A Wind Tunnel Investigation of Roughness Parameters for Surfaces of Regularly Arrayed Roughness Elements

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Introduction

A few recent studies (5, 7) have attempted to assess the impact of surface roughness on laboratory simulated tornado-like vortices. In these studies, the roughness properties of the surface have been described only qualitatively, or estimated by semi-empirical methods (6, 9). The parameter most frequently cited to quantify the degree of roughness of a surface is the roughness length, z_0, because it is an invariant characteristic of a given surface and is dependent only upon its physical properties.

Dessens (5), in a study using small pebbles to form a rough surface, applied Lettau's (9) formula to estimate z_0. Leslie (7), assumed z_0 to be about 1/30 of the height of the individual roughness elements. However, Leslie did not account for the area density of the elements. He did recommend that it would be desirable to evaluate z_0 qualitatively. This provided the motivation for the current investigation, which is the first part of a two phase research project aimed at determining the effect of varying degrees of surface roughness on vortices produced in the Purdue Tornado Vortex Chamber (TVC). (The reader is referred to Church, *et al.* (3) for a schematic diagram of the Purdue TVC.)

Presented here are preliminary results of an experiment to estimate the roughness length, z_0, friction velocity, V*, and zero plane displacement, D for several surfaces of regularly arrayed roughness elements. This investigation has been performed to develop a set of standard, reproducible rough surfaces for which the above parameters (in particular, the roughness length) are known. These surfaces will then be used to determine the effects variations in surface roughness have on tornado-like vortices.

Simulating the Atmosphere

To study the effects of surface roughness on *tornado-like* vortices, the roughness properties of the surface to be used in TVC must be properly scaled to those of surfaces likely to be encountered in nature. The roughness properties of a surface affect the overlying swirling flow by modifying the properties (in particular, the depth of δ) of the boundary layer that feeds into the base of the vortex. If δ is directly related to z_0, the desired similarity can be obtained by matching the ratio z_0/δ in the TVC to that in the atmosphere.

$$\left.\frac{z_0}{\delta}\right|_{ATM} = \left.\frac{z_0}{\delta}\right|_{TVC.} \quad (1)$$

For sink-type flow in the TVC, the boundary layer depth has been found by Baker (1) to be given by

$$\delta_{TVC} = 7.5 \text{ r } Re_r^{-0.5}, \quad (2)$$

where r is the radial distance inward from the outer edge of the lower surface, and Re_r is the radial Reynolds number given by

$$Re_r = U_0 r_0/\nu, \qquad (3)$$

where U_0 is the radial velocity at r_0,
r_0 is the radius of the updraft hole, and
ν is the kinematic visosity.

By Eq. 2, using typical values for U_0 and r_0, the boundary layer depth in the TVC at r_0 has a range from 6 to 19 cm. Cermak (2) indicates that a typical boundary layer depth of the atmosphere is of the order of 500 m. With these values, the ratio of the depth of the atmosphere boundary layer to that of TVC boundary layer is between 3000 and 8000. Naturally occurring roughness lengths for the Earth's surface are nominally less than 2 m. (It is generally assumed that a highly urbanized area has $z_0 \sim 2$ m.) Using this maximum value to obtain a bound for similarity in the inflow layer, Eq. 1 indicates that z_0 in the TVC should be no greater than 0.08 cm.

Experimental Procedure

Since the direction of the surface inflow varies in the TVC, symmetric roughness elements must be used. Also, distribution of the elements over the surface must be reasonably uniform in all directions. These two conditions ensure that the surface roughness characteristics will be independent of the inflow angle. Further, the individual roughness elements must be reproducible and uniform in size and shape. We have chosen to use 0.64 cm diameter cylindrical pegs mounted on commercial pegboard.

It was impractical to directly investigate the roughness properties of the roughened disk due to its size. Instead, a test surface of similar characteristics was fabricated by mounting pegs on a sheet of pegboard 122 by 244 cm, and having a square arary of holes on 2.54 cm centers. The pegboard surface and the wooden pegs were given two coats of marine varnish before assembly. This test surface was then placed in the working section of a large wind tunnel. Once in place, the peg area density (number of pegs per unit area) could be variable by systematically removing pegs.

