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United friction resistance in open channel flows*

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Abstract: It is now over half a century since Keulegan conducted his open channel flow experiments. Over the past decades, many empirical formulae were proposed based on his results, however, there is still not a combined expression to describe the effects of friction over all hydraulic regions in open channel flows. Therefore, in this letter, based on the analysis of the implicit model and the logarithmic matching method, the results of Keulegan (for authentic experiment data are no longer available, here we adopt the analytical solutions given by Dou) are rescaled into one monotone curve by combining the Reynolds number and the relative roughness of the river bed. A united expression that could cover the entire turbulence regions and be validated with Dou's analytical solutions is suggested to estimate the friction factor throughout the turbulent region in open channel flows, with higher accuracy than that of the previous formulas.

Key words: open channel flows, frication factor, united formula, implicit model, logarithmic matching method

The friction factor f is a very important parameter in the river engineering and the environmental hydraulic engineering. It is a critical parameter, among other things, in the calculations of the flow resistance and the average velocity. Generally speaking, there are two distinct types of flow regimes–the pipe flow and the open channel flow–which are controlled by different physical mechanisms. In the case of the pipe flow, the flow is mainly driven by the water pressure. The open channel flow, on the other hand, is usually driven mainly by gravity. Yet in spite of their differences, the flow resistance in both flow regimes can be described by a friction factor. For example, the head loss in both types of flows can be determined by the Darcy–Weisbach formula $h_f = f(L/4R)(U^2/2g)$ [1], where U is the mean velocity of the flow, g is the gravitational acceleration, h_f is the friction head loss, L is the length of the flow path, and R is the hydraulic radius.

Nikuradse determined the friction factor in pipes with artificial (but measurable) roughness and presented a graph to describe the way in which this roughness influences the pipe flows[2]. While in open channel flows (without vegetation, as in vegetated flows, the flow structure is usually affected by vegetation[3]), the irregularities or the roughness of the riverbed bring about resistance. In order to disclose the congruence between the pipe flows and the open channel flows, Keulegan conducted simulation experiments in artificial channels[4]. As a result, a graph (Keulegan graph) similar to that for the pipe flows was produced. To better explain the inner relationship, Dou gave a theoretical description of Keulegan's curves, which fitted well with the experimental data shown in Fig.1[5].

For open uniform laminar channel flows, $fRe =$ 24 can be obtained from basic physical equations[2]. For the turbulent flows near a solid channel wall，the flow field can usually be divided into three regions:

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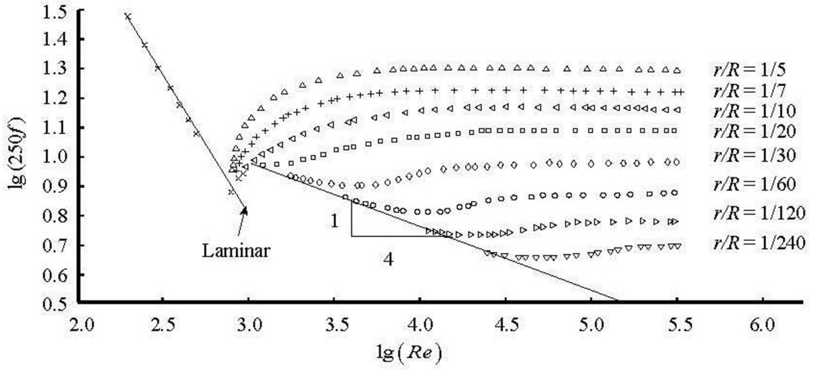

Fig.1 Dou’s analytical solutions for Keulegan graph in open channel flows[5]

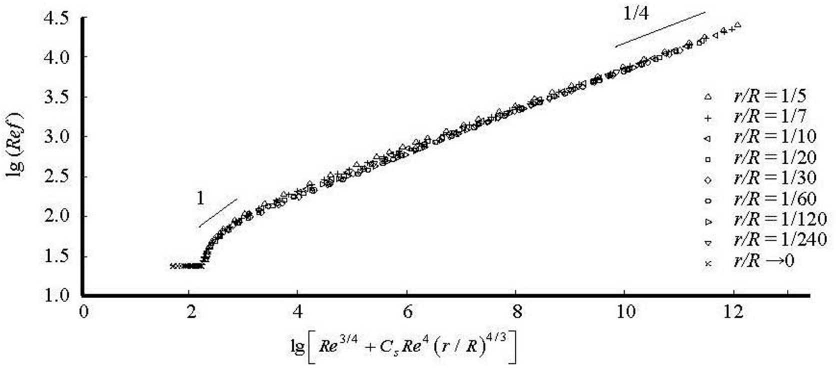

Fig.2 Friction factor as a function of the combined variable in open channel flow

the hydraulically smooth region, the transition region and the hydraulically rough region[2]. In the hydraulically smooth region, Blasius suggested a formula for the pipe flows[6]

$$f \sim Re^{1/4} \tag{1}$$

Equation (1) is also applicable for the open channel flows as we could see the line with a gradient of 1/4 in Fig.1. For the hydraulically rough region, Strickler proposed another formula for the pipe flows in the form of a power law and dependent on the relative roughness height r/R, where r is the equivalent height of irregularities on the bed surface[7] and it is expressed as follows

$$f \sim \left(\frac{r}{R}\right)^{1/3} \tag{2}$$

Previously justified by Gioia and Bombardelli[8], Eq.(2) is equally valid for the turbulence flows in the hydraulically rough region of open channel flows.

Given fRe as a constant in the laminar regime, integration is made as a whole in both the laminar and turbulence regimes. In the low Reynolds number region (i.e., with Reynolds number between 200 and 160 000) where the friction factor has no relationship with the relative roughness, analysis shows that we may assume that $r/R \to 0$. Therefore we could obtain $fRe = F(Re^{3/4})$ according to Eq.(1), where $F(x)$ is an implicit function of x.

In the high Reynolds number region, it is appropriate to apply the formula proposed by Goldenfeld[9], so we have $fRe = F[Re^{\alpha}(r/R)^{\alpha/3}]$ based on Eq.(2). According to Tao[10], naturally, we could use Eq.(3) combined with the two boundary conditions to cover both laminar and turbulence regimes

$$fRe = F\left[Re^{3/4} + C_S Re^{\alpha}\left(\frac{r}{R}\right)^{\alpha/3}\right] \tag{3}$$

where α and C_S are two constants to be determined in order to ensure that all six curves will merge to form one single curve.

Therefore, by processing the experimental data directly extracted from Fig.1 (since the original data of Keulegan’s experiments are no longer available),