An Independent Method to Determine the Surface Roughness Parameter

By Jia-Yi CHEN[1], Jie-Ming WANG[2] and Yasushi MITSUTA

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Abstract

A technique for independent evaluation of surface roughness length has been suggested. This approach only uses mean wind speed and friction velocity data measured at a single level. It was checked at first by using the data of the Kansas Experiment. Inter-consistent Z_0 derived from 5.66m and 22.6m data has been obtained and compares well with that derived from wind profiles. The technique was applied for determining the Z_0 of the Gobi desert in the HEIFE area and was based on the sonic anemometer-thermometer data collected during 1988 Pilot Observation Period. The estimation has been repeatedly conducted by using the data collected in 1990 and again reached a value of Z_0, which is also in good argeement with the value derived from wind profiles. The estimation of surface roughness for the Gobe desert is between 1.1×10^{-3}m to 1.5×10^{-3}m. The method presented here for roughness estimation has the advantage of determining Z_0 with simultaneous flux measurements, and without need for wind profile data.

I. Introduction

The surface aerodynamic roughness length Z_0 is a scale height which characterizes the surface absorption of the momentum of atmospheric movement, and is also a basic parameter in the parameterization scheme of trubulent fluxes in the atmospheric boundary layer. Knowing surface roughness, we may simply calculate the surface fluxes of momentum, sensible and latent heat with the measurments of wind speed at a single level, temperature and humidity at two levels. The traditional method in determining aerodynamic roughness is by extrapolating the wind profile within the surface layer under neutral conditions down to the height with apparent zero mean wind velocity or by iterative calculation of the diabatic wind profiles. These techniques need multi-height wind velocity measurements. This paper suggests a method which requires only non-dimensional wind velocity measured at one height by using instrument such as a three-dimensional sonic anemometer instead of profile data. The technique has been tested on the data of the Kansas Experiment and shown a fair accuracy. It has the advantage in combining the determination of Z_0 together with the measurement of turbulence fluxes without need of wind profile data. Along with the popularization of the direct measurement technique of turbulent fluxes, this method would be an independent

Permanent address; [1] Dept. of Geophysics, Peking Univ.
[2] Lanzhou Inst. of Plateau Atmospheric Physics, CAS

approach in reliably determining Z_0. The data with diabatic stabilities may simply be used as well, if an approximate flux-gradient relationship is assumed. It is particularly of importance in the cases we meet in the large Gobi desert of the HEIFE* experimental area, where stability in the surface layer usually is substantially different between day and night and storong wind conditions in the transient period of morning and late afternoon with high-variability. This is a less reliable basis for utilizing the data to determine the surface roughness except that the measurements may be taken at very low levels. Futher more drag near neutral stratification occurs only under the unfavorably sandy condition, and wind gradients are small over the Gobe desert. It is difficult to obtain a good estimate of Z_0 if there is no high quality profile data available.

Based on the wind profile data collected in the HEIFE pilot observation in 1988, Hu et al.[1] (1990) estimated the roughness of the Gobe Desert to be about 2×10^{-4}m, a value which appears to be too much small. With the new method suggested in this note and based on the data of turbulence characteristics, an independent estimation of Z_0 of about 1.1×10^{-3}m to 1.5×10^{-3}m has been obtained. It agrees with that determined by the lower level wind profile data collected in the latest experiment and roughly one order larger than the estimate of Hu et al[1].

II. Determining surface roughness by non-dimensional wind velocity

The generalized wind profile in the atmospheric surface layer can be formulated in terms of Monin-Obukhof similarity as a universal stratification function of Z/L (Panofsky and Dutton, 1983)[2]

$$U=(U_*/\kappa)\{\ln(Z/Z_0)-\psi m(Z/L)\}, \tag{1}$$

where $\psi m(Z/L)$ is the integral form of the shear function $\{\phi m(Z/L)=(\kappa_a Z/U_*)(\partial U/\partial Z)\}$ and

$$\psi m(Z/L)=\int_{Z_0/L}^{Z/L}\{1-\phi m(\zeta)\}\frac{d\zeta}{\zeta}. \tag{2}$$

The other notations are as normally used.