Figure 1 is a view looking downstream in the wind tunnel and it shows the surface completely covered with some 4600 pegs (0.155 pegs cm^{-2}) of height 1.27 cm. The test surface has been raised above the lower surface of the wind tunnel to escape the surface boundary layer. Vertical profiles of the horizontal wind in the boundary layer over the surface were measured using a hot film anemometer system. The measured uncertainty of the velocities was ± 1.0 cm s^{-1}. The anemometer probe was rigidly attached to a remotely controlled movable arm in the wind tunnel (Figure 2). The movable arm was connected to a transducer which produced a voltage proportional to the position of the arm. This system was calibrated with respect to height to determine each measurement level to within ± 0.1 cm.

To obtain a velocity profile in the surface boundary layer, the probe was positioned 219 cm downstream of the leading edge of the test surface. The freestream velocity was then set to a nominal value of 10 m s^{-1}. This value was selected to give a good signal throughout the boundary layer. The noted freestream velocity and the distance of the measurement position downstream from the leading edge gives a Reynolds number of 1.4×10^6 (the average wind tunnel temperature was 23°C). The flow in the boundary layer over the surface was therefore very turbulent. The probe was then moved down through the boundary layer and measurements were taken at various levels. These levels were chosen on the basis of the "double-levels" rule described by Lettau (8).

To obtain a good estimate of the mean velocity, the output signal of the anemometer was first linearized, then filtered with a passive first-order filter having

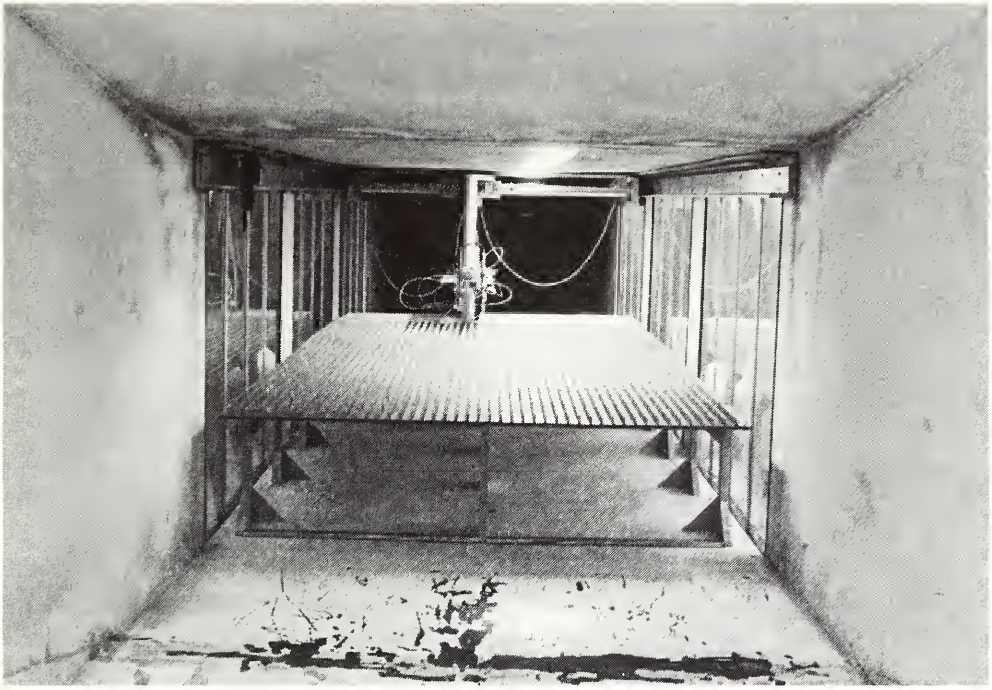

FIGURE 1. Test surface completely filled with pegs looking downstream into the working section of the wind tunnel. The wind tunnel carriage with hot-film anemometer probe is in the background.

