INTERACTION BETWEEN A SUBMERGED VANE AND THE CHANNEL BANK

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Submerged vane system is a common technique for river management. By installing a row of small flat plates vertically on the channel bed, the bed shear stress is redirected and the bed profile is modified. The study aims to investigate the effect of channel bank on the performance of the vane. A theoretical model capable of determining the bed profile induced by a submerged vane under the effect of channel bank is developed. Investigation on a case study shows that within the distance of 1.8 water depths, the presence of the channel bank increases the performance of the vane. However, for distance larger than 1.8 water depths, the bank decreases the performance of the vane. The effect is not negligible and should be considered in analyzing the performance of a vane.

Key Words : *submerged vane, channel bank, interaction, sediment management*

1. INTRODUCTION

Submerged vane is a technique for sediment management in alluvial rivers. By installing a series of flat plates vertically on the channel bed to generate a coherent vortex downstream, the secondary current in a channel bend, which is known a potential threat for the stability of the channel bank, is significantly reduced. Along with the altered flow pattern, the bed profile in the channel bend is also changed as well. The bed elevation near the outer bank, which is usually suffering from erosion problem due to the secondary current in the channel bend, is raised and the foundation of the bank is thus strengthened.

The location of vane is usually close to the channel bank in order to produce higher sediment management effect. However, the performance of the vane is also affected by the bank due to certain interaction effect when the distance between the vane and the bank is small. The study aims to investigate this interaction between the vane and the channel bank. The effect of this vane-bank interaction on the sediment management capacity of the vane is also studied.

2. VANE-BANK INTERACTIONS

A submerged vane installed vertically on the channel bed with an angle of α to the flow is considered. The coordinate system is as shown in fig.1. The *s*-axis is along the channel center-line, positive in the streamwise direction; the *n*-axis is perpendicular to the *s*-axis and positive toward the concave bank; the z-axis is vertically upward from the river bed. The velocity components in the s-, n-, and z-directions are u, v, and w, respectively. The initial height and length of the vane is H_0 and L, respectively. The cross-sectional averaged water depth is d_0 and the channel width is b.

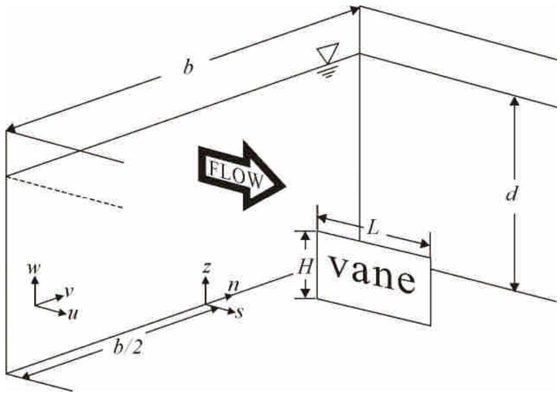

Fig.1 Schematic sketch showing a submerged vane and the coordinate system

By using the Method of Image, the effect of the vertical channel bank is simulated by a vane image on the opposite side with the same size as the real vane but opposite angle of incidence to the incoming flow. Fig. 2 gives an illustrative sketch of the real vane and the associated vane image. For simplicity, the viscous effect is neglected and the flow field is calculated by considering the real vane and the vane image as if there was no channel bank exists.

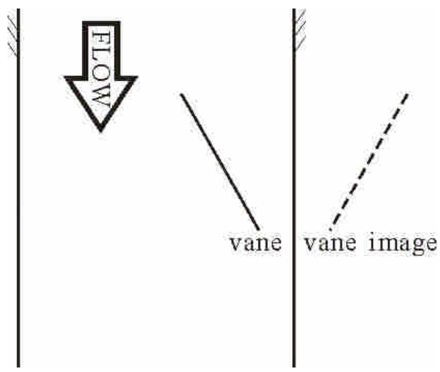

Fig.2 A submerged vane and the vane image for the effect of channel bank

The circulations of the vortices generated by the real vane and the vane image can be derived by modifying the Bi-plane theory (Milne-Thomson, 1966) with opposite angle of incidence for one of the vane. The equations read

$$\Gamma_1 = \pi L u_a (\alpha - \frac{v_1}{u_a})$$
$$\Gamma_2 = \pi L u_a (-\alpha + \frac{v_2}{u_a}) \tag{1}$$

where Γ_1 and Γ_2 are the circulations generated by the real vane and the vane image, respectively. v_1 and v_2 are the velocity deflections in the direction normal to the incoming flow for the real vane and the vane image, respectively. These velocity deflections can be calculated by the following form

$$v_i = \sum_{j=1}^{2} (W_{ij} + B_{ij}), \quad i = 1,2 \tag{2}$$

where W_{ij} and B_{ij} are the transverse velocity components at vane i induced by the wake vortex sheet and the bound vortex of vane j, respectively.

