



## Effects of submerged sheet pile vanes on mobile river beds

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**Abstract:** Submerged vanes are low-height flow-training structures emerging from the riverbed with a suitable angle of attack to the incoming flow. These structures redirect the stream flow and modify erosion and depositional rates in the bottom and in the banks of a river as a result of the secondary currents generated by their installation. For this reason they have many applications in river hydraulics for controlling river bed morphology. An experimental investigation is carried out to compare the efficiency of sheet-piling vanes versus thin plane ones in controlling sediment redistribution in the channel bed. In particular, experimental tests were carried out within a straight water channel, in conditions of bed load motion. The morphology of the river bed both in the area close to the structure and in the far field was examined at different angles of attack of the vane to the incoming flow and at different values of the submergence parameter, which is the ratio between the height of the water above the structure and the water level. The experimental results show that both the shape of the vanes as well as the angle of attack affect their performance in terms of the effects on the bed morphology, especially for greater submergence parameters. Specifically, plane and sheet-piling vanes produce comparable remodelings of the channel bed in the downstream region, but when the attack angle is increased, the thin plane vane causes deeper scour holes close to the structure. This last effect is probably due to the increased erosive capacity of the horseshoe vortex associated with the plane vane, while the uneven surface of the sheet-piling vane mitigates the erosive strength of that vortex.

**Key words:** Vanes, Sediment, Scour, River hydraulics, Experimental hydraulics

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### 1 Introduction

A submerged vane is a vortex-generating device that is able to control river bed evolution in natural stream channels. The vane is a low-height baffle that is positioned on the river bottom at a particular angle of attack which diverts the flow of a river and thereby generates secondary currents in the main stream. As a consequence, the intensity and direction of the bottom shear stresses are modified and sediments are redistributed within the channel cross-section. For this reason, these devices have found many applications in river hydraulics, such as bank protection for curved channels, protection of bridge abutments and

piers, and prevention of sediment drift in hydropower or irrigation channel junctions. Moreover, they are used to produce the optimal depth of the riverbed, to reduce unwanted scour or the deposition of sediments and improve overall river navigability, to settle braided and wandering rivers with the consequent removal of bars and shoals, and to create a suitable habitat for aquatic fauna.

While previous studies indicate that submerged vanes or similar devices were used in the past for the stabilization of rivers and channels (Potapov and Pyshkin, 1947; Potapov, 1951; Chabert *et al.*, 1961; Jansen *et al.*, 1979), the first attempt to develop a theory-based design for them was made at the Iowa Institute of Hydraulics Research by Odgaard and Kennedy (1983) and by Odgaard and Spoljaric (1986). Odgaard and Kennedy (1983) mainly aimed at preventing erosion on the outer banks of river

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bends, where the flow is commonly characterized by separation, secondary fluxes, energy losses, and water surface variations. In this context, the vanes were used to counteract the 3D natural velocity field with the secondary current that was generated by their installation.

Furthermore, Odgaard and Spoljaric (1986) arranged the vanes in various laboratory and field tests to change the profile of the mobile bed in straight channels for the resolution of issues related to the formation of shoals and sandbars in rivers and artificial channels. They obtained significant results without changing the overall balance of the watercourse bed-load. In a straight channel configuration, the secondary currents induced by the vane generate crosswise shear stresses on the bottom and the transport of sediments in the orthogonal direction to the main flow with consequent modification of the riverbed profile. Examples of using submerged vanes within straight channels can be found in Council Bluffs, Iowa with the Power's Power Station (Nakato *et al.*, 1990) on the Missouri River and on the West Fork of the Cedar River in Butler County, Iowa (Odgaard and Wang, 1990). For channel bend applications, a field test was firstly carried out with positive results in a bend of the East Nishnabotna River, Iowa (Odgaard and Mosconi, 1987a). Further positive tests were also reported by Fukuoka and Watanabe (1989). Recently, Han *et al.* (2011) showed that vanes are effective in reducing flow separation, the intensity of secondary flows, and the turbulence generated downstream from sharp open-channel bends, which are frequently encountered in hydraulic engineering design.

Bank-attached vanes, also known as submerged groins, have been proposed for bank protection and habitat improvements (Hey, 1996; Rosgen, 1996; 2001a; 2001b; FISRWG, 1998), and their efficiency is usually tested as a function of the shape and the angle of attack (Bhuiyan *et al.*, 2010). Vanes have also been promoted to reduce the amount of local scour near bridge abutments and bridge piers as pointed out respectively by Johnson *et al.* (2001) by means of clear-water laboratory experiments and Espa and Magini (2000). However, the effect of these structures needs further clarification when considering riverbeds with the presence of bed forms (Barkdoll, 2003).