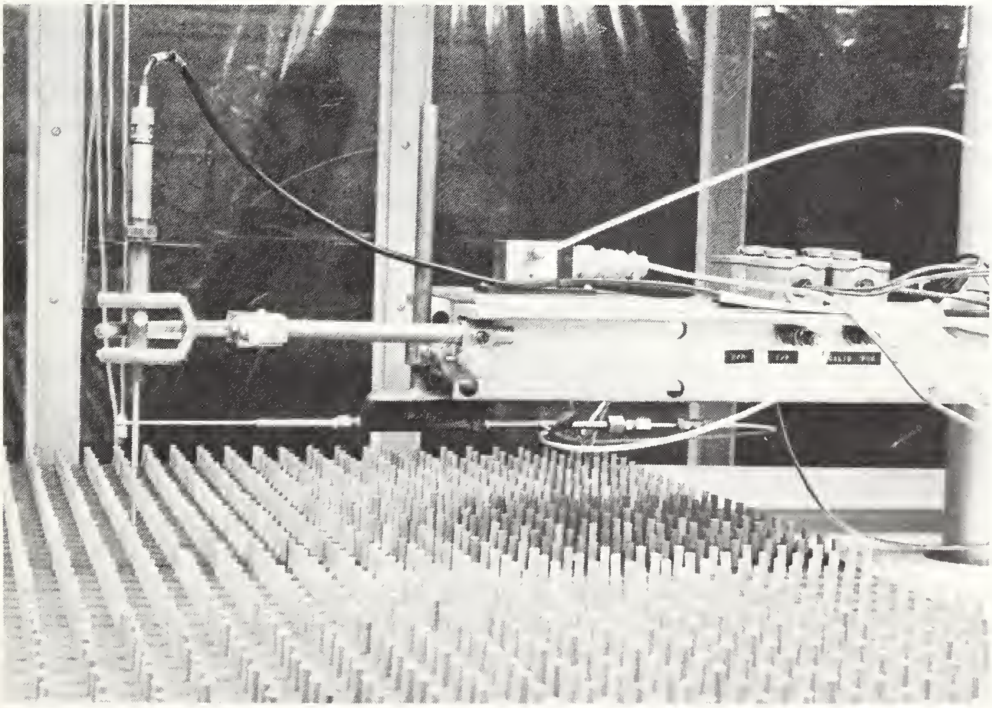

FIGURE 2. Close-up of the instrumented carriage. The sensing probe is held in the clamp that extends to the left of the arm.

a 5 s time constant. Preliminary measurements showed that below two peg heights above the surface, the air flow reflected details of the flow around individual pegs. For this reason, measurements were taken only above two peg heights.

Reduction of Data

A modified form of the log-linear wind profile that is appropriate for rough surfaces is given by

$$U(z) = \frac{V^*}{k} \ln \frac{(z - D)}{z_O}, \tag{4}$$

where U(z) is the velocity at some height z,

V^* is the friction velocity,

k is von Kármán's constant (= 0.4),

z_O is the roughness length, and

D is the effective obstacle height, $= d - z_O$ where

d is the zero plane displacement.

Figure 3 is a sketch of a typical boundary layer wind profile; superimposed is the corresponding "best fit" log-linear profile. There are three important regions in this idealized profile. Region I is the flow in the canopy region. It is in this region that the wind interacts with the individual roughness elements. Region II is where the flow reflects the integrated effects of the full rough surface. In this region, the shear stresses are approximately constant (10). It is in this constant stress layer that the log-linear wind profile is valid and closely coincides with the observed boundary-layer wind profile. Region III is the freestream region of the profile where the velocity becomes nearly independent with height.

Figure 3 also illustrates the relationships between D, z_O, and d. The displacement, d, is obtained by extrapolating the log-linear wind profile downward to the height when $U = 0 \text{ m s}^{-1}$. The extrapolation is shown as the lower dashed portion of the curve in Figure 3. The effective height D is related to the area density of the obstacles. As more obstacles are added to a given area, the value of D approaches the height of the obstacles. The parameter z_O is the difference between d and D.

The friction velocity, V^*, is equal to $(-\overline{u'w'})^{0.5}$, where $(-\overline{u'w'})$ is the Reynolds stress. Therefore, the constant stress region is also a region of constant V^*. From mixing length theory, the differential equation for the wind profile is given by:

$$\frac{du}{dz} = \frac{1}{k}\left(\frac{V^*}{z-D}\right) \tag{5}$$

Rearranging Eq. 5 to obtain an expression for V^* and using a centered finite difference scheme to estimate du/dz from the measurements,

$$V^* = (z - D)k \frac{\triangle u.}{\triangle z} \tag{6}$$

Values of V^* can be computed in this manner, and a region of nearly constant friction velocity (therefore constant stress) identified. Eq. 4 can then be fit to the portion of the observed velocity profile that exhibits a reasonably constant V^* to estimate the roughness parameters.

