# The effect of roughness obstacles on flow and dispersion in urban and industrial areas

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## 1 Introduction

The authors have prepared a handbook on the topic of flow and dispersion in urban and industrial areas (Hanna, Britter and Franzese, 2001) and this paper summarizes the major findings and recommendations. A review of the literature was carried out, which led to the recommendation of a hierarchy of methods for estimating the surface roughness length, $z_o$, and the displacement length, d. The simplest methods, based on land-use classes, lead to estimates of $z_o$ of about 1 m and d of about 5 m in urban and industrial areas. More accurate estimates of $z_o$ and d have been suggested by many researchers (e.g., Petersen 1997 and Macdonald et al. 1998), based on parameterizations involving the height of the roughness obstacles, $H_r$, and measures of their spacing (i.e., $\lambda_f$ = (obstacle frontal area)/(obstacle lot area) and $\lambda_p$ = (obstacle plan area)/(obstacle lot area)). $H_r$ and $\lambda_f$ or $\lambda_p$ can be estimated based on experience for certain well-known urban and industrial land-use types (Grimmond and Oke, 1999), or can be calculated in detail using data on actual building shapes and sizes in an area.

Given $z_o$, d, $H_r$, and $\lambda_f$, it is possible to express wind and turbulence profiles, using standard Monin-Obukhov similarity theory, as a function of height, for elevations near the ground well below $H_r$ to elevations at 10 or more times $H_r$. These fundamental boundary layer formulas are valid over very rough surfaces, as long as $H_r$ is less than the surface boundary layer height (about 50 to 100 m). The friction velocity, u*, is a key scaling parameter for all boundary layer phenomena. The effects of the roughness on stability (as measured by the Monin-Obukhov length, L) can be estimated, using the fact that increases in u* over rough surfaces can lead to much larger L (due to the dependence of L on $u*^3$).

These estimates of $z_o$, d, $H_r$, u*, and L over rough urban or industrial surfaces can be used as a basis for calculation of transport and dispersion. The methods are consistent with standard boundary layer theory for plume dispersion (e.g., Arya, 1999).

## *2* Geometric area over which $z_o$ and d are to be calculated

When a pollutant cloud travels over a distance, $x_t$, from the source to a given receptor position, it may pass over surfaces characterized by two or more roughness obstacle types.

The effective $z_o$ and d over the distance, $x_t$, and a 30 degree sector (since this is approximately the angle covered by a pollutant plume) can be estimated using the following formulas for the geometric mean:

$$\ln z_o = \Sigma\, ((\Delta x_i)/x_t) \ln z_{oi} \quad (1a) \qquad \ln d = \Sigma\, ((\Delta x_i)/x_t) \ln d \quad (1b)$$

where $z_{oi}$ is based on the distance $\Delta x_i$. This method weights all roughness surfaces equally, with no dependence on nearness to the source or the receptor. This method also gives no weight to roughness upwind of the source.

More detailed considerations are given in Hanna, Britter and Franzese (2001)

## 3 Methods for determination of $z_o$ and d

Recommended formulas for $z_o$ and d are given below for a hierarchy of complexity. For all techniques described below, it is assumed that an equilibrium boundary later has developed. Although there is no firm rule for the development of an equilibrium boundary layer, it can be recommended that, for fairly regular spacings of obstacles, a $z_o$ and d approach is useful only if there are at least five rows of obstacles.

### 3.1 Methods of estimating $z_o$ and d based on experience

*Experience Method (1)* - Detailed studies of urban areas and industrial sites and more complex calculations at specific sites suggest that $z_o$ will be within the range from 0.2 to 3.0 m, with a reasonable estimate being 1 m (e.g., Grimmond et al. 1998 and Davenport et al. 2000). The displacement length, d, can be assumed to be about 5 m for first-cut scoping studies.