For all their possible applications, the primary advantages of using submerged vanes, compared to

other techniques, are their low cost and low environmental impact. However, the effects that they have on the flow and on the river bed are strictly dependent on their shape, dimensions, and geometric arrangement. Most vanes are constructed in the shape of a rectangle, as this is found to be the simplest shape to effectively divert water flow within a river system. However, some more complex shapes have been built and tested in laboratory studies. For example, an airfoil-like cross-sectional profile (Odgaard and Spoljaric, 1989; Ouyang, 2009) that is similar to a propeller twisted from the base to the top exists (Odgaard and Spoljaric, 1989). In particular, Ouyang (2009) investigated the effects of dimensions and shape on vane performance in a sediment controlled channel, focusing on a rectangular plate, a trapezoidal tapered plate, and a plate in the shape of a parallelogram with its top swept forward or backward to the approaching flow. Behbahan (2011) showed that curved and angled vanes are 35% and 20% more effective, respectively, in stabilizing river banks than flat ones. However, while these complicated designs perform well in laboratory tests, they are not often used in field applications, mainly due to their high manufacturing costs. In such circumstances, the flat-plate vanes still prevail. Nevertheless, Azizi *et al.* (2012) pointed out that flat plate vanes with leading edges reduce local scour around the structure and also reduce costs.

As already mentioned, in addition to the form, other important factors that affect the efficiency of the vanes are their size and their arrangement, with particular reference to how they are angled. In fact, the effectiveness of a submerged vane in sediment diversion depends on the vane alignment to the approaching flow, and on the height and length of the vane. In particular, prescribing the optimum angle of the vane relative to the channel axis is a basic issue, due to the fact that this angle changes with the stage levels (Odgaard and Mosconi, 1987b). The angle of attack to the approaching flow is usually maintained at less than 20° (Gupta *et al.*, 2010), because the greater the angle, the deeper the local scour holes that are usually formed. However, Tan *et al.* (2005) in a laboratory experiment concluded that the optimum angle of attack to divert sediment is about 30°. But these authors did not take into account local scour phenomena. The results of Tan *et al.* (2005) also showed that a vane higher than two to three

times the height of the bed form would create too much blockage to the flow and reduce the mobility of the sediment significantly. Conversely, if the vane is lower than the optimum height, bed load particles can easily climb over the vane, thereby reducing its effectiveness.

Obviously, the shape of these devices also depends on the material used in their construction. In field applications, the material of the vanes is often different from project to project. In the installation of the East Nishnabotna River (Odgaard and Mosconi, 1987a), vanes were employed to form steel axles, supported by a system of metal profiles (H-piles) planted in the bottom of the riverbed. For the Japanese project on the Kuro River (Fukuoka and Watanabe, 1989), wood piles were joined together to form rectangular elements. In these cases, the vanes essentially had a flat rectangular shape. Such a design remains valid and effective until the thickness is negligible compared to its height and the width. The Kuro River vanes are also provided with a large diameter circular pile at the leading edge, which reduced flow separation and local scour. For installations in the Wapsipinicon and Cedar Rivers in Iowa (Odgaard and Wang, 1990), concrete vanes were used. In this case, the form was studied to equip them with a rounded front edge that was able to minimize the damage caused by the impact of logs, ice, or whatever else might be transported by the flow. Moreover, these vanes were twisted from the base to the top. In other words, they exhibited varying angles of attack at different water levels, with higher values of the angle for lower levels.

In considering the abovementioned issues, the shape of the vanes strongly influences their degree of efficiency. For example, a thin vane type is very efficient, especially if equipped with camber or twist. However, on one hand, these geometric characteristics produce advantages in terms of their performance; on the other hand, they can create considerable problems when it comes to constructing them. The use of a sheet pile vane could reduce installation costs significantly. In fact, a metal sheet pile has a sufficient amount of stiffness to allow relatively easy insertion into the ground. Moreover, their scalability enables large structures without undue problems of transport.

This study proposes an experimental investigation that will evaluate the use of sheet-piling vanes

instead of thin plane vanes. Experimental tests were carried out in a straight laboratory channel where the effects of the device on river bed morphology were compared with a thin plane vane type that had the same size and angle of attack. Firstly, the linear theory proposed by Odgaard and Spoljaric (1986) which furnishes the simplest interpretation of the effect of the structure on the bottom of a straight channel is mentioned. The most recent theory developed by Odgaard and Wang (1991) and Wang and Odgaard (1993) is able to take into account the interaction between vanes in an array, but, compared to the first model, is much more complex and less suitable for a first rough design of these structures (van Zwol, 2004). A parametric investigation is then presented considering different angles of attack to the incoming flow and different ratios between the height of the water above the structure and the water level in the channel. The results for both the sheet-piling vane and thin plane vane are shown and compared to each other and with linear theory results. The efficiency of the device is also evaluated according to the amount of the diverted sediment and the local scour. Some concluding remarks are provided with the aim of supporting the design and arrangement of these structures in riverbeds.