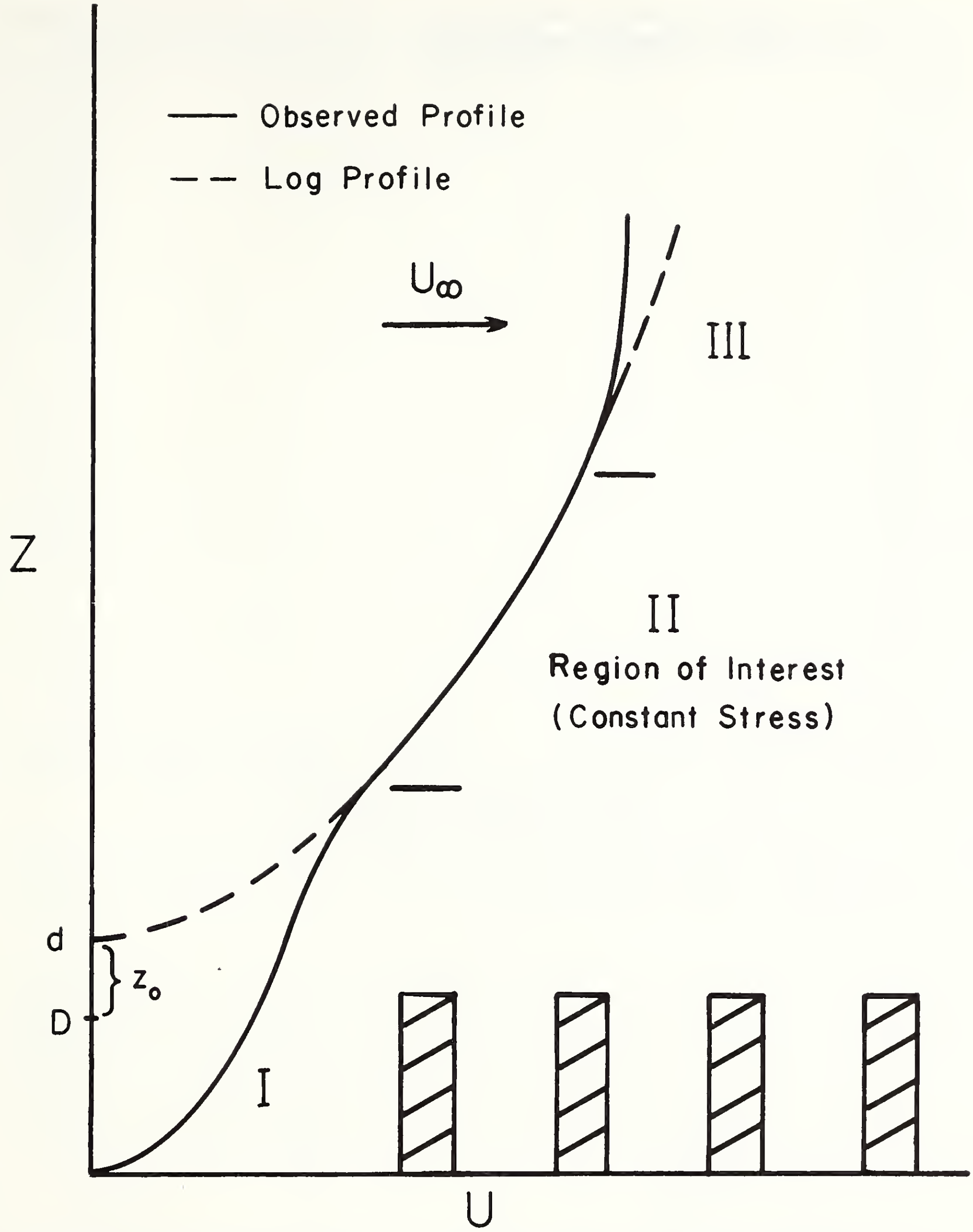

FIGURE 3. Idealized boundary layer profile with a corresponding log-linear wind profile. The hatched boxes represent typical roughness elements. The three regions are: I., canopy flow; II., constant stress flow; III., freestream flow

Figure 4 is a typical wind profile for the most dense array of pegs (0.155 pegs cm^{-2}). Notice that the velocity at high levels is approaching a constant value in agreement with Figure 3. Since the lowest measurement level is approximately two peg heights above the surface, the flow in the canopy does not appear in this profile. Figure 5 is a profile of friction velocity computed using Eq. 6. The values were computed for the data shown in Figure 4, and then smoothed using a five point moving average. Figure 5 shows that a region of nearly constant V* exists between 3 and 6 cm.