*Experience Method (2)* - More discrimination can be provided in a second approach by comparing a specific site with the characteristics of standard sites, for which measured or calculated values of $z_o$ and d have been obtained. Three categories can be considered, based on discussions by Davenport et al. (2000):

> Category 1 – There are scattered buildings and/or industrial obstacles at relative separations of 8 to 12 obstacle heights. This category corresponds to a moderate-sized fairly-open residential area or industrial site with $H_r$ = 5 m and $\lambda_f$ and $\lambda_p$ = 0.01 to 0.05. In this case $z_o$ is about 0.25 m and d is about 2 m.
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> Category 2 – There is moderate-sized typical congestion, covered by low buildings and/or industrial tanks at relative separations of 3 to 7 obstacles heights, with $H_r$ = 5 to 10 m and $\lambda_f$ = 0.1 to 0.3. In this case $z_o$ is about 0.5 to 1.0 m and d is about 5 m. This category would apply to most urban and industrial sites.
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> Category 3 – This is a large and compact (many close obstacles) urban or industrial site, possibly surrounded by other industrial sites or urban areas with $H_r$ = 10 to 20 m and $\lambda_f$ = 0.4 or 0.5. In this case $z_o$ is about 1.0 to 2.0 m and d is about 5 to 10 m.

### 3.2 Methods of estimating $z_o$ and d based on simple geometric descriptions

If we accept an uncertainty of a factor of two in $z_o$, then the review by Grimmond et al.(1998) suggests that for $\lambda_f$ between 0.1 and 0.4, or for $\lambda_p$ between 0.2 and 0.6, we might simply assume the rules of thumb:

$$z_o/H_r = 0.1 \quad (2a) \qquad\qquad d/H_r = 0.5 \quad (2b)$$

For a typical urban or industrial site, the $\lambda_f$ and $\lambda_p$ parameters are nearly always between about 0.1 and 0.3. Since the average building or obstacle height, $H_r$, is about 10 m, it follows that $z_o = 0.1*10$ m = 1 m and d = 0.5 * 10 m = 5 m. These estimates are consistent with the estimates for the typical "Category 2" site in the previous section, and the data in the references show that they are likely to be within a factor of two of the local "observed" values at individual field sites.

It is important to mention the upper limit to $H_r$ in these geometric methods. Because the $z_o$ concept is valid only in the surface boundary layer, which is about 50 m to 100 m deep, the obstacle heights, $H_r$, should not exceed about 20 m. This means that the geometric methods should not be used when $H_r$ is greater than about 20 m and therefore formulas such as $z_o = 0.1\ H_r$ are not valid in the centers of large cities with tall skyscrapers.

Furthermore, it must be noted that the determination of the "roughness element height" or the "average building height", $H_r$, will produce the greatest uncertainty in application. Di Sabatino et al. (2001) find that the standard deviation in obstacle heights, $\sigma_{Hr}$, is approximately equal to 0.5 or 1.0 $H_r$ for several urban areas.

### 3.3 Methods of estimating $z_o$ and d based on $H_r$, $\lambda_f$, and $\lambda_p$

For the general situation where the roughness obstacles could have any types of spacing, and a more accurate estimate of $z_o$ and d is desired, it may be appropriate to account for the non-linear dependency of $z_o/H_r$ and $d/H_r$ on $\lambda_f$ and $\lambda_p$. A set of simple analytical equations has been developed that provides a fit to the observed urban data reported by Grimmond et al. (1998). These formulas account for the fact that, in a real industrial plant or urban area, the ratio $z_o/H_r$ does not approach zero as obstacles become very close together, since real obstacles (e.g., buildings and tanks) are not cubes with uniform heights and shapes, but have a relatively large effective roughness even when packed closely. Therefore we assume a value of $z_o/H_r = 0.15$ at the limit of close obstacle packing. The formulas are based on $\lambda_f$ (normalized frontal area), since we believe that parameter is the best indicator of $z_o$ and d, because the obstacle drag is related more to the frontal area than the top area. However, since $\lambda_f$ can exceed 1.0, for closely-packed obstacles that are much taller than they are wide, we restrict $\lambda_f$ to be less than 1.0 in these formulas.

For the entire range of obstacle densities ($\lambda_f$), the following formulas account for the limit at large $\lambda_f$ and provide reasonable fits to the data at smaller $\lambda_f$:

$z_o/H_r=\lambda_f$ for $\lambda_f<0.15$ (3a) $z_o/H_r=0.15$ for $\lambda_f\geq0.15$ (3b)

$d/H_r=3\lambda_f$ for $\lambda_f<0.05$ (4a) $d/H_r=0.15+5.5(\lambda_f-0.05)$ for $0.15>\lambda_f\geq0.05$ (4b)