## 2 Straight channel theory

The most significant feature of the flow field, when a 2D boundary layer developing over a flat surface encounters a protrusion, is the appearance of three complex vortical systems: the horseshoe vortex, the wake vortex, and the tip vortex. The first one is generated by an adverse pressure gradient upstream of the obstacle and is characterized by a horizontal axis and two counter-rotating legs that wrap the toe of the obstacle. The wake vortices, characterized by vertical axes, are due to a boundary layer separation on the obstacle surface. Finally, the tip vortex, typical of submerged obstacles, is generated by pressure gradients between different sides of the protrusion as a consequence of 3D lift generation.

In particular, a submerged vane induces both crosswise velocity components in the flow downstream and crosswise bed shear stresses in the bottom as a consequence of the helical motion associated with the tip vortex. Accordingly, the river bed

topography is modified. The crosswise velocity components associated with this vortex are related to bed shear stresses, which produce changes in bed topography (Wang and Odgaard, 1993). Particularly, the river bed aggrades on one side of the channel cross-section and deepens in the other.

Following Odgaard and Spoljaric (1986), without a lateral pressure gradient and by neglecting the effect of fluid viscosity, the streamwise variation of the induced transverse velocity  $v$  can be obtained using the  $y$ -component of the momentum equation, where  $x$ ,  $y$ , and  $z$  indicate the streamwise, transverse, and vertical directions, and  $u$ ,  $v$ , and  $w$  the corresponding velocity components, respectively:

$$u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} + w \frac{\partial v}{\partial z} = \frac{\partial}{\partial z} \left( \varepsilon \frac{\partial v}{\partial z} \right). \quad (1)$$

A parabolic profile for the eddy viscosity  $\varepsilon$  and a linear profile for the induced transverse velocity  $v$  are adopted, that is

$$v = 2v_s(z/d - 1/2), \quad \varepsilon = Ku^*z(1 - z/d), \quad (2)$$

where  $d$  is the depth of the flow,  $v_s$  is the transverse velocity component at the water surface,  $u^*$  is the shear velocity, and  $K$  is von Karman's constant. Other analytical expressions have been considered but the solution is not influenced much by the shape of the  $v$  and  $\varepsilon$  profiles (Odgaard and Spoljaric, 1986).

Moreover, to account for the helical motion induced by the vane, they proposed the following equation for  $v_s$  along the  $y$  direction

$$v_s = v_{sc} \cos(\pi y/d), \quad -d/2 < y < d/2, \quad (3)$$

where  $v_{sc}$  is the value of  $v_s$  at the channel-centre line ( $y=0$ ).

Then, at the water surface  $z=h$  and the centre line  $y=0$ :

$$V_{sc} = \exp \left( - \frac{2K}{1/K + \sqrt{8/f}} X \right), \quad (4)$$

where  $X=x/d_0$ ,  $d_0$  is the average flow depth,  $V_{sc}=v_{sc}/v_{so}$ ,  $v_{so}=v_s$  at  $(x, y)=(0, 0)$ , and  $f$  is the Darcy-

Weisbach friction factor.

The induced transverse velocity component  $v$  gives rise to a transverse bed-shear stress, which generates a new crosswise bed profile described by

$$\frac{z}{d_0} = - \frac{av_{sc}}{\pi} \sin \left( \pi \frac{y}{d_0} \right), \quad (5)$$

in which

$$a = (3\beta/2)(\sqrt{\theta/k}) / \sqrt{gD(\rho_s - \rho)/\rho}, \quad (6)$$

where  $\beta$  is the ratio of projected surface area to volume for a sediment particle divided by that for a sphere of the same volume ( $\beta \approx 1.27$  for ordinary river sand),  $\theta$  is Shields' parameter,  $D$  is the particle diameter,  $\rho_s$  is the density of sediment,  $\rho$  is the density of water,  $k \approx 1$  is the ratio of a critical near bed velocity to the critical shear velocity (Odgaard and Spoljaric, 1986). Other analytical theories have been developed by Odgaard and Wang (1991) validating the effects of vanes in sediment management.

### 3 Experimental

In this study, laboratory tests were carried out to evaluate the effectiveness of submerged vanes, comparing sheet-piling vanes against thin ones in controlling the sediment redistribution of the channel bed. Different experimental configurations were tested for the simple geometry of the thin plane vane and the more complex geometry of the 603 K vane. In particular, Fig. 1 shows the scaled geometry of the sheet-piled vane.