The three roughness parameters were estimated by means of a non-linear least squares fit of the log-linear profile to the data. This fitting was accomplished using

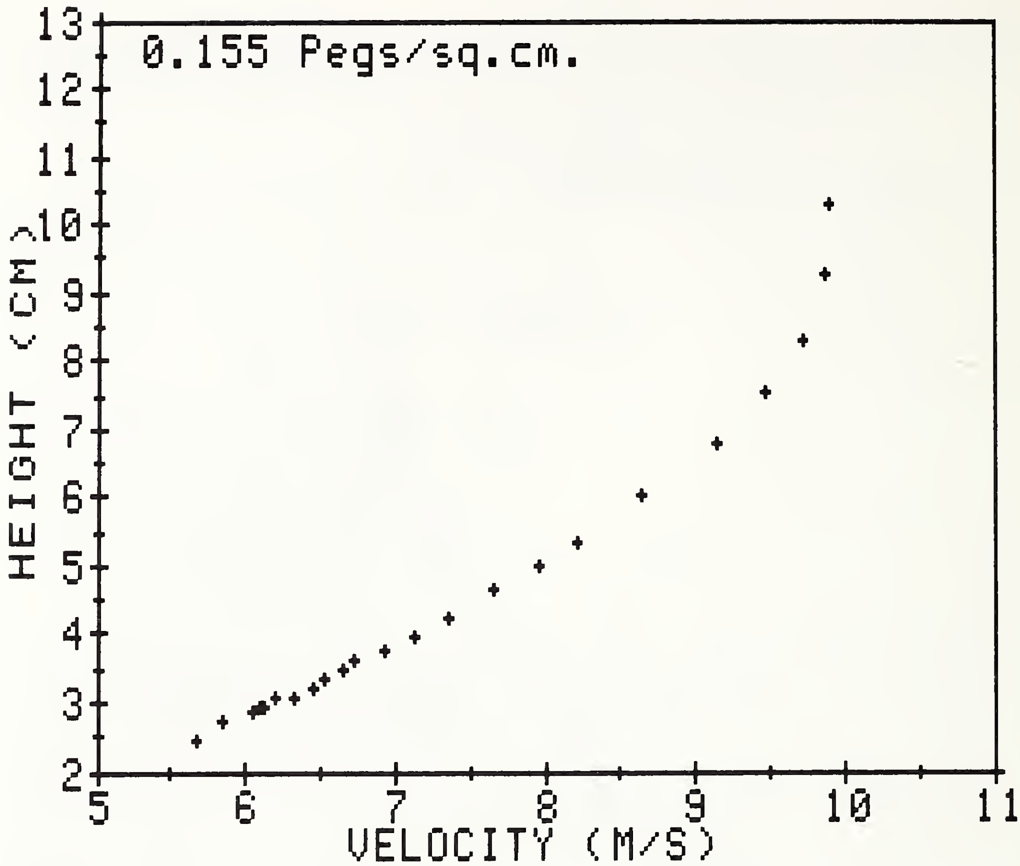

FIGURE 4. Observed boundary layer wind profile for the most dense array of pegs (peg area density = 0.155 pegs cm $-^2$).

a numerical routine similar to that of Covey (4). This scheme first minimizes the square error in the velocities by picking successive values of D. Once this has been done, the values of z_0 and V* are computed along with the standard errors for D, z_0 and V*. By fitting the log-linear wind profile to the observed data in Figure 4 only in the constant stress region (Figure 5), the roughness parameters are found to be:

V* = 1.41 ± 1.43 m s^{-1},

D = 0 ± 1.73 cm, and

z_0 = 0.565 ± 0.70 cm.

The large standard errors are due in part to large turbulence at low levels. Even though the linearized output from the anemometer was filtered, obtaining a mean velocity value was difficult. In the future, work such as this should make use of computer data acquisition to more objectively determine mean velocity values.

Results

Table 1 gives the results for four surfaces using 1.27 cm high by 0.64 cm diameter pegs, plus results for a pegboard surface and a plywood surface (the plywood surface is the "smooth" surface which most closely resembles the normal TVC surface). These results are as one would expect in that both V* and z_0 decrease with decreasing peg area density. The effective obstacle height is zero, even in the case of the most dense array of pegs tested, because the maximum peg/surface interface area is still a small fraction of the entire test surface.