From (1) we have,

$$\ln(Z/Z_0)=(\kappa U/U_*)+\psi m(Z/L). \tag{3}$$

*HEIFE: the Heihe River Basin Field Experiment, A Sino-Japanese Cooperational Program on the Atmosphere-Land Surface Processes Experiment.

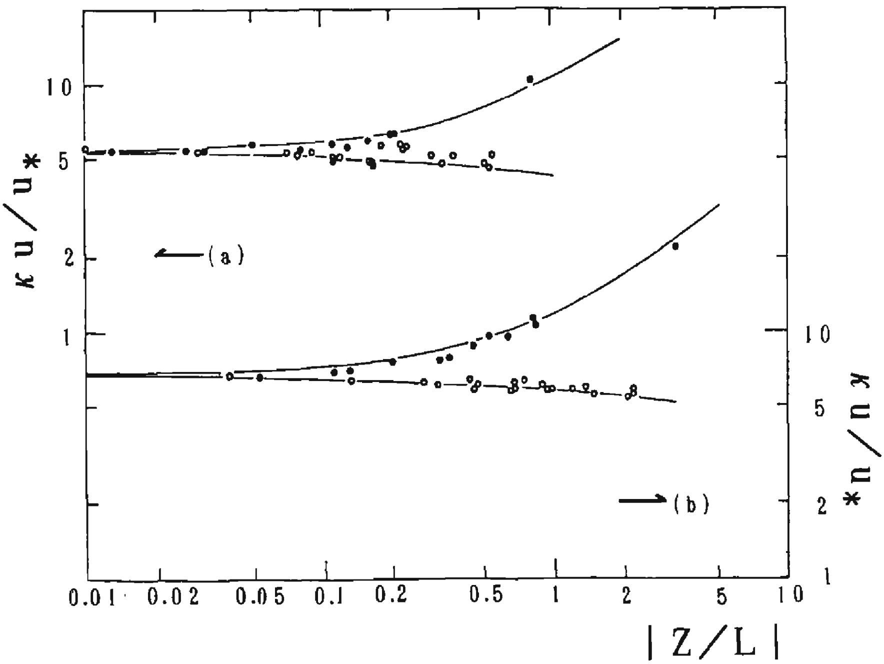

Fig. 1. The variations of non-dimensional wind speed $\kappa U/U_*$ with stability parameters Z/L for Kansas Experiment 5.66m data (a), and 22.6m data (b). Solid circle shows stable side and open circle shows unstable side. The solid curves are drawn from neutral values $\kappa U/U_*=5.40$ and 6.80 respectively for 5.66m and 22.6m by using Businger flux-profile scheme.

Knowing the von Karman constant and flux-profile relationship, the roughness parameter Z_0 can be derived from the measurements of a single height non-dimentional wind speed under different stabilities Z/L. If there are enough measurements under near nertral conditions, $\psi_m(Z/L)$ can be neglected in Eq. (3), and we can calculate Z_0 directly from the observed values of $\kappa U/U_*$.

