Journal of Hydrology 537 (2016) 10–17

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

Technical Note

Kinetic energy and momentum correction coefficients in straight compound channels with vegetated floodplain

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ARTICLE INFO

Article history:
Received 23 November 2015
Received in revised form 13 March 2016
Accepted 14 March 2016
Available online 23 March 2016
This manuscript was handled by Tim R. McVicar, Editor-in-Chief, with the assistance of Ioannis K Tsanis, Associate Editor

Keywords:
Compound channel flow
Kinetic energy coefficient
Momentum correction
Floodplain vegetation
Velocity distribution

SUMMARY

In this paper, the effect of flow relative depth (ratio of the floodplain to the main channel flow depths) and vegetation density on the kinetic energy and momentum correction coefficients (termed as α and β, respectively) was described based on an experimental study. A series of experiments was run using rigid dowels with seven flow relative depths and four vegetation densities in an asymmetric compound channel. The local flow velocities were measured using an acoustic Doppler velocimeter (ADV). Using regression analysis, velocity data were considered and equations were developed for calculating the kinetic energy and momentum correction coefficients as a function of the flow relative depth and vegetation density. The results show that the values of α and β decrease as the relative depth increases. Also, as the vegetation density increases, the effects of the vegetation on α and β increase too. Finally, by comparing with the findings of the previous researchers, it was found that the average values of the α for asymmetric compound channels with vegetation are 26.5% and 43.3% greater than those for asymmetric and symmetric compound channels without vegetation respectively while these values for β are 12.7% and 18.1%, respectively. Furthermore, the floodplain vegetation can increase the average values of coefficients α and β by 52.8% and 21.6%, respectively, in comparison with single channels.

1. Introduction

Many natural rivers and man-made channels are composed of a main channel which always carry low flows bounded by one or more floodplains which carry flow above the bank full stages. As a result of different flow depth and hydraulic roughness and subsequently the difference of velocity between the main channel and the floodplain, a complicated flow structure characterized by large mixing layers and secondary currents develops (Knight and Demetriou, 1983; Shiono and Knight, 1991; Myers et al., 2001; Wilson et al., 2002; Stocchino and Brocchini, 2010; Azamathulla and Zahiri, 2012; Hamidifar and Omid, 2012; Bellahcen et al., 2014). Hence, the hydraulics of compound channels must be investigated more thoroughly due to the interaction and consequently a lot of momentum exchanges that take place between the floodplains and main channel.

There are many important topics in river hydraulics such as discharge prediction, bank protection, navigation, bed shear stress distribution, sediment transport and heat and mass transport that require accurate knowledge on velocity distribution (Wormleaton and Hadjipanos, 1984; Myers, 1986; Mizanur Rashid and Chaudhry, 1995; Patra et al., 2004; Huthoff et al., 2008; Hamidifar et al., 2015). If the velocity is not uniformly distributed, the velocity head is generally greater than $V^2/2g$ where g (m/s^2) is the acceleration due to gravity and V (m/s) is the mean flow velocity defined as (Chow, 1959):

$$V = \frac{Q}{A} \quad (1)$$

where Q (m^3/s) and A (m/s) are the discharge capacity and the cross-sectional area of the channel, respectively. Similarly, the non-uniform velocity distribution affects the momentum equation. Hence the momentum of the fluid passing through a channel section per unit time (ρQV), where ρ (kg/m^3) is the fluid density, must be multiplied by a correction factor if the average velocity is used. The kinetic energy coefficient (α; dimensionless) is also called the Coriolis coefficient and the momentum correction coefficient (β; dimensionless) is also known as the Boussinesq coefficient. The α and β coefficients are defined as:

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http://dx.doi.org/10.1016/j.jhydrol.2016.03.024
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$$\alpha = \frac{\int_A v^3 dA}{V^3 A} \quad (2)$$

$$\beta = \frac{\int_A v^2 dA}{V^2 A} \quad (3)$$

where v (m/s) is the local fluid velocity.

Applying two-dimensional hydraulic models in river engineering which require hard to get parameters is more complex than simple one-dimensional models. Furthermore, some studies have shown that using two-dimensional models do not necessarily show expected enhancements in outcomes (e.g. Hardy et al., 1999; Marks and Bates, 2000; Bates et al., 2003; Aggett and Wilson, 2009). Hence, modifying one-dimensional models, for example by applying accurate values for the velocity distribution coefficients α and β, will increase the accuracy of a model's predictive ability. It is generally found that $1 < \beta < \alpha$. For simple channels of regular geometrical sections and uniform flow across the channel, the coefficients are often assumed to be unity and hence the effects of these coefficients can be ignored. The further the flow deviated from uniform, the greater the coefficient become. The magnitude of α may be well over 2 for natural waterways with severely non-uniform velocity distributions (Henderson, 1966). Fenton (2005) reported that neglecting the appropriate consideration of energy and momentum coefficients in practical flow problems can leads to a 5–10% error even in simple flow calculations.