Tests were focused on finding a possible loss in efficiency of the sheet-piling vane due to the non-hydrodynamic shape of this structure, which could cause a large flow separation at the leading edge. The evaluation of the efficiency was also based on comparing changes in the bed morphology. The experimental tests were repeated for different values of the angles of attack and of the submergence parameter. The submergence parameter is defined as the ratio between the height  $T$  of the water above the structure and the water level  $d_0$ .



**Fig. 1** One experimental configuration of the sheet-piling vane Larssen 603 K

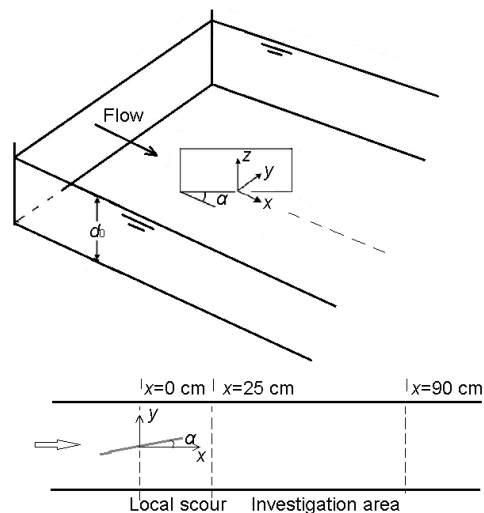
A 12 m long and 0.40 m wide channel was used for all the experimental tests. The flow rate was set to  $Q=0.022 \text{ m}^3/\text{s}$  and the flow depth to  $d_0=0.15 \text{ m}$ . Therefore, the mean velocity was  $U=0.36 \text{ m/s}$ . The quartz sand used for the experiments had a density  $\rho_s=2650 \text{ kg/m}^3$  and was fairly uniform in size with a diameter  $D_{90}=0.5 \text{ mm}$ . The conditions of incipient motion for the riverbed sand occurred for the mean velocity:  $U=0.28 \text{ m/s}$ . The use of previous values of velocity, water level, and flow rate was dictated by a need to have an appreciable mobility of sand along the bottom.

A continuous recirculation of sand was guaranteed to have a constant solid flow rate. The submerged vane was installed 6 m downstream of the channel inflow in the middle of the flume. The origin of the reference system is positioned at the centre of the vane and on the undisturbed bottom of the channel (Fig. 2).

Four different shapes have been tested for describing the effects on the riverbed morphology:

- an aluminium sheet plane thin vane with a length of 17 cm and a height of 5 cm ( $T/d_0=0.7$ );
- an aluminium sheet plane thin vane with a length of 25 cm and a height of 7.5 cm ( $T/d_0=0.5$ );
- an aluminium sheet-piling vane reproducing a steel sheet-piling Larssen 603 K (scale 1:20) with a length of 17 cm and a height  $H=5 \text{ cm}$  ( $T/d_0=0.7$ );
- an aluminium sheet-piling vane reproducing

a steel sheet-piling Larssen 603 K (scale 1:20) with a length of 25 cm and a height  $H=7.5 \text{ cm}$  ( $T/d_0=0.5$ ).



**Fig. 2** Reference system and measurements area

The dimensions of the tested devices were determined by taking into account the results from Odgaard and Wang (1991) and in an effort to limit the boundary effects of the laboratory channel. All the vanes that were analysed had a thickness of  $s=0.5 \text{ cm}$  and a surface roughness of  $e=0.05 \text{ mm}$ . Two different angles of attack,  $\alpha$ , were tested for each of the shapes:  $\alpha=10^\circ$  and  $\alpha=20^\circ$ . The level of the water surface and the bottom of the riverbed were measured to the nearest 0.1 mm with a point-gage. In particular, the measurements of the bed bottom were carried out in the cross-section at  $x=0$  to evaluate the local scour and at regular intervals of  $\Delta x=5 \text{ cm}$  downstream of the vane, beginning at station  $x=25 \text{ cm}$  and ending at station  $x=90 \text{ cm}$ . The crosswise intervals were also set to  $\Delta y=5 \text{ cm}$ . The chosen measurement area downstream of the vane is the one that best describes, according to the laboratory tests, the phenomena of the redistribution, and remodelling of the channel bed.