$d/H_r=0.7+0.35(\lambda_f-0.15)$ for $1.0\geq\lambda_f\geq0.15$ (if $\lambda_f>1.0$, then set $\lambda_f=1.0$) (4c)

## 4 General simple formulas for u*, u(z), and turbulent velocities

Given the estimates of $z_o/H_r$ and $d/H_r$ from Section 3 and assuming neutral conditions, the friction velocity can be estimated from a wind speed observation or estimate, u, at some height, z, which is above $H_r$:

$$u^* = 0.4u(z)/\ln((z-d)/z_o) \qquad (5)$$

Hanna, Britter and Franzese (2001) show that, within the urban or industrial site, the wind speed, $u_c$, below the obstacle heights, $H_r$, is given by:

$$u_c/u^* = (z_o/2H_r)^{-1/2} \text{ or } (\lambda_f)^{-1/2} \qquad (6)$$

The log-linear wind equation (5) is assumed to apply down to a height, $z_{int}$, such that $u(z_{int}) = u_c$.

The turbulent velocities in the urban or industrial region are given by the following relations at all heights, above and below $H_r$ (Roth, 2000):

$$\sigma_u/u^* = 2.4 \quad \sigma_v/u^* = 1.9 \quad \sigma_w/u^* = 1.3 \qquad (7)$$

## 5 Selection of an appropriate mean wind speed and stability

Transport and dispersion models can be typically run in the hypothetical or “what-if” mode, or in the real-time or retrospective mode. In the first mode, the worst-case conditions may be arbitrarily chosen as light winds and stable conditions. But in the second mode, where observations must be used, the available observations are usually not from the best location.

We argue that the wind speed at a height of 30 m, say, will be similar at the site of interest (with $z_{o2}$) and at a flat measuring station nearby. Then

$$u_2(10m) = u_1(30m)\ln(10m/z_{o2})/\ln(30m/z_{o2}) \qquad (8)$$

Because of the increased mechanical turbulence over an urban or industrial site, at any given time the stability is closer to neutral than the stability over the airport or other nearby flat site. This is because the increase in $z_o$ over the rough site causes increases in u*. And since u* is cubed in stability parameters such as L, a factor of two increase in u* results in a factor of 8 increase in L.

## 6 Dispersion models in urban and industrial areas

The document by Hanna, Britter, and Franzese (2001) provides detailed formulas for dispersion calculations. A brief overview is given in this section.

*Dispersion models for clouds extending above $H_r$* - Many operational models exist for this scenario. These models often require flow parameters such as $z_o$, d, and u* as inputs, and methods for determining these parameters have been provided earlier. For passive releases at any height we have suggested the Gaussian model for concentration in terms of the dispersion coefficients, which are expressed in terms of u* and (in the far-field) the integral time scale $T_I$.

*Dispersion models for clouds released above or near $H_r$* - No distinction is made between this scenario and that addressed above. The implication of this choice is that the flow in which the release is dispersing is that determined by the underlying roughness. This will be a less valid assumption for releases well above $H_r$ and when the release is close to the upwind edge of the roughness but this would be an unlikely situation. This statement holds for passive and light gas releases. It is likely to hold for heavy gas releases until the cloud trajectory descends well inside the roughness obstacles.

*Dispersion models for clouds below $H_r$* - Currently there are no widely-used operational models for this scenario. There is evidence that a Gaussian model is appropriate for this case. This requires specification of a characteristic velocity, $u_c$, and correlations for the dispersion coefficients. For a continuous plume, the concentrations initially decrease with increasing roughness but eventually become constant and then may increase for very large roughness. For puffs, the correlations predict a monotonic decrease in concentration with increasing roughness. These statements are applicable for passive and light gas releases. For heavy gas releases, a modification would be required to existing operational models; the principal modification being the modification to the velocity profile within the roughness.

*Dispersion models for clouds when downwind of the roughness* - Here we account only for the effects of roughness downwind of the source. Thus the roughness to be considered is an average of the roughness between source and receptor (see equation 1a). This approach may lead to concentration overprediction close to the source for the situation where the source is near the downwind edge of the roughness.

*Dispersion models for clouds released upwind of the roughness and traveling into and through the roughness* - The approach is to consider the roughness between the source and receptor, and by implication to use an advection velocity determined by this roughness. This is a very simplistic model of the complex flow as the atmospheric boundary layer impinges upon a finite area of increased roughness.

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