1.6	0.5
Grassland, meadows	0.75	0.75	0.75	0.75	1.15	1.6	2.0	2.0	2.0	2.0	1.4	0.75
Grassland, some trees	1.0	1.0	1.0	1.0	2.5	4.0	5.5	5.5	5.5	5.5	3.25	1.0
Brushland, open	1.6	1.6	1.6	1.6	4.0	6.4	8.0	8.0	8.0	8.0	4.8	1.6
Brushland, dense	2.5	2.5	2.5	2.5	6.3	10.2	14	14	14	14	8.2	2.5
Deciduous forest	18	18	18	18	45	72	100	100	100	100	59	18
Mixed forest	64	64	64	64	78	91	105	105	105	105	85	64

Table 4. Agricultural-Related Roughness Lengths

Type of Surface	z_o cm	Source	
University research farm	0.11	Sterns	1970
Rice paddie, after harvest	2	Kondo and Yamazawa	1986
Alfalfa	2.7	Jenner and Pelton	1960
Agricultural areas, Japan	3 - 11	Kondo and Yamazawa	1986
Cashew orchard, 2 m high	3.5 - 4	Panchal and Chandrasekharam	1983
Potatoes, 60 cm	4	Brown	1976
Farmland, few trees	6	ESDU	1972
Bean crop 1.2 m high	7.4	Thom	1971
Farmland, many hedges	8	ESDU	1972
Low crops, some large obstacles	10	Davenport	1967
Cotton 1.27 m high	13	Stanhill	1976
Fields, trees, hedges, buildings	20	ESDU	1972
Wheat	22	Penman and Long	1960
Tall crops, scattered obstacles	25	Davenport	1967
Farmland, European	25	Van Dop	1983
Citrus orchard 3.2 m	31	Brooks	1959
Citrus orchard 4 m	40	Kalma and Fuchs	1976
Citrus orchard 4.35 m	40	Kalma and Fuchs	1976
Corn 2.2 m	74	ESDU	1972

Table 5. Inhabited Areas by Population Ranges

Type of Settlement	Population	Remarks
Hamlet	< 1,000	A settlement too small to be called a village; a grouping of dwellings in a rural setting; especially one without a church, being in a parish belonging to a village or town. Sometimes the distinction is that a village has a constable and a hamlet none. Police protection provided by county, but normally has volunteer fire department.
Village	1,000 to about 2,500	Can be unincorporated. If incorporated, usually has a board of three or more trustees, a mayor, treasurer, municipal clerk, and a police official. Residents usually practice a variety of trades and professions, and several levels of society are present. Has county or volunteer fire department.
Small Town	2,500 to about 10,000	First level of true urbanization. In general, a place that is a population and business center and is recognized as such geographically and politically. A compact settlement engaged mostly in nonagricultural occupations.
Town	10,000 to about 50,000	Considered to be a municipal corporation with a well-structured street pattern. Usually provides full services to population (that is, public transportation, garbage collection, police and fire protection). Does not quite qualify as a metropolitan statistical area (MSA). Some industry. Well-defined down-town area surrounded by suburbs.
Small City	50,000 to about 100,000	Metropolitan statistical area (population > 50,000). Regional banking center. Usually has complex governmental structure, that is, mayor-council, council-city manager, paid elected officials. Occasional air pollution problems. Small high-rise central core; industrial area, extensive suburbs.
Medium-sized City	100,000 to about 250,000	Major political subdivision. High rise central core area. Center for heavy industry. Complex social and business activities. Experiences extensive air pollution episodes.
Large City	> 250,000	Extensive high-rise core area. Nonagricultural; industrialized. Suffers from urban blight, pollution, social, ethnic problems.
Metropolitan Area	500,000 to about 1,000,000	Alternate definitions for large city. Also defined as primary metropolitan statistical area (PSMA).
Megatropolis	> 1,000,000	

Table 6. Generic Urban Roughness Lengths

Type of Surface	z_o cm	Source	
Blacktop or concrete	0.002	Rider et al.	1963
Lawn, 1 cm high	0.1	Deacon	1953
Cut grass, few trees	1	ESDU	1972
Airport runway areas	3	ESDU	1972
Village	40	Leurs et al.	1981
Highways, railways	50	van Dop	1983
Towns	55	Leurs et al.	1981
Light density residential	110	ESDU	1972
City park	130	ESDU	1972
Office buildings	175	ESDU	1972
Urban sprawl	260	Slade	1969
Central business district	330	ESDU	1972
High rise apartments	370	ESDU	1972

Table 7. Urban Roughness Lengths, North America

City and State or Province	z_o cm	Source	
Columbia, MD	70	Landsberg	1981
Cambridge, MA	74	Dobbins	1977
Montreal, PQ	100	Davenport	1967
Worchester, MA	112 - 168	Yersel and Goble	1986
St. Louis, MO		Clarke et al.	1982
Central core	170		
Industrial area	140		
Suburbs	30		
Minneapolis, MN	200	Deland and Binkowski	1966
London, ON	240	Davenport	1965
Austin, TX	242	Peschier	1973
Philadelphia, PA	260	Slade	1969
Fort Wayne, IN	300	Bowne and Ball	1970
New York, NY	330	Davenport	1960