## 4 Results and discussion

### 4.1 Bed morphology measurements

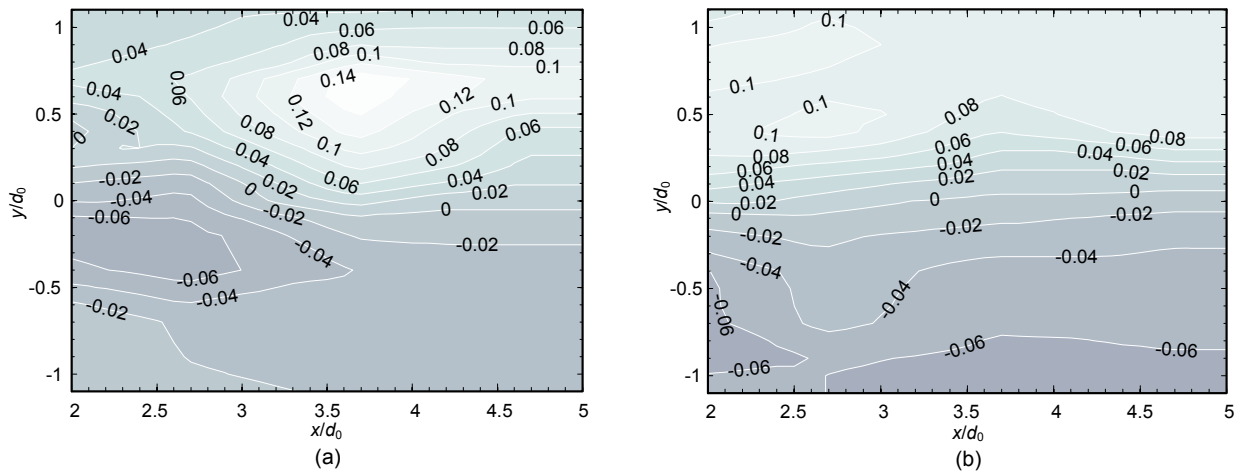
Experimental tests were carried out to analyse the influence of the structure on the morphology of the riverbed for each of the four vane shapes. The

duration of the experiments was set to 4 h until a quasi-steady condition was reached, that is the condition in which the morphology of the live river bed fluctuates around an equilibrium state in response to the passage of bed forms. During these tests, it was observed that a dune grew longitudinally along the left side of the vane and moved slowly downstream for the entire duration of the experiments, modifying the river bed profile as far as  $x/d_0=6.00$ . At the conclusion of the experiments, a sand ridge just downstream of the vane was observed. The channel bed was then divided in a sedimentation area and an erosion area.

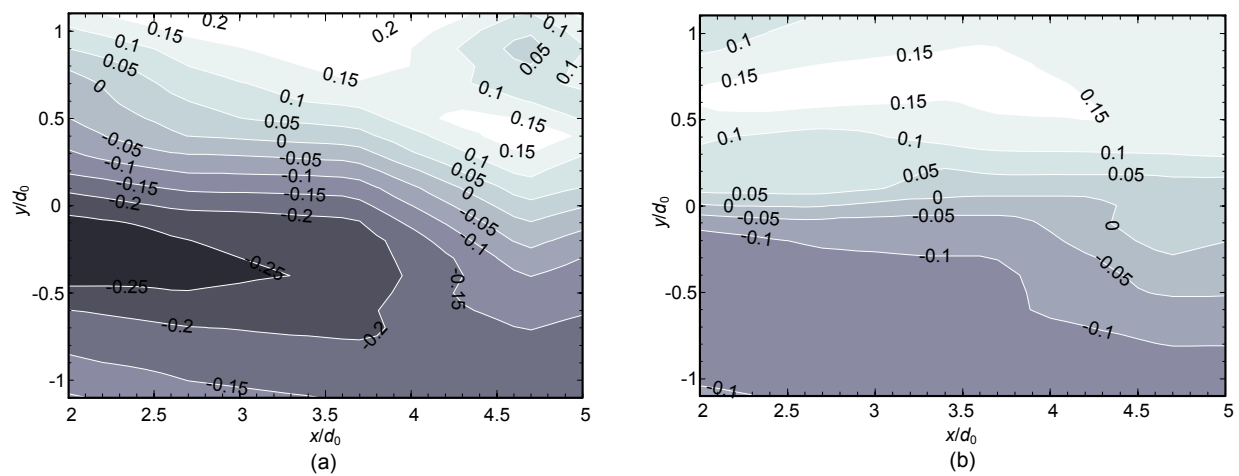
The morphology of the channel bed was investigated both close to the obstacle and in the area

downstream which is not affected by local scour phenomena. Excluding the crosswise sections around the obstacle where the local scour occurs, the more relevant changes in the bed morphology were localized between 30 cm ( $x/d_0=2$ ) and 75 cm ( $x/d_0=5$ ) downstream of the vane. The morphology of the channel in this area is represented by the bottom contour lines (Figs. 3–6).

