velocity distributions in open channels showed that, in uniform equilibrium open channel flows, the velocity distribution exponent is related to the flow resistance:

\[ N = K \times \sqrt{\frac{k_s}{f}} \]

where \( f \) is the Darcy-Weisbach friction factor and \( K \) is the von Karman constant (\( K = 0.4 \)) (CHEN 1990, CHANSON 1999).

### 3.2 Roughness effects

The boundary roughness has an important effect on the flow in the wall-dominated region (i.e. "viscous" sub-layer region and turbulent zone). Numerous experiments showed that, for a turbulent boundary layer along a rough plate, the "law of the wall" follows:

\[ \frac{V_x}{V_*} = \frac{1}{K} \times \ln\left(\frac{V_* \times y}{\nu}\right) + D_1 + D_2 \quad \text{Turbulent zone: } \frac{y}{\delta} < 0.1 \text{ to } 0.15 \quad (4-24) \]

where \( D_1 = 5 \) and \( D_2 \) is a positive function of the type of roughness and of roughness shape, height and spacing (e.g. SCHLICHTING 1979, SCHETZ 1993). For smooth turbulent boundary layer flows, \( D_2 \) equals zero.

In the turbulent zone, the roughness effect (i.e. \( D_2 > 0 \)) implies a downward shift of the logarithmic velocity distribution (Fig. 4-10). Figure 4-10 illustrates some effect of the boundary roughness on the law of wall. For example, let us compare Figure 4-9A (smooth boundary) and Figure 4-11B (rough plate). For large roughness, the "viscous" sub-layer region disappears and the flow is said to be "fully-rough".

For fully-rough turbulent flows in circular pipes with uniformly distributed sand roughness, \( D_2 \) equals:

\[ D_2 = 3 - \frac{1}{K} \times \ln\left(\frac{k_s \times V_*}{\nu}\right) \quad \text{fully-rough turbulent flows in circular pipes} \quad (4-25) \]

where \( k_s \) is the equivalent sand roughness height. After transformation, the velocity distribution in the turbulent zone for fully-rough turbulent flow becomes:

\[ \frac{V_x}{V_*} = \frac{1}{K} \times \ln\left(\frac{y}{k_s}\right) + 3 + D_1 \quad \frac{y}{\delta} < 0.1 \text{ for fully-rough turbulent flow} \quad (4-26) \]

Figure 4-11 illustrates some turbulent velocity measurements above a flat, rough plate. Figure 4-11A presents the time-averaged velocities and turbulent intensity distributions. Figure 4-11B compares the velocity distributions with Equation (4-26). The results show that the data followed closely Equation (4-26) for \( y/k_s < 5 \) to 30 depending upon the longitudinal distance \( x \) from the leading edge.

**Note**

The velocity distribution in the turbulent zone for fully-rough turbulent flow becomes:

\[ \frac{V_x}{V_*} = \frac{1}{K} \times \ln\left(\frac{y}{k_s}\right) + 8 \]

with \( D_1 = 5.0 \).