Table 8. Comparison of z_o Values Estimated in Two Ways

Wind Direction	z_o (log-profile assumption) (m)	z_o(h/8)(m)
10 to 50°	2.54 ± 0.41	1.68
51 to 90°	1.71 ± 0.10	1.60
190 to 220°	1.18 ± 0.20	1.23
221 to 249°	0.57 ± 0.25	1.12
250 to 284°	1.06 ± 0.45	1.16
285 to 330°	0.82 ± 0.17	1.23

Table 9. Urban Roughness Lengths, British Isles and the Continent

City and Country	z_o cm	Source	
Leipzig, FRG	38	Davenport	1960
Kew, Coryton, Hampton, UK	43	Heliwell	1971
Reading, UK	70	Marsh	1969
London, UK	78	Heliwell	1971
Uppsala, Sweden	90	Hogstrom et al.	1977
Liverpool, UK	123	Jones et al.	1971
Leningrad, USSR	246	Ariel	1960
Moscow, USSR	300	Ivanov and Klinov	1961
*Kiev, USSR	450	Ariel and Kliwchnikova	1960
Copenhagen, Denmark	750	Jensen	1958

*Hanna (1969) determined that the roughness for Kiev had been calculated without consideration of a zero plane displacement. Hanna found z_o = 150 cm for Kiev.

Table 10. Urban Roughness Lengths, Japan

City and Prefecture	z_o cm	Source	
Akita, Akita	19	Kondo and Yamazawa	1986
Ryugasaki, Ibaraki	26	Kondo and Yamazawa	1986
Honjo, Akita	26	Kondo and Yamazawa	1986
Tsuruoka, Yamagata	30	Kondo and Yamazawa	1986
Isesaki, Gunma	31	Kondo and Yamazawa	1986
Noshiro, Akita	32	Kondo and Yamazawa	1986
Sano, Tochigi	34	Kondo and Yamazawa	1986
Kooriyama, Fukashima	42	Kondo and Yamazawa	1986
Shiura, Aomori	42	Kondo and Yamazawa	1986
Tatebayashí, Gunma	42	Kondo and Yamazawa	1986
Shitotsuma, Ibaraki	44	Kondo and Yamazawa	1986
Funchiki, Fukushima	48	Shiotani	1962
Kokubanji	48	Kondo and Yamazawa	1986
Sendai, Miyagi	52	Kondo and Yamazawa	1986
Furukawa, Miyagi	52	Kondo and Yamazawa	1986
Tsukidate, Miyagi	53	Kondo and Yamazawa	1986
Sakata	58	Kondo and Yamazawa	1986
Maebashi, Gunma	76	Kondo and Yamazawa	1986
Aomori, Aomorí	79	Kondo and Yamazawa	1986
Kamagaya, Scitama	81	Kondo and Yamazawa	1986
Onahama, Fukushima	92	Kondo and Yamazawa	1986
Ishinomaki, Miyagi	104	Kondo and Yamazawa	1986
Koga, Ibaraki	161	Kondo and Yamazawa	1986
Mito, Ibaraki	168	Kondo and Yamazawa	1986
Tokyo, suburbs	40	Shiotaní	1962
Tokyo	145 - 185	Yamamoto and Shimanaki	1964
Tokyo	150	Kamei	1955
Tokyo	170 - 232	Kondo	1971
Tokyo	232	Kawanabe	1964
Tokyo	400	Shiotaní	1948
Tokyo	400	Naito	1962

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INFORMATION

ERRATA PAGE

ARL-TR-61, Surface Roughness Lengths

Replace pages 21 and 22 with the enclosed new pages.

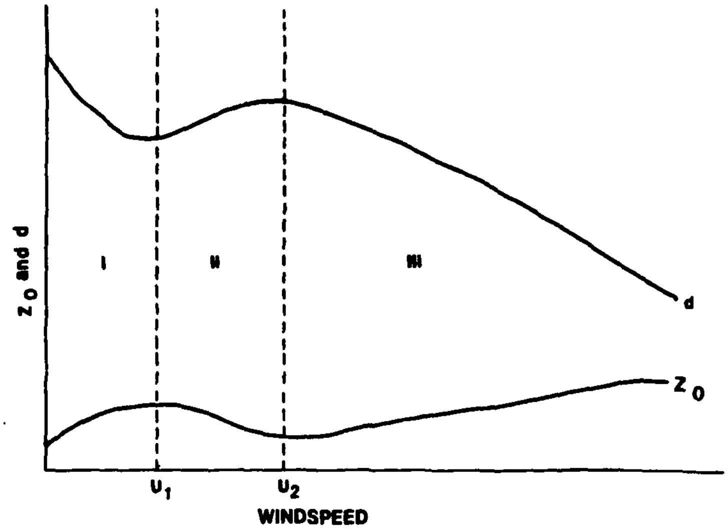

Figure 3. Zero plane displacement shown as a function of wind speed (see text for details of regions I, II, and III).