As a test of this method the data collected in the Kansas Experiment (Izumi et al.[3], 1971) have been used. Based on the measured mean wind speed and friction velocity at 5.66m and 22.6m, and the recommended value $\kappa=0.35$ (Businger et al.[1], 1971) for that experiment, the variations of $\kappa U/U_*$ with stability are shown in **Fig. 1.** Using Businger's flux-profile scheme for height 5.66m (**Fig. 1. a**) the best extrapolated neutral value of $\kappa U/U_*$ is 5.30 from the stable side, and 5.50 from the unstable side with a few data being excluded. The mean value 5.4 is the same as the average of near neutral ($|Z/L|<0.1$) data. A value of roughness length $Z_0=0.0256\pm0.0025$m is derived. For 22.5m data, the value of $\kappa U/U_*=6.80$, except for a few rather lower data points, can be seen in **Fig. 1. b** for the unstable side, and $Z_0=0.0251$m have been recommended. The surface roughness estimated above for the Kansas Experiment site from observations taken from two heights agrees well with that determined from high quality wind profile measurments, i, e, 0.024m, reported by Bradley[5] (1971). It shows that single height wind speed and friction velocity could well be used in evaluating the surface aerodynamic roughness.

For observation data in nearly neutral stability, the relative error in determining Z_0 by this method can be estimated from (1) or (3),

$$dZ_0/Z_0 = -(dM/M)\ln(Z/Z_0) \tag{4}$$

where $M=\kappa U/U_*$ (neutral). This means that the relative error of Z_0 is in proportion to the relative error of $\kappa U/U_*$ and also weakly depends on Z/Z_0. When Z/Z_0 is in the order of 100 to 1000, a 10% non-dimensional wind speed error would result in about a 50% error in the estimation of Z_0. Therefore, the method suggested requires higher accuracy of U/U_* measurements, and less systematic error. In principle, this method could use observational data of different stabilities, however, it is better to have enough nearly neutral data in order to reduce the influence of the accuracy of the flux-profile relationship itself.

In the calculation of **Fig. 1** a contentious value of $\kappa=0.35$ has been used. Weiringa[6] (1980) has argued that the abnormally low value of κ in the Kansas Experiment was mainly from flow interference of the auxiliary tower installations, which resulted in a lower evaluation of the turbulence shear stress. After a proper correction for primary and secondary factors, κ should be near the commonly acceptable value of 0.40. That is, the κ, U, and U_* in the Kansas Experiment each presented different degrees of error. However, the composite value of $\kappa U/U_*$ still remained reliable.

III. The aerodynamic roughness of Gobi desert of the HEIFE Area.

The Gobi Desert is one of the main underlying surfaces spread over the concerned area of the HEIFE Cooperational Program. A basic station, Huayin numbered as 004, was located on the flat Gobi surface. The soil consists of coarse sand grains and small pebbles. The location and site features were described in details by Mitsuta[7] (1988) and Wang et al.[8] (1990).

Based on a 20m tower profile data of the 1988 observations, Hu et al.[1], (1990) indicated the roughness of the Gobi surface around the site to be about 2.0×10^{-4}m. This is unusually small. By using the method presented above and the data collected by a 3-dimensional sonic anemometer at the same period, the result could be checked in an independent manner. An experiment emphasizing the comparison of the instruments for turbulence measurements was undertaken in the summer of 1990. A portion of the data including that measured by sonic anemometer, as well as high quality wind profiles have become available so far to support the checking.

The observations for turbulent fluctuation and fluxes in the experiment of 1990, are the same as that used in 1988 (Wang et al.[8], 1990, and Wang and Mitsuta[9], 1990). A system which consists of seven accurately calibrated cup anemometers was put into operation for a few days during the experiment to measure the wind profile between 0.32 m to 5.40m above the surface (Chen et al.[10], 1991). **Fig. 2** shows the comparison