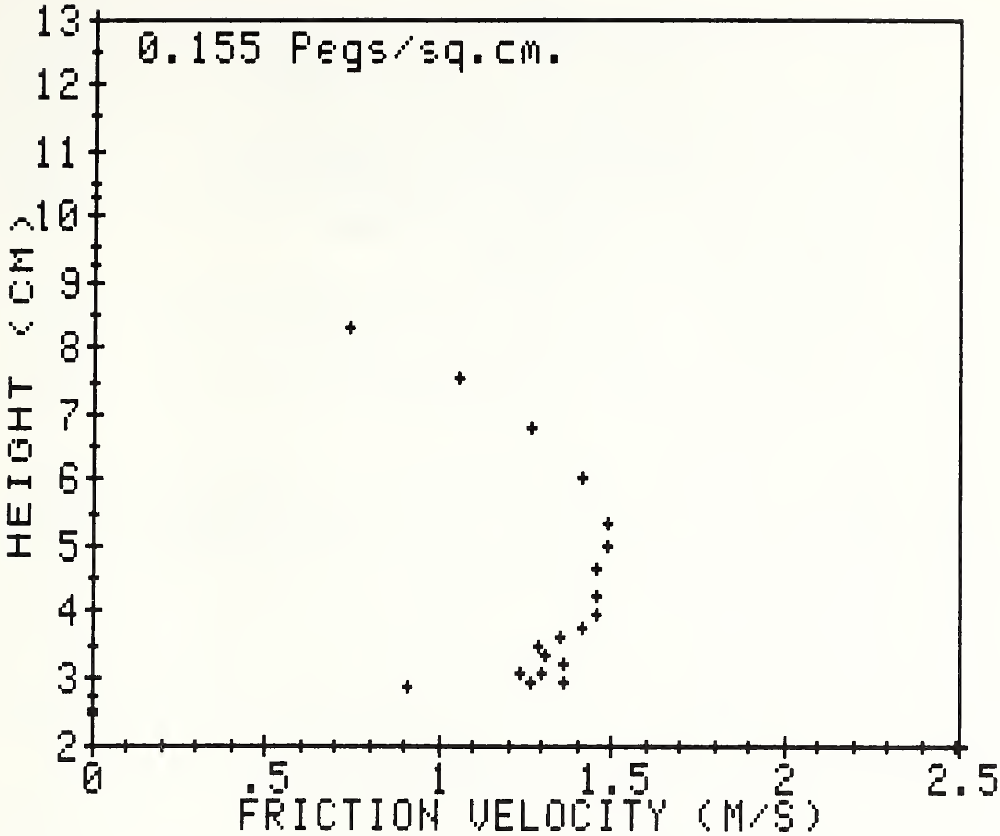

FIGURE 5. Friction velocity profile corresponding to velocity profile in Figure 4. Values are obtained using Eq. 5.

Area Density Peg cm^{-2}	V* $m\ s^{-1}$	D cm	z_o cm	z_o (ATM) m
0.155	1.44	0	0.565	33.2
0.078	1.37	0	0.460	27.0
0.039	1.17	0	0.278	16.3
0.019	0.94	0	0.144	8.5
PEGBOARD	0.50	0	2.41×10^{-3}	0.14
PLYWOOD	0.44	0	5.29×10^{-4}	0.03

TABLE 1. Roughness characteristics of the family of surfaces which use 1.27 cm high by 0.64 cm diameter cylindrical pegs as roughness elements. The rightmost column is z_o based on TVC conditions of r_o = 40 cm and Re_r = 5 x 10^3.

The last column in Table 1 shows z_o scaled up to the atmosphere for TVC conditions of r_o = 40 cm and Re_r = 5 x 10^3 giving δ_{TVC} = 8.5 cm. Recalling from above that for the natural surfaces, $z_o \leq 2$ m, one can see that the test surfaces considered to this point correspond to extremely rough surfaces in the atmosphere. Because of this, we are now examining surfaces with pegs that are only half as tall as those used in this study. Preliminary results indicate that surfaces with these shorter pegs will be better scaled to the atmosphere by being within the desired upper limit of $z_o \leq$ 0.08 cm.

Summary

A family of surfaces, each consisting of a field of cylindrical pegs of uniform size arrayed in a regular pattern, has been developed to simulate the rough surface of the earth. By measuring the velocity profile in the boundary layer above these surfaces when installed in a wind tunnel, then fitting a log-linear profile to the constant stress portion of the wind tunnel boundary-layer profile, values for z_0, V*, and D have been obtained for each surface. Since z_0 is dependent only upon the surface itself, it can be used to characterize each surface.

As expected, the values of z_0 decreased with decreasing peg area density. However, the z_0 values for the 1.27 cm high pegs were all "large" when scaled to the atmosphere. Because of this, additional surfaces with pegs that are only half as tall as now being examined. Preliminary results indicate that the roughness properties of these additional surfaces will be better scaled to the atmosphere.

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