Applying the Biot-Savart Law and assuming elliptic circulation distribution along the trailing edge of the vane, W_{ij} becomes

$$W_{ij} = \xi^{ij} \frac{\Gamma_j}{4H} \tag{3}$$

where Γ_j = effective circulation generated by vane j; with ξ^{ij}

$$\xi_1^{ij} = -\frac{1}{\pi} \int_{-1}^{1} \frac{\eta^2}{\left[\left(\delta_{ij} / H \right)^2 + \eta^2 \right] \sqrt{1-\eta^2}} d\eta \tag{4}$$

where $d\eta = (1/H)dz$. δ_{ij} is the distance between the vanes. The transverse velocity components B_{ij} is derived as

$$B_{ij} = \zeta^{ij} \frac{\Gamma_j}{\pi L} \tag{5}$$

where

$$\zeta^{ij} = -\frac{1 - 2(\delta_{ij}/L)\sin\alpha}{1 + 4\left(\delta_{ij}/L\right)^2 + 4(\delta_{ij}/L)\sin\alpha} \tag{6}$$

To study the vane effectiveness, an interaction coefficient i defined as the ratio of the effective circulation to the undisturbed circulation is introduced

$$\lambda_i = \frac{\Gamma_i}{(\Gamma_0)_i}, \qquad i = 1, \cdots, N \tag{7}$$

where Γ_i = effective circulation for vane *i* under the effect of vane interactions; $(\Gamma_0)_i$ = undisturbed circulation for vane *i* which has been derived as follows (Odgaard and Mosconi, 1986)

$$\Gamma_0 = \frac{\pi L u_a \alpha}{1 + \pi L / 4H} \tag{8}$$

By definition, the interaction coefficients represent the effectiveness of the vane and the vane image under the effect of vane-interaction. Substituting Eqs. (2), (3), (5), and (7) into Eq. (1) yields a system of linear equations

$$\begin{bmatrix} 1 + \frac{\pi L}{4H} & \zeta^{12} + \xi^{12} \frac{\pi L}{4H} \\ \zeta^{12} + \xi^{12} \frac{\pi L}{4H} & 1 + \frac{\pi L}{4H} \end{bmatrix} \begin{bmatrix} \lambda_1 \\ \lambda_2 \end{bmatrix} = \begin{bmatrix} 1 + \frac{\pi L}{4H} \\ 1 + \frac{\pi L}{4H} \end{bmatrix} \tag{9}$$

By solving Eq. (9), the interaction coefficient for each vane within a vane system is determined. Note that the interaction coefficients thus obtained are functions of the vane dimensions *H* and *L* and the distance between the vanes δ_{ij}.

3. TRANSVERSE BED SHEAR STRESS DISTRIBUTION AND DEPTH PROFILE

The bed shear stress distribution induced by the vane and the vane image is calculated by using the superposition principle to sum up the contributions form each vane. The interaction coefficients determined by Eq. (9) are incorporated into the calculation to account for the interaction between the vanes as

$$\tau_{vn} = \sum_{i=1}^{2} \lambda_i (\tau_{vn})_i \tag{10}$$

where the transverse bed shear stress distribution induced by a single vane is calculated by Odgaard and Wang's (1991) single vane model

$$(\tau_{vn})_i = \frac{F_L k \kappa^2}{\pi m^2 H} \frac{u_m}{u_a} \times \sum_{j=1}^{\infty} \frac{(-1)^{j+1}}{r_j} [1 - \exp(-\frac{u_a}{4\varepsilon s} r_j^2)] \frac{z_j}{r_j} \tag{11}$$

where $F_L = \rho \Gamma_0 u_m H$ horizontal lift force induced by a vane, ρ = fluid density, u_m = depth averaged stream velocity, s = downstream distance, k = ratio of average velocity to near bed velocity, m = velocity power law index, κ = von Karman constant, $\varepsilon = \kappa^2 u_m d/[6m(1+1/m)(1-1/2m)(1-1/3m)]$ eddy viscosity (Odgaard and Spoljaric 1989), d = flow depth, z_j = vertical distance from the wake vortex center to the bed, and r_j = distance from the wake vortex center to the bed.

The transverse depth profile is calculated by adopting Odgaard and Wang's (1991) bend flow model

$$\frac{\mathrm{d}(d)}{\mathrm{d}n} = -\frac{m}{\rho k u_m B \sqrt{\theta \Delta g D}} \tau_{bn} \tag{12}$$

where B = a function of Coulomb's friction law and the ratio of lift to drag force for a bed particle. The value of B is between 3 and 6 (Ikeda and Nishimura 1985), θ = critical Shields stress, $\Delta = (\rho_s - \rho)/\rho$ specific weight of submerged sediment, ρ_s = sediment density; D = median grain size, and τ_{bn} = transverse shear stress distribution on channel bed.