In particular, for a submergence parameter equal to 0.7, the conformation of the bottom, both for the thin vane and the 603 K vane is shown in Figs. 3a and 3b with an angle of attack of  $10^\circ$  and in Figs. 4a and 4b with an angle of attack of  $20^\circ$ . A similar behaviour can be observed for both shapes, despite the fact that the thin vane shows a more



**Fig. 3** Bed morphology contour map of  $z/d_0$  values downstream of the vane for  $T/d_0=0.7$ ,  $\alpha=10^\circ$   
 (a) Plane vane; (b) 603 K vane. Lighter shades indicate deposition, and darker shades excavation



**Fig. 4** Bed morphology contour map of  $z/d_0$  values downstream of the vane for  $T/d_0=0.7$ ,  $\alpha=20^\circ$   
 (a) Plane vane; (b) 603 K vane. Lighter shades indicate deposition, and darker shades excavation

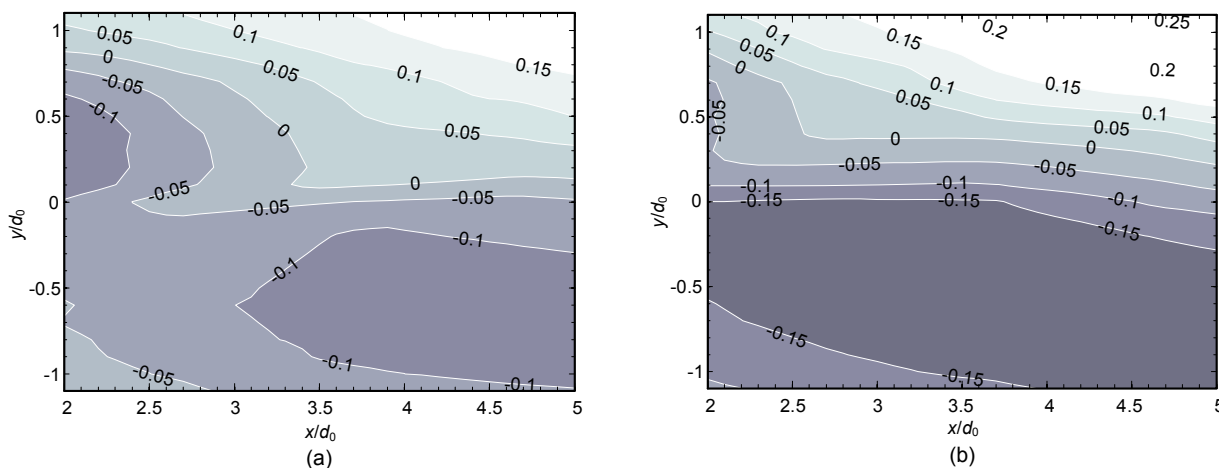
extended excavation area in a crosswise direction with higher depths of scour. Moreover, the thin vane produces more excavation in the area immediately downstream of the obstacle, especially for the angle of attack  $\alpha=20^\circ$ , as a consequence of local scour phenomena.

A similar representation of the bottom is shown in Figs. 5 and 6 for a submergence parameter value of 0.5. Also, in this case, for the two vane shapes, a similar morphology of the bottom was obtained. In this situation, the excavation zone extends more in a crosswise direction close to the obstacle. This is attributable to the greater length of the devices and then to a greater connection between the investigated area and the erosion area located next to the obstacle.

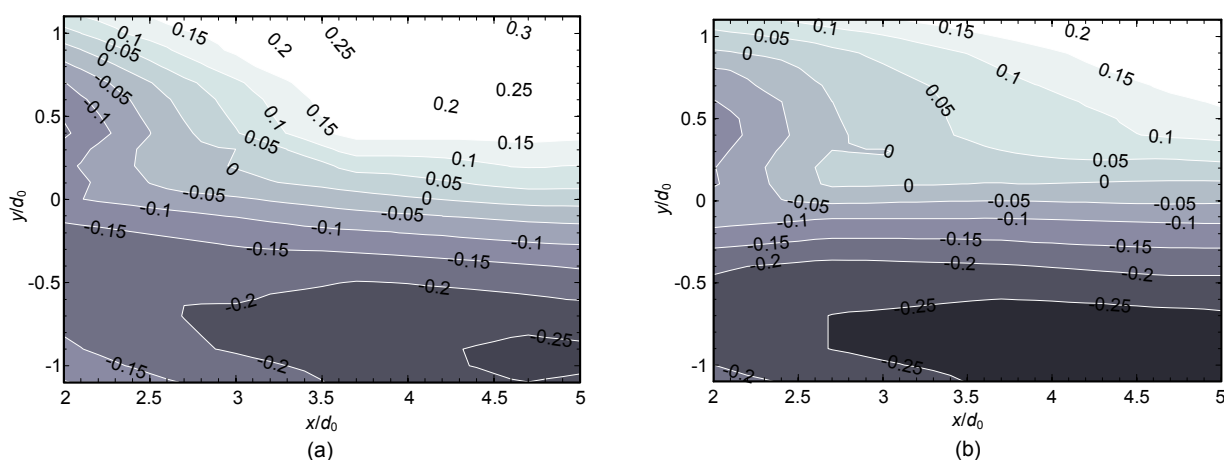
With this submergence, higher values for the depth of the excavation can be observed far away from the vane for all the shapes, and especially, for the  $20^\circ$  angle. Overall, it can be said that the sheet-piling vane produces an effect globally comparable with the thin vane except that a little more excavation at  $20^\circ$  is produced by the sheet-piling vane.

