# Objective Method for Estimating Surface Roughness Length for Industrial Facilities

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## INTRODUCTION

Accurate and objective surface roughness length estimates are needed by the petroleum and chemical industries for dispersion modeling applications. Dispersion models for neutrally buoyant, buoyant and heavier-than-air plumes require a direct or indirect surface roughness length input, and the resulting ground level concentration estimates are sensitive to the value that is selected. Presently, many of the toxic gas models[1] allow for a direct surface roughness length input. Petersen and Ratcliff[2] conducted wind tunnel tests that showed that maximum ground-level concentrations for heavier-than-air vapor clouds (of toxic gas) decrease by a factor of 2 to 4.5 with a factor of 10 increase in surface roughness length ($z_o$ from 0.03 m to 0.50 m). They further showed that two frequently used toxic gas models predicted the expected decrease due to increased surface roughness length. These results have subsequently been confirmed by Roberts[3]. EPA[1] tends to agree that this effect is real, but suggests that the surface roughness length should not exceed 0.01 m for model input unless more studies are conducted to further confirm the validity of the models for larger surface roughness lengths.

Most EPA models currently used for new source permitting have an indirect surface roughness length input (i.e., urban or rural site classification). Once this classification is made, different dispersion coefficients are used depending upon the classification. To determine the site classification, EPA[4] suggests using either a land use classification scheme[5] or population density to establish whether a site has urban or rural roughness. The EPA[4] states that the land use classification method is the preferred method. Neither of these methods rely on building dimensions or spacings, and neither method provides a direct surface roughness length estimate. Future model developments for EPA approved models will most likely include the addition of surface roughness length as a direct model input. This conclusion is based on Weil[6], who summarized the objectives of AERMIC (AMS/EPA Regulatory Model Improvement Committee) with regard to updating the ISC model. In addition, the new fugitive dust model[7] which has been approved for regulatory applications does utilize the surface roughness length.

Clearly, the present state-of-the-art in regulatory modeling does not allow much flexibility in specifying or even using an appropriate surface roughness length. However, as more sophisticated models are approved for routine regulatory use or when industry wants to use advanced unapproved models, an objective, accurate method for estimating surface roughness length will be needed. Various researchers[8,9] have provided simple methods for estimating surface roughness length based on a visual inspection of a site, but these methods are not objective or reproducible. Wieringa[9] and EPA[10] also discuss methods where the surface roughness length can be estimated from on site measurements. These methods require field measurements, and even with these measurements large errors in the surface roughness length estimate can still occur.

Hence, the overall objective of the study discussed in this paper was to develop and test three objective, reproducible, analytical methods for estimating surface roughness as a function of wind direction at refineries (or other areas of interest). The estimation techniques use physical dimensions and spacings of the structures at refineries or other built up sites and are referred to as the Lettau[11], Counihan[12] and Simplified Counihan methods. The three methods are statistically evaluated in this paper by comparing their predictions against surface roughness length estimates obtained from wind speed measurements over scale models of three refineries and two uniform roughness configurations. The Lettau method has been verified against field observations for a homogeneous roughness configuration; however, Wieringa[9] concludes that the Lettau method is limited to moderately inhomogeneous situations. The Counihan[12] methods have only been tested against homogeneous roughness configurations in a wind tunnel. This paper will show whether the methods can be extended to moderately inhomogeneous situations like a refinery based measurements in scale model refineries. The paper also discusses the future validation of the wind tunnel results through an upcoming field evaluation.

## METHODOLOGY FOR ESTIMATING SURFACE ROUGHNESS FROM DIMENSIONS AND SPACINGS OF STRUCTURES

Lettau[11] and Counihan[12] have provided analytical methods whereby the surface roughness can be estimated directly based on the dimensions and spacings of the structures at a site. Lettau[11] presents the following equation for estimating surface roughness length, $z_o$:

$$z_0 = \frac{0.5\, h^* s}{A} \qquad \textbf{(1)}$$

where

$h^*$ = the average obstacle height,
$s$ = the total silhouette area of all obstacles in the area $A$, measured in vertical-crosswind plane (m$^2$),
$A$ = the area over which $z_o$ is to be estimated (m$^2$),
0.5 = an average drag coefficient for the obstacles.