In a river bend containing a vane system, both the secondary current of the bend flow and the vanes contribute certain portions to the transverse bed shear stress as

$$\tau_{bn} = \tau_{fn} + \tau_{vn} \tag{13}$$

where τ_{fn} = transverse bed shear stress component induced by the secondary current in bend flow = $-d u_m^2 \kappa (2m+1)(m+1)/(m^2[2m^2+\kappa(m+1)r]$ (Odgaard and Wang 1991), in which r = local radius of curvature for the channel bend. Equation (12) was solved numerically using the MATLAB software package. The interaction coefficients for the vane and the vane image were calculated with Eq. (9). The computation is then performed starting at the channel center. The approach flow depth at the starting point is equal to the cross-sectional averaged flow depth do, and the transverse depth profile was calculated along a cross-section of the channel. The discharge was checked once the depth profile was computed. If the discharge continuity was not satisfied, a new starting flow depth was selected and the process repeated until a convergence criterion was fulfilled. Note that the heights of the vanes changed during the computational process because of bed profile deformations. Consequently, the interaction coefficients are changing as well and are updated accordingly in each iteration.

4. RESULTS AND DISCUSSION

The interaction effect between the vane and the channel bank is investigated. Fig. 3 shows the variation of the interaction coefficient of a submerged vane as a function of the non-dimensional distance between the vane and the channel bank, δ_b / d_0. As shown in the figure, the interaction coefficient drops down to slightly less than 1.0 when δ_b / d_0 is larger than 1.5, and then gradually returns to 1.0 as the distance between the vane and the channel bank is increasing. When δ_b / d_0 is less than 1.5, however, it is seen that the interaction coefficient increases drastically with decreasing δ_b / d_0. When δ_b / d_0 is 0.4, the interaction coefficient has reached 1.2, i.e. 20% increase in the effectiveness of the vane. With further smaller δ_b / d_0, the viscous effect might prevail and the model is therefore not applicable.

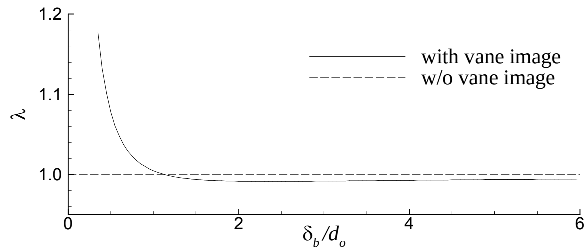

Fig.3 Interaction coefficient of a submerged vane as a function of δ_b/d_o (b/d_o =50, r_c/b=10, α=20°, L/d_o=1, H/d_o =0.5)

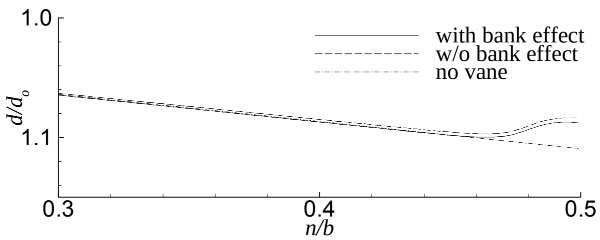

Fig.4 Comparison of the transverse bed profiles (δ_b/d_o=1.0)

Fig. 4 shows the transverse bed profiles in a channel cross section induced by a vane with and without considering the effect of channel bank. For the purpose of comparison, the bed profile prior to the installation of the vane is also shown in the figures. As seen, the pre-vane bed profile inclines to the concave bank due to the secondary current in the bend flow. After installation of the vane, the bed elevation near the bank is uplifted, and the foundation of the bank is strengthened. It is seen that the simulated bed elevation near the bank with bank effect included is lower than that without bank effect. The difference is about 19% of the vane-raised bed elevation. This indicates that the channel bank will result in significant reduction on the performance of the vane, which has to be taking into account for bed profile calculations.

5. CONCLUSIONS

The interaction effect between a submerged vane and the vertical channel bank is studied. A theoretical model is developed to take into account the interaction effect in the bed profile calculation in a channel cross section. The results show that the interaction coefficient of the vane increases drastically when the distance between the vane and the channel bank is less than 1.5 water depths. When δ_b / d_0 is 0.4, the effectiveness of the vane is uplifted by 20%. However, for δ_b / d_0 larger than 1.5, the interaction coefficient of the vane drops down to less than 1 and the effectiveness of the vane is deteriorated. The interaction coefficient gradually returns to 1 with increasing distance between the vane and the channel bank and the interaction effect is eventually fading away.

Bed profile simulations show that the performance of the vane is reduced by the channel bank with significant degree, indicating that the bank effect is not negligible in vane-induced bed profile calculations.

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