### 4.2 Bed profile

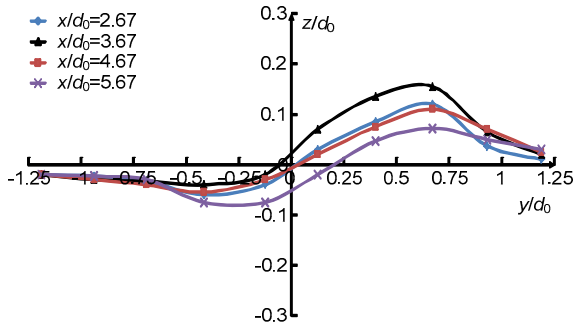
In Figs. 7 and 8, experimental measurements of the bed crosswise sections for  $\alpha=10^\circ$  and  $\alpha=20^\circ$  and  $T/d_0=0.7$  are described for the thin vane at different downstream distances of  $x/d_0$ . In particular, Fig. 7 shows the bed profiles at  $x/d_0=2.67, 3.67, 4.67,$  and  $5.67$  obtained with an angle of attack  $\alpha=10^\circ$ . Similar



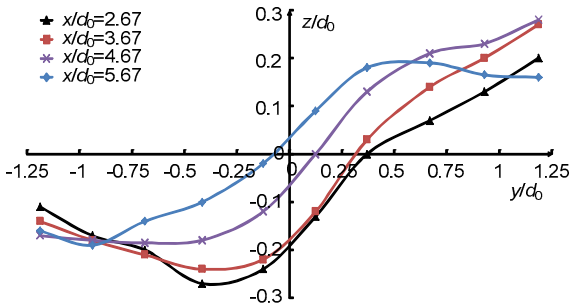
**Fig. 5** Bed morphology contour map of  $z/d_0$  values downstream of the vane for  $T/d_0=0.5, \alpha=10^\circ$   
 (a) Plane vane; (b) 603 K vane. Lighter shades indicate deposition, and darker shades excavation



**Fig. 6** Bed morphology contour map of  $z/d_0$  values downstream of the vane for  $T/d_0=0.5, \alpha=20^\circ$   
 (a) Plane vane; (b) 603 K vane. Lighter shades indicate deposition, and darker shades excavation



**Fig. 7** Bed crosswise morphology for plane thin vane at different  $x/d_0$  values for  $T/d_0=0.7$ ,  $\alpha=10^\circ$



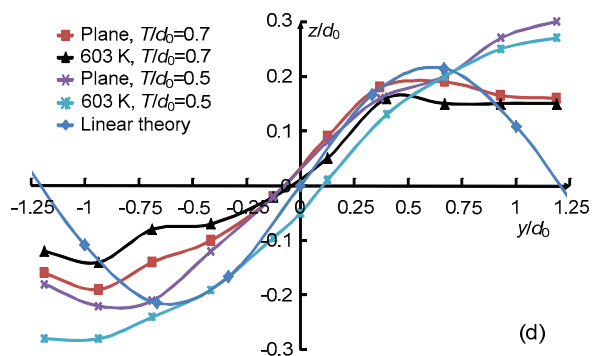
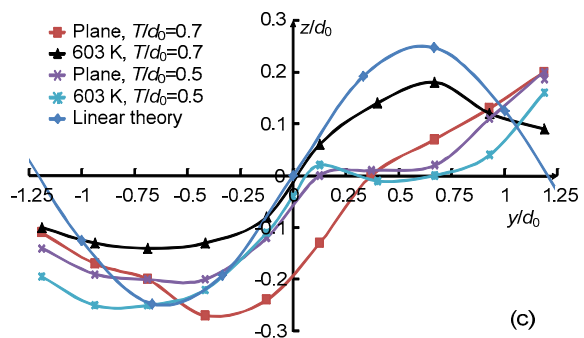
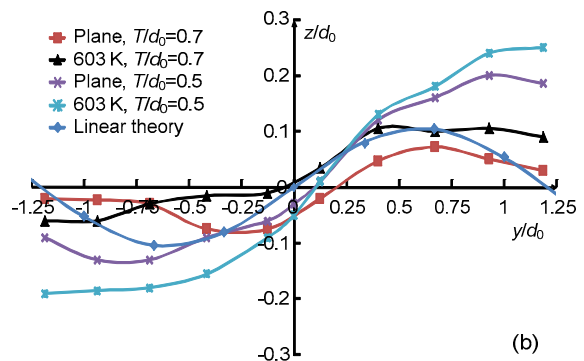
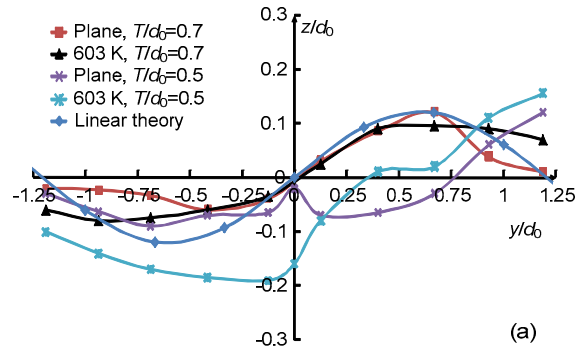
**Fig. 8** Bed crosswise morphology for a plane thin vane at different  $x/d_0$  values for  $T/d_0=0.7$ ,  $\alpha=20^\circ$