Counihan[12] presents the following relation for estimating the surface roughness length:

$$z_0 = h^* \left[ 8.2 \frac{h^*}{f} + 1.08 \frac{A_r}{A} - 0.08 \right] \tag{2}$$

where $A_r$ is the total plan surface area of the roughness elements in area $A$ and $f$ is the upwind fetch (i.e., the upwind distance to the next roughness change). The author states that the equation is only valid for $A_r/A$ values less than 0.25 and greater than 0.1. When $h^*/f$ approaches zero (i.e., equilibrium boundary layer or infinite fetch) the equation reduces to:

$$z_0 = h^* \left[ 1.08 \frac{A_r}{A} - 0.08 \right] \tag{3}$$

Even though Equations (2) and (3) have a limited range of recommended $A_r/A$ application, the methods were used for cases slightly outside the recommended range so that an estimate could be obtained. It should be noted that only a few cases evaluated were outside the range.

Throughout this paper, Equation (1) will be referred to as the Lettau method, Equation (2) as the Counihan method, and Equation (3) as the Simplified Counihan method. For actual sites the upwind fetch will be a difficult parameter to estimate, and it seems the Simplified Counihan method would be preferable over the Counihan method.

Early in the process of evaluating the model refinery complexes using the above equations it became evident that the volume of data and the potential number of permutations necessitated the development of a computer program. The program is described in Petersen and Parce[13]. It should be noted that the method is appropriate not only for refineries, but for estimates at any site that has buildings and structures. It can be applied to regions that are smaller and larger than those discussed in this paper.

## DESCRIPTION OF SURFACE ROUGHNESS DATABASES

Five wind tunnel databases were used to evaluate the Lettau and Counihan methods. The databases consisted of the physical dimensions of structures in three different scale model refineries and the dimensions of two uniform roughness configurations. The structural and roughness element dimensions were subsequently used to estimate surface roughness length using the Lettau and Counihan methods as described previously. Along with the dimensions of the structural or roughness elements, wind profile measurements were obtained at various locations over the models so that the actual surface roughness length could be established.

Figure 1 shows a photograph of one of the three refineries that was evaluated. Each refinery was tested for two wind directions. Figure 2 shows the wind tunnel test configuration with the refinery model. Figures 3 and 4 describe the uniform roughness patterns that were evaluated. The wind tunnel setup for the uniform roughness tests was similar to that shown in Figure 2, only the entire tunnel floor was covered with the roughness patterns shown in Figures 3 and 4.

The model refineries and uniform roughness configurations were installed in CPP's open circuit boundary layer wind tunnel which has a test section length of 78 ft, width of 12 ft and height of 7 ft. Upwind of the refinery models, uniform roughness and other flow conditioning devices were installed.

The dimensions of all the structural elements within the three refineries were specified using the drawings used to construct the scale models of the refineries. These dimensions were tabulated as described in Petersen and Parce[13]. For the uniform roughness, the dimensions in Figures 3 and 4 were utilized.

With regard to wind profile measurements, profiles of mean velocity and turbulence intensity were obtained at several locations. The profiles obtained for Refineries 1 and 2 were from previous wind tunnel experiments that were designed for a different purpose and consequently no consistent measurement location pattern was used. For Refinery 1, all profiles were taken along the wind tunnel centerline (i.e., $y = 0$), and for Refinery 2 profiles were taken along the tunnel centerline and at $y = \pm100$ and $\pm200$ m. For Refinery 3, profiles were taken at the downwind extent of the refinery (at $y = 0$, $\pm100$ and $\pm200$). For estimating the roughness of the upwind refinery, locations at the downwind extent of the evaluated region are the preferred measurement locations since all measurement points have the maximum upwind fetch available for profile development. For the uniform roughness tests, a single profile was measured in the center of the wind tunnel at the downwind edge of the roughness.

Wind profile measurements were made using a single hot-film anemometer mounted on a computer-controlled vertical traverse. Constant-temperature anemometers with platinum-film sensing elements were used to obtain the velocity measurements. A PC based computer system equipped with an A/D interface was used to monitor and control the position of the hot-film probe as well as to convert the anemometer output into useful velocity measurements and store the test results.

## SURFACE ROUGHNESS ESTIMATES FROM WIND PROFILES

Wieringa[9] presents a comprehensive summary of surface roughness length estimation methods and site surface roughness classifications. He points out that surface roughness length estimates obtained from wind profile analysis can have large errors resulting from the analysis method, best fit errors, and measurement errors. He further states that reliable profiles should meet the following criteria: 1) observations should be made on a slender mast with boom extensions such that mast interference effects are negligible; 2) well calibrated anemometers should be used and measurements should be averaged over at least 10 minutes; 3) analysis should be limited to situations that are neutral, or temperature profiles should be collected; 4) non-stationery situations should be avoided; 5) several cases should be obtained; 6) the appropriate height range should be utilized; 7) at least three height levels should be monitored in high roughness, four levels in moderate roughness, and five levels in smooth roughness for the measured $z_o$ to be within a factor of 2 of the actual $z_o$. The profiles collected and analyzed in the wind tunnel met these criteria.

