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Influence of macro-rough banks on steady flow in a channel

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ABSTRACT: High-head storage hydropower plants operate their turbines during periods of high energy demand. The starting and stopping of turbines results in rapid fluctuations of discharge and water levels in rivers called hydropeaking, which are unfavorable from an ecological point of view. Morphological measures might help to reduce the fluctuations by increasing the natural retention capacity of rivers. With this practical background, the experimental investigations presented in this paper focused on the determination of the flow resistance under steady flow conditions caused by large scale roughness elements at the channel banks, namely rectangular cavities (depressions). The experiments conducted in 41 different geometrical configurations showed various two dimensional flow characteristics in the cavities. The overall head-loss of the flow is governed by the existence of different phenomena such as vertical mixing layers, wake-zones, recirculation gyres, coherent structures and skin friction. The analysis of the experiments for steady flow conditions showed that the flow resistance is significantly increased in the macro-rough configurations due to the disturbance of the bank geometry. Three different approaches have been considered relating the additional flow resistance due to macro-roughness to the forms of the banks. By separating the observed flow conditions into a square grooved, a reattachment and a normal recirculating flow type, the developed macro-rough flow resistance formulas are in good agreement with the laboratory experiments. Furthermore, water body oscillations have been observed in axi-symmetric macro-rough configurations. They lead to water-surface oscillations and transverse velocity components.

Keywords: Macro-roughness, Flow resistance, Cavity flow, Steady channel flow

1 INTRODUCTION

High-head storage hydropower plants operate their turbines during periods of high energy demand. The starting and stopping of turbines result in rapid and frequent fluctuations of discharge and water levels in rivers, called hydropeaking, which are unfavorable from an ecological point of view.

Literature reviews on the effects of hydropeaking (e.g. Baumann and Klaus 2003, Cushman 1985) report the stranding of macro-invertebrates due to rapid ramping or an increase of catastrophic drift (e.g. Céréghino et al. 2002) during sudden increases in discharge, water levels and flow velocities. Morphological measures might help to reduce the fluctuations further downstream by increasing the natural retention capacity since the propagation and attenuation of the (surge) waves are influenced by the channel slope and roughness (Favre 1935) as well as the river morphology (passive retention, Stranner 1996).

With this practical background, experimental investigations have been conducted in a large number of different geometrical configurations, namely rectangular cavities at the river banks. The steady flow experiments consisted in a preliminary step for unsteady flow experiments (Meile 2007, Meile et al. 2008). They focused on the determination of the flow resistance and flow conditions caused by large scale roughness elements (rectangular cavities) at the channel banks.

2 THEORETICAL CONSIDERATIONS

2.1 *Macro-rough flows*

Flows might be classified regarding the effect of the viscosity relative to the inertia in laminar, turbulent and transitional flows. The turbulent flows can again be divided into three types: smooth turbulent flows, fully rough turbulent flows and transitional turbulent flows.

When the relative roughness becomes high, which means that the size of roughness elements approaches the order of magnitude of the flow depth h or the hydraulic radius R_h, the flow is called macro-rough. The roughness elements can cover the entire channel section or only a part of the section as the bottom or the bank. The roughness generating elements may are boulders or pebbles, artificial elements as cubes, spheres, cones or depressions, different types of vegetation, bed forms in mountain streams and torrents, bed forms in mid- and lowland streams or abrupt changes of channel sections respectively profile.

Table 1. Flow types and head-loss governing phenomena.

Flow type		Head-loss due to
Laminar flow ($Re = 4UR_h / \nu < 2300$)		Viscous friction
Transitional flow ($2300 < Re < 4500$)		Viscous and turbulent friction
Turbulent flow	Smooth turbulent flow	Turbulent friction in the shear layer; no influence of ε
	Transitional turbulent flow	Turbulent friction in the shear layer (influence of Re and ε)
	Fully rough turbulent flow	Turbulent friction in the shear layer; no influence of Re
Macro-rough flow	Well inundated flow	Principally turbulent friction in the shear layer
	Marginally inundated flow	Turbulent friction in the shear layer & wake dissipation
	Partially inundated flow	Principally jet dissipation and wake dissipation

Macro-rough flows have only marginally been studied before 1970. The first systematic investigations on macro-roughness in open channel flow have been done by Bathurst (1978) and on roughness elements in pipe flow by Morris (1955). A further separation of the macro-rough flow can be undertaken using the definitions of Lawrence (1997) into well inundated flow regimes, marginally inundated flow regimes and partially inundated flow regimes (Table 1). Weichert (2006) reviewed flow resistance formulas in mountain streams including macro-rough flows. He divided flow resistance formulas into logarithmic laws with modified constants, modified logarithmic laws, power laws, and laws for macro-and meso-scale features (e.g. Ferro 2003, Wang Zhao-Yin et al., 2009).

An important and general finding of the various studies on macro rough flow resistance is the fact that high roughness density does not automatically mean high flow resistance. Particular arrangements can lead to maximum flow resistance. This has been confirmed by recent studies on boulders and pebbles (Canovaro and Solari 2006, Pagliara and Chiavaccini 2006) even for numerical simulations of artificially roughened beds (Leonardi et. al 2003).

2.2 *Composite and compound channel sections*

The flow resistance and thus water levels of rivers are influenced by the roughness of the bed and the roughness of the banks. For low relative flow depths the roughness of the banks is of secondary importance. This is generally the case for wide rivers at low and moderate discharge.

With increasing relative flow depths, the influence of bank roughness becomes more significant. Different equations issuing from various researches for composite channel resistance exist. They are based on numerous assumptions summarized in Yen (2002). Most of them require an assumption on how the composite/compound channel section is divided. Few others are free of this assumption (Einstein 1934). The concept of the approach of Einstein (1934) is based on the assumption that the total cross sectional mean velocity U is equal to each sub-area mean velocity U_i. The composite Manning coefficient n_c of the section calculates than as:

$$n_c = \left[\frac{1}{P} \sum \left(n_i^{3/2} P_i \right) \right]^{2/3} \qquad (1)$$

where P = wetted perimeter, n_i = the Manning coeffient of the sub-area and P_i = wetted perimeter of the sub-area.

The uniform cross sectional velocity hypothesis (single channel method SCM) assumption is quite reasonable for a channel section of composite roughness. However, it becomes more doubtful for a compound channel having a main channel and floodplain(s) where the flow velocities are obviously different from the main channel flow velocity. In this case, the section is divided into subsections and the discharge is computed in each individually (divided channel method DCM). Furthermore, the turbulent exchange (momentum flux due to the velocity gradient)and the geometrical transfer (discharge flux due to geometrical changes of the floodplain) should be taken into account (e.g. Bousmar and Zech 1999).

2.3 *Skin friction and form drag*

In addition to the effect of bed and bank, the total resistance in a channel is depending on both, grain