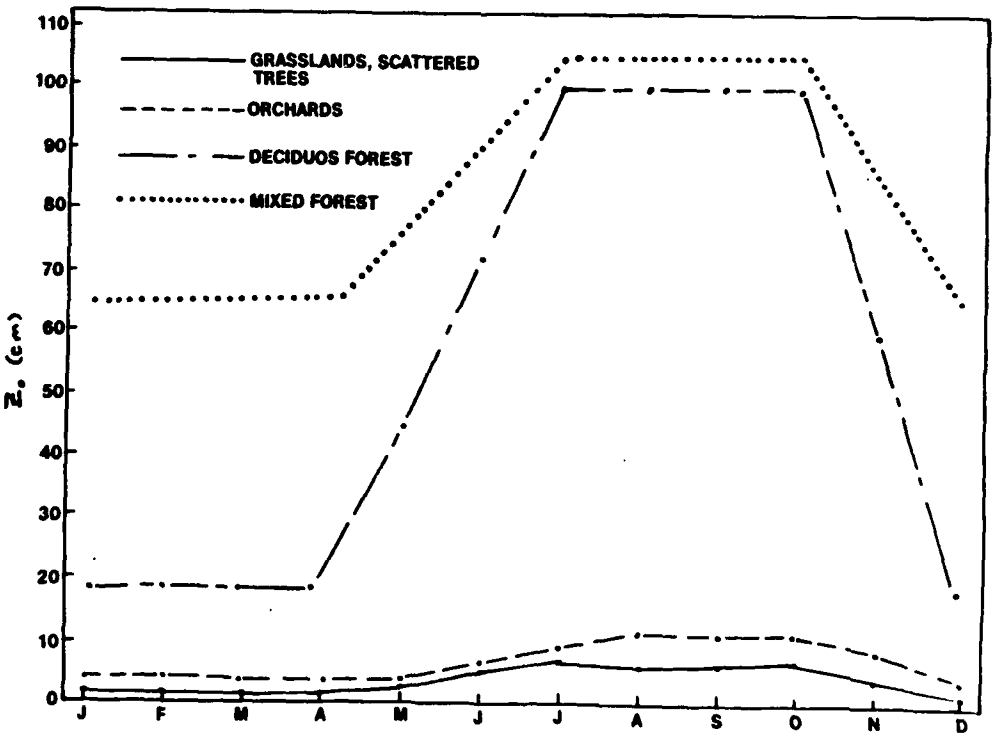

Figure 4. Annual cycle of surface roughness lengths for selected surfaces.

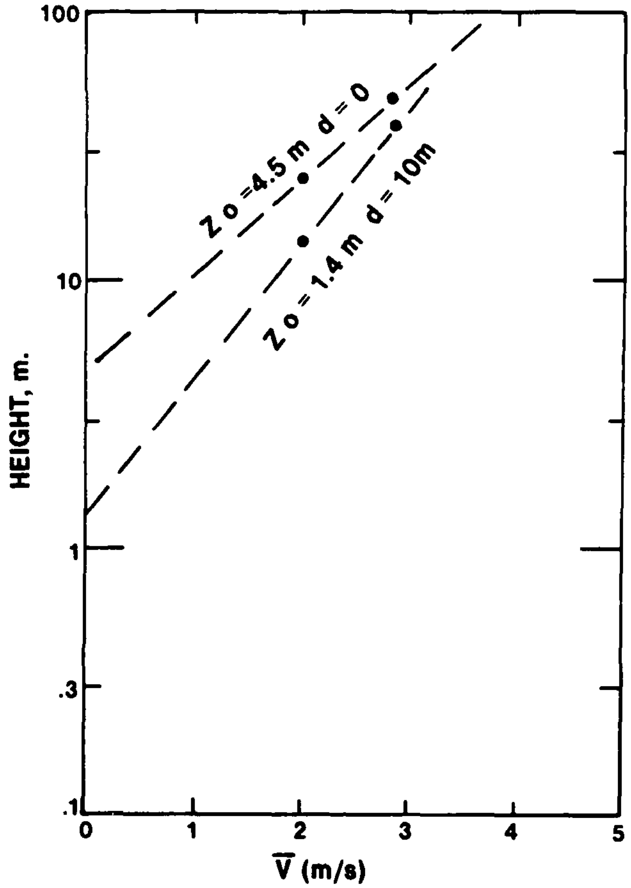

Figure 5. Illustration of the consequence of failing to include a zero plane displacement in surface roughness analyses (after Hanna (1969) and Ariel and Kliwchnikova (1960)).