Seven different methods were used to estimate the surface roughness from the wind profiles measured over the various model refineries and roughness patterns. Different methods were used to determine the range of values that could be estimated using commonly accepted methods for estimating surface roughness length. Along with surface roughness length, the displacement height (*d*) was also estimated. Definitions for surface roughness length and displacement height can be found in Petersen and Parce[13], which also describes in detail the methods utilized to estimate surface roughness length and displacement height from the velocity profile measurements and includes a detailed discussion of the calculated results.

Based on the analysis in Petersen and Parce[13], one method was selected as the “ground truth” method. The “ground truth” method was then used as the basis for evaluating the Lettau and Counihan methods, which is covered in Section 6. The “ground truth” method selected was Method 6. This method is based on the following equation recommended in the EPA On-Site Meteorological Program Guidance[10]:

$$z_0 = \left( \frac{z}{\exp\left(\dfrac{u}{u'}\right)} \right) \tag{4}$$

where $z$ is the measurement height, $u'$ is the root mean square velocity in the longitudinal direction, and $u$ is the mean velocity.

The guideline states that measurement heights between $20 z_o$ and $100\ z_o$ should be used in the analysis. This height range, however, produced unrealistic results and did not make practical sense. For example, for a 1 m surface roughness, the EPA guidance would suggest using data between 20 and 100 m. For a refinery situation with a limited fetch, the internal boundary would not most likely be developed up to 100 m at any location within or immediately downwind of the refinery. Wieringa[9] reports that additional equilibrium fetch is required for turbulence profiles to establish the characteristics of the upwind fetch. For this reason, the average $z_o$ value was calculated using the turbulence measurements between 10 and 40 m.

This method was selected because it was found to be the most objective of all the methods analyzed, the least sensitive to measurement errors, required no best fit analysis, would be the easiest to implement in the field, and is consistent with the EPA[10] recommended approach. The statistical evaluation further suggested that this method provides estimates that are similar to several other valid methods that use best fits to the velocity profiles. Table 1 provides a summary of the surface roughness length estimates obtained using this method.

## LETTAU AND COUNIHAN SURFACE ROUGHNESS LENGTH ESTIMATES

Surface roughness lengths were estimated using the Lettau and Counihan methods described previously for the three refineries and two uniform roughness configurations. This section provides documentation regarding the method for selecting the width and length of the region to be used for obtaining these estimates, and provides information on the sensitivity of the estimates to region width, region length and wind direction.

## Specification of Region Length

With regard to the longitudinal extent of a refinery (or other area under evaluation) that should be used to estimate surface roughness length, consider Figure 5. The figure shows the internal boundary layer growth and the transition region for a flow from one surface roughness to another. At $x \geq$ ! $L$, the roughness is characterized by a roughness length which is equivalent to the refinery surface roughness. At $x <$ ! $L$, the roughness length is characterized by the roughness upwind of the refinery, $z_o$N. In Figure 5, the region from $z = 0$ to $z_i$ has the flow in equilibrium with the new surface and the wind profile can be approximated using the logarithmic wind profile equation with $z_o$ and $u^*$ as inputs. Deaves[14] presents the following two equations for estimating $z_i$, one for low to high roughness changes (denoted $S \longrightarrow R$, smooth to rough) and a second equation for high to low roughness changes ($R \longrightarrow S$, rough to smooth):

$$S \rightarrow R \qquad \frac{z_i}{z_0} = 0.36\left(\frac{x}{z_0}\right)^{0.75} \tag{5}$$

$$R \rightarrow S \qquad \frac{z_i}{z_0} = \frac{0.07\,x}{\sqrt{z_0 z'}}\,. \tag{6}$$

For most refinery situations, the surface roughness approaching the refinery will be less than that for the refinery (i.e., $z_o >$ $z_o$N). Typically, the refinery roughness length will be 0.5 m or greater.

Let us assume that we want the internal boundary layer developed up to at least 30 m at the downwind extent of the area of interest ($x = L$). Using Equation (5) would suggest that a distance of 457 m upwind ($x =$ ! 457 m) is required for the internal boundary layer to be developed up to the 30 m height. For a 1 m refinery surface roughness the distance would be 358 m. For boundary layer development up to greater heights a longer upwind fetch would be required.