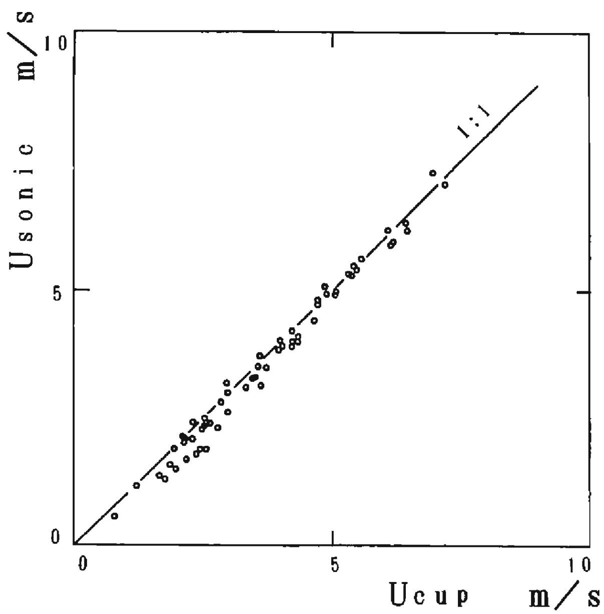

Fig. 2. The comparison of averaged wind velocity at 2.45m measured by sonic anemometer and by cup anemometer. For cup anemometer the wind velocities were measured at 2.10m and 3.23m and then interpolated into 2.45m.

between averaged wind velocity measured at 2.45m by sonic anemometer, DAT-300 with TR-61A sensor, and the interpolated wind velocity measured by cup anemometers at neighboring levels, 2.10m and 3.23m. Both data are in reasonable agreement with each other, except for the overestimates by the cup anemometers during lower wind speeds. This was apparently due to the overspeeding of the cup anemometers as expected[11]. The comparison between the turbulent quantities is to be discussed in a coming paper.

Figs. 3 and 4 show the variation of non-dimensional wind speed with stability parameter Z/L, calculated from the sonic anemometer-thermometer data measured at 2.45 m above the surface for both 1988 and 1990, respectively. In the calculation, the von Karman constant, which has again taken on the value $\kappa=0.40$ in recent years, is in agreement with our conclusion (Chen et al., 1991[10]). The solid curves are drawn from neutral values $\kappa U/U_*=7.5$ and 7.7, respectively, for the data of 1988 (**Fig. 3**) and 1990 (**Fig. 4**) by using the Businger flux-profile scheme[4], but applying the von Karman constant of 0.4. The data collected during the wind direction unfavorable for sonic anemometer measurement were exculded, and a grouped average for 1988's data was made in order to reduce the scatter. The present figures indicate the surface roughness length of the Gobi Desert to range between 1.1×10^{-3}m to 1.5×10^{-3}m with an average of 1.3×10^{-3}m. The evaluation of Z_0 by Chen et al.[10] (1991) from wind profile data by using a traditional approach has suggested $Z_0=1.2\times10^{-3}$m, that strongly supports the result obtained by present approach.