The kinetic energy and momentum correction coefficients have been intensively studied by many researchers (e.g., O' Brien and Johnson, 1934; Watts et al., 1967; Strauss, 1967; Jaeger, 1956; Jaganadha Rao et al., 1970; Streeter and Wylie, 1979; Li and Hager, 1991; Roberson and Crowe, 1998; Chanson, 2004). The methods for calculating α and β can be categorized as approximate methods, graphical methods and theoretical methods. In some of the studies, both α and β were expressed as a function of the ratio of maximum to the average cross-sectional velocity (Rehbock, 1922; Chow, 1959; Mazumder, 1971). Li and Hager (1991) recommended that for practical purposes α and β may be considered up to 1.15 and 1.06, respectively.

As velocity distribution in compound channels is severely non-uniform (Myers, 1978; Rajaratnam and Ahmadi, 1981; Knight and Demetriou, 1983; Tominaga and Nezu, 1991; Pezzing, 1994; Fernandes et al., 2012; Al-Khatib et al., 2013; Mohanty and Khatua, 2014; Shiono and Rameshwaran, 2015), correction factors must be introduced in the energy and momentum equations. Mohanty et al. (2012) investigated the kinetic energy and momentum correction coefficients in a smooth straight compound channel with wide symmetric floodplains. They obtained 2.09 and 1.39 for α and β values, respectively. Kolupaila (1956) recommended average values of α and β as 1.75 and 1.25, respectively, for over flooded rivers. Seckin et al. (2004, 2009) experimentally investigated the kinetic energy and momentum correction coefficients in a symmetrical rectangular compound channel and obtained average values of α and β as 1.094 and 1.034, respectively. Luo (2012) conducted an experimental study in a straight symmetric compound channel with smooth floodplains and presented a series of equations for determination of α and β. Also, Keshavarzi et al. (2010) studied the effects of submerged vanes on the energy and momentum coefficients in a compound channel. They concluded that the energy and momentum coefficients decrease significantly with the installation of a submerged vane in the main channel. Furthermore, the results of a theoretical study conducted by Parsaie (2016) showed that α and β can be as high as 2.2 and 1.4, respectively, in smooth symmetric compound sections.

Floodplain vegetation is one of the main elements that can affect the velocity distribution in compound channels (Helmiö, 2004; Yang et al., 2007; Huai et al., 2008; Liu et al., 2014; Kubrak et al., 2015). The hydraulics of the flow in compound channels can be significantly affected by the floodplain vegetation (Hamidifar and Omid, 2013; Hamidifar et al., 2013; Sun et al., 2013; Jiang et al., 2015). This may be due to that vegetation increases the overall resistance and consequently leads to a reduction in the mean velocity on the floodplain (Stone and Shen, 2002; Yen, 2002; Järvelä, 2002, 2004, 2006; Nikora, 2010; Aberle et al., 2010). For densely vegetated floodplains, the vegetated portion conveys only a small fraction of the total discharge (Helmiö, 2002). Some experimental studies have shown that flow velocity in the main channel increased significantly after the floodplains were vegetated (Huang et al., 1999, 2002). Kubrak et al. (2015) found that for partly vegetated sections a higher energy and momentum coefficient values than those given by the present literature should be used. Some of the most relevant kinetic energy and momentum correction coefficients researches conducted in different channel shapes and vegetation conditions are summarized in Table 1.

Table 1
Summary of relevant kinetic energy and momentum correction coefficients researches conducted in different channel shapes and vegetation conditions. Some of the information were not found in the literature and these are denoted with a N/A representing 'not available'.

Study	Channel shape	Vegetation	Key results
Kolupaila (1956)	Over flooded rivers	N/A	Average values of α and β were recommended as 1.75 and 1.25, respectively
Li and Hager (1991)	N/A	N/A	Values of α and β depend significantly on the manning roughness coefficient
Al-Khatib and Gögüs (1999)	Symmetric compound flume	Non-vegetated	Values of α and β do not significantly vary with increasing main channel height
Fenton (2005)	Pipes and open channels	N/A	Traditional Coriolis and Boussinesq coefficients have been found to be defective, as they neglect the effects of turbulence and secondary currents
Seckin et al. (2004, 2009)	Symmetric compound channel	Non-vegetated	Average values of α and β were obtained as 1.094 and 1.034, respectively
Keshavarzi et al. (2010)	Symmetric compound channel	Non-vegetated	Values of α and β decreased significantly with the installation of the submerged vane inside the main channel
Mohanty et al. (2012)	Compound channel	Non-vegetated	Floodplain width strongly affects the values of α and β
Luo (2012)	Symmetric compound channel	Non-vegetated	A series of equations was presented for determination of α and β
Al-Khatib (2013)	Asymmetric compound flume	Non-vegetated	Average values of α and β were found to be 1.15 and 1.12
Kubrak et al. (2015)	Simple rectangular channel	Partly vegetated	Values of α and β can be as high as 2.8 and 1.5, respectively
Parsaie (2016)	Symmetric compound channel	Non-vegetated	Values of α and β can be as high as 2.2 and 1.4, respectively