Next, consider the case when the surrounding roughness is greater than that found within the refinery. For example, let $z_o = 0.5$ m and $z_o$N = 2 m (i.e., a downtown area). For this case a distance of 857 m is required before the internal boundary is developed up to 30 m. Based on these analyses, the recommended longitudinal region for both the Lettau and Counihan methods is from the upwind edge ( ! $L$) of the refinery to be the downwind edge (+$L$). This will give a total alongwind extent of 800 to 1000 m for the three refineries studied. That means at the downwind edge of the refineries, the internal boundary layer will be developed up to a height of about 50 m.

## Specification of Region Width

With regard to the lateral extent of the region, a logical approach would be to ensure that the region is wide enough to include all obstructions that may influence plume dispersion. One method for estimating the cloud width is to run a dispersion model and obtain the cloud width at the end of the area of interest. For illustrative purposes, assume that the cloud width (*W*) is equal to 4.3 times $\sigma_y$ which can be approximated from the following equation[15]:

$$W = 4.3\sigma_y = 0.16x\frac{4.3}{\left[1 + 0.0004x\right]^{0.5}}. \qquad \textbf{(6)}$$

Equation (7) is recommended for urban conditions, neutrally buoyant plumes and D stability. For the three refineries under evaluation, $x$ is approximately 500 m, and $W$ then becomes 314 m. Based on this calculation, a region width of 400 m would be sufficient to include all structures that would affect the dispersion.

## Sensitivity to Region Length and Width

To assess the sensitivity of the results to the specified region width and length, surface roughness length estimates were obtained for the various regions (or domains). The results of this analysis (see Petersen and Parce[13]) showed some variation of surface roughness length estimates with region length or width, but the variations were relatively small.

Based on this evaluation, estimates from the Lettau and Counihan methods for comparison with observations were obtained for a region width of 400 m (±200 m) and region length from ! $L$ to $L$ (the entire refinery length modeled). For the uniform roughness, region width and length will not affect the resulting calculation since the roughness pattern is repeating.

## EVALUATION OF SURFACE ROUGHNESS ESTIMATION METHODS

Table 2 shows a comparison of the Lettau and Counihan surface roughness length estimates with the observed values computed using Method 6 as the true estimator of surface roughness length. Inspection of the table shows that the Lettau method estimates agree well with observations for all cases while the Counihan method estimates are generally significantly higher than observations. The Simplified Counihan method also tends to overpredict observations, but by a lesser degree than the Counihan method. A qualitative assessment of the results in Table 2 would suggest that the Lettau method provides reasonable surface roughness length estimates and estimates that are better than either the Counihan or Simplified Counihan methods.

To more objectively assess the performance of the Lettau, Counihan and Simplified Counihan methods, a statistical evaluation was conducted using the BOOT program[16]. The fractional bias (FB) and normalized mean square error (NMSE) between observed and computed surface roughness length were computed. The results are shown in Table 3 and Figure 6.

Considering individual data sets and all data sets combined, Table 3 shows that the Lettau method has the lowest FB and NMSE. As a further illustration, Figure 6 shows the FB with the 95 percent confidence interval versus NMSE for the entire data set. Also of interest in Figure 6 is that while the FB for the Lettau method is significantly different than zero (although by a small margin), it is within 50 percent of the true surface roughness length, where a 50 percent difference is indicated by a FB of approximately 0.4. Additionally, the NMSE is almost at the theoretical minimum which is represented by the solid line in the figure. The solid line (or theoretical minimum) represents the case when there is only a mean bias in the predictions and no random scatter[16].

## CONCLUSIONS

Overall, the results presented here show that the Lettau method provides a good estimate (i.e., within 50 percent of the true value) of surface roughness length for refinery type roughness configurations. Since actual measurements of surface roughness length based on wind profile analysis are most likely not this accurate for heterogeneous roughness[9] and since Lettau verified his approach through field measurements, it is suggested that the Lettau method be utilized for estimating surface roughness length at refineries. This study also provides evidence to alter Wieringa's[9] conclusion that the Lettau method is only applicable up to moderately inhomogeneous situations. The results presented here extend the applicable range of the Lettau method to at least moderately inhomogeneous situations (i.e., refineries, or other similar roughness configuration.

To provide further evidence that the Lettau method can be used for estimating surface roughness and that increased roughness length values can be input into the models, a field measurement program is planned at the Nevada test site in August of 1995. The field testing will included the installation of roughness elements that will be designed to simulate the dispersion and air flow characteristics at a refinery. The roughness pattern will be designed based on the Lettau method. Subsequent field measurements will then verify whether the Lettau roughness estimate is valid and more importantly whether the dispersion is enhanced by the larger roughness.