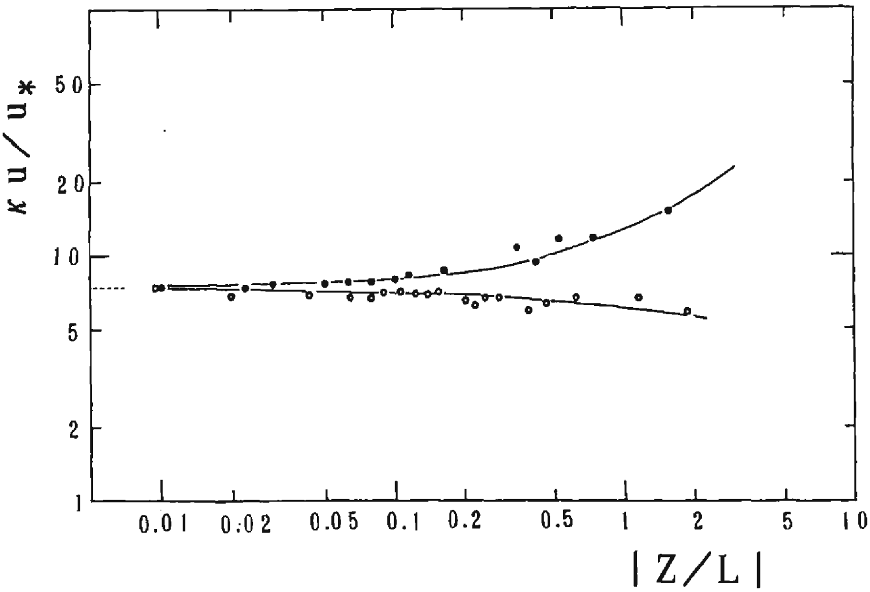

Fig. 3. The variation of $\kappa U/U_*$ as function of Z/L with $\kappa=0.40$ for data measured by sonic anemometer at 2.45m above the Gobi desert in 1988. The solid circle shows stble side and open circle shows unstable side. Solid curves are drawn from neutral value $\kappa U/U_*=7.50$ by using Businger's flux-profile scheme.

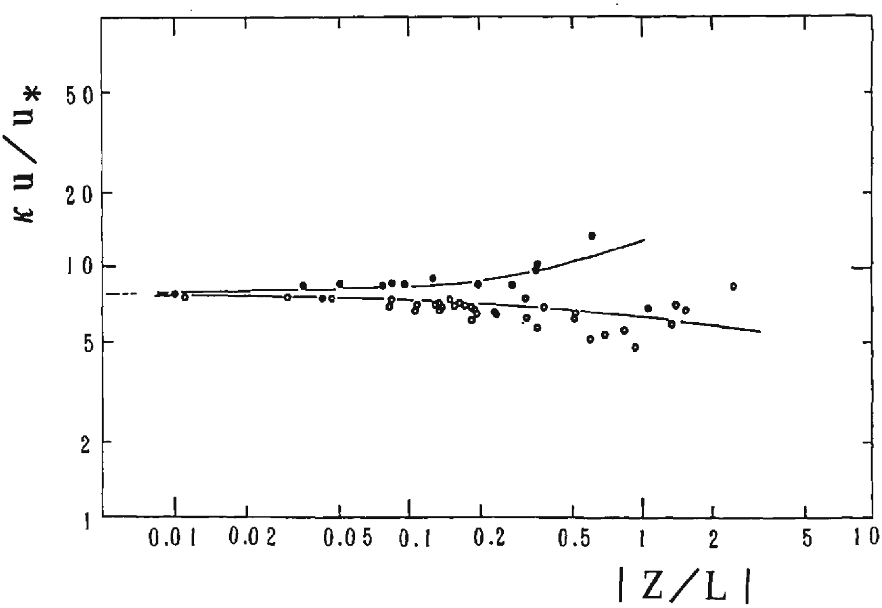

Fig. 4. Same as Fig. 3 except for the data of 1990 and with neutral value $\kappa U/U_*=7.70$.

IV. Conclusive Remarks

We conclude that the surface roughness parametger can be derived by using mean wind speed and friction velocity measured at a single level. The approach presented in this paper was proven to be feasible. It is obvious that resulting accuracy is sensitive to the values of $\kappa U/U_*$. Fortunatly, the latest arts of turbulence measurement are so well developed that accurate measuring for $\kappa U/U_*$ may not be difficult in principle. Apparently, caution should be paid to the desirable selection of the von Karman constant. However, analysis has shown that the erroneous Z_0 derived from assuming κ may not result in an error in the flux estimation if both are used simultaneously in the flux calculation.

For the HEIFE Gobi Station the surface roughness is estimated to be 1.1×10^{-3}m to 1.5×10^{-3}m, which is quite comparable with the extrapolated value of high quality wind profile measurements. It is well known that the aerodynamic roughness is closely related to the surface roughness elements, their height and spacing scale. There are many formulae based on this kind of analysis in the literature, among those that of Kondo and Yamazawa[12] (1986). If we take the surface pebbles as the main roughnesds elements in the Gobi Desert and consider most of their diameters not larger than 5cm and only part of them being exposed to the surface air, we can also estimate the roughness parameter in the order of 10^{-3}m based on the statistics of the pebble height and cross area.

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