In conclusion, over-conservatism in dispersion modeling may be very costly to the petroleum and chemical industries and in turn to consumers of those products. For example, under Section 112 of the Clean Air Act, sources throughout the industry are installing Maximum Achievable Control Technology (MACT). The need for further controls (and expense) beyond MACT will be determined by the residual risk requirements of Section 112 (f). This residual risk is likely to be calculated inpart by a dispersion model. Therefore the need for non-conservative, accurate dispersion model estimates is extremely important. This study will ultimately provide additional tools so that more accurate and less conservative estimates can be obtained.

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Table 1. Summary of surface roughness estimates from velocity profile analysis—Method 6.

| Site Description | Wind Direction (degrees) | Surface Roughness Length (m) |
|---|---|---|
| Refinery 1 | 337.5 | 0.73 |
| | 247.5 | 0.47 |
| Refinery 2 | 180.0 | 0.53 |
| | 112.5 | 0.27 |
| Refinery 3 | 0.0 | 0.35 |
| | 67.5 | 0.33 |
| Uniform Roughness 1 | NA | 0.65 |
| Uniform Roughness 2 | NA | 0.01 |

Table 2. Comparison of Lettau and Counihan estimates with velocity profile estimates (Domain !*L* < X *L*; !200 < Y < 200).

| Wind Direction | Lettau Estimated $z_o$ (m) | Counihan Estimated $z_o$ (m) | Simplified Counihan Estimated $z_o$ (m) | Method 6 (Log Ave) $z_o$ (m) |
|---|---|---|---|---|
| *Refinery 1* | | | | |
| 337.5 | 0.90 | 2.85 | 1.51 | 0.73 |
| 247.5 | 0.85 | 2.88 | 1.88 | 0.47 |
| *Refinery 2* | | | | |
| 180 | 0.40 | 1.85 | 1.22 | 0.53 |
| 112.5 | 0.45 | 2.06 | 1.46 | 0.27 |
| *Refinery 3* | | | | |
| 0 | 0.36 | 1.02 | 0.28 | 0.35 |
| 67.5 | 0.45 | 1.42 | 0.50 | 0.33 |
| *Mixed 2 and (double stacked) 4 in. cube at a 1:240 scale* | | | | |
| NA | 0.73 | 2.45 | 0.32 | 0.65 |
| *1/2 in. cube roughness at a 1:240 scale* | | | | |
| NA | 0.02 | NA | NA | 0.01 |

Table 3. Summary of normalized mean square error and fractional bias (Domain $-L < X < L$; $-200 < Y < 200$).

| | NMSE | FB |
|---|---|---|
| | Method 6 | |
| *Refinery 1* | | |
| Lettau | 0.16 | −0.37 |
| Counihan | 2.99 | −1.31 |
| Simplified Counihan | 1.27 | −0.95 |
| *Refinery 2* | | |
| Lettau | 0.14 | −0.05 |
| Counihan | 3.11 | −1.31 |
| Simplified Counihan | 1.73 | −1.07 |
| *Refinery 3* | | |
| Lettau | 0.05 | −0.06 |
| Counihan | 1.94 | −1.12 |
| Simplified Counihan | 0.12 | −0.13 |
| *2 in. and 4 in. cube roughness* | | |
| Lettau | 0.01 | −0.12 |
| Counihan | 2.03 | −1.16 |
| Simplified Counihan | 0.52 | 0.68 |
| *0.5 in. cube roughness* | | |
| Lettau | 0.50 | −0.67 |
| Counihan | NA | NA |
| Simplified Counihan | NA | NA |
| *All surfaces* | | |
| Lettau | 0.14 | −0.21 |
| Counihan | 2.89 | −1.25 |
| Simplified Counihan | 1.34 | −0.73 |

Figure 1. Photographs of Refinery 2: 180 degree wind direction.

Figure 2. Wind tunnel setup for Refinery 2 tests at a 112.5 degree wind direction.

Figure 3. Drawings of Uniform Roughness 1 (mixed 2 and 4 in. cubes).

Figure 4. Drawings of Uniform Roughness 2 (0.5 in. cubes).

Figure 5. Growth of internal boundary layer after a change in surface roughness.

Figure 6. Normalized mean square error (NMSE) and fractional bias (FB—with its 95 percent confidence limits) for different surface roughness length estimation methods with Method 6 as the true estimator of surface roughness length. Also included are the "factor of two" lines and "minimum" NMSE curve.