behaviour is shown at different positions. The maximum value of the deposition is located between  $y/d_0=0.6$  and  $y/d_0=0.7$ .

As the angle of inclination of the vane increases to  $\alpha=20^\circ$ , the profiles differentiate themselves more (Fig. 8). In particular, at the positions closest to the obstacle ( $x/d_0=2.67$  and  $x/d_0=3.67$ ) they seem to be affected by localized phenomena. As the distance increases ( $x/d_0=4.67$ ,  $5.67$ ), the crosswise sections highlight a line of separation between the zone of deposition and a scour close to the middle of the channel, showing a behaviour similar to that when  $\alpha=10^\circ$ .

The Odgaard linear theory, which does not take into account localized phenomena, better approximates the bed profile for an angle of  $\alpha=10^\circ$  (Figs. 9a and 9b).

This theory may only be used at greater distances from the obstacle in the case of an attack angle of a submerged vane that is equal to  $20^\circ$  (Figs. 9c and 9d). In both cases, the linear theory may represent the bed profile only in the middle of crosswise



**Fig. 9** Bed crosswise morphology, experimental, and theoretical results

(a)  $\alpha=10^\circ$ ,  $x/d_0=2.67$ ; (b)  $\alpha=10^\circ$ ,  $x/d_0=5.67$ ; (c)  $\alpha=20^\circ$ ,  $x/d_0=2.67$ ; (d)  $\alpha=20^\circ$ ,  $x/d_0=5.67$



sections. It was also observed that the maximum slope of the crosswise profile is almost constant for each angle  $\alpha$  of the vane that is tested. In particular, for an angle  $\alpha=10^\circ$ , the value of this slope is approximately equal to  $20^\circ$ , while for  $\alpha=20^\circ$  the maximum slope is approximately  $26^\circ$ . The result in both cases is that this is smaller than the angle of repose of the dry material, which is equal to  $31^\circ$ .

In Fig. 10 a bed crosswise morphology for a 603 K vane at different  $x/d_0$  values for  $T/d_0=0.7$  and  $\alpha=10^\circ$  is shown. The effects of the device on the bottom are comparable to those of the plane vane, but with some other differences. Firstly, we can notice a deeper scour hole in the sections closer to the device due to the influence of a local kinematic field. Moreover, a lower efficiency of this shape of vane is also highlighted as one moves away from the obstacle. In fact, the erosion and the deposition depths tend to diminish and be redistributed all over the cross-section.

For an attack angle equal to  $20^\circ$ , we notice that the sheet-piling vane gives a smaller difference

among the profiles in the downstream crosswise sections (Fig. 11). In this case too, the depth of the eroded area is lower than that for the thin plane vane and the profiles are more symmetric with respect to the channel axis.

For the lower value of the submergence parameter  $T/d_0=0.5$ , only the results for  $\alpha=20^\circ$  are shown, which are the most interesting in describing the influence of this parameter. We can observe that in this case, the profiles for the thin plane and sheet-piling vanes are very similar, both in their shape and values. Obviously, with this submergence, higher values of deposition and erosion rates all over the crosswise section are produced. Moreover, we can also notice a similar behaviour of the erosion profiles for the plane vane and the sheet-piling vane at different downstream sections (Figs. 12 and 13).

For this value of the submergence, if the crosswise bottom profile is schematized as a sine wave, an increasing of the amplitude and period of the wave, both for the thin vane and the sheet-piling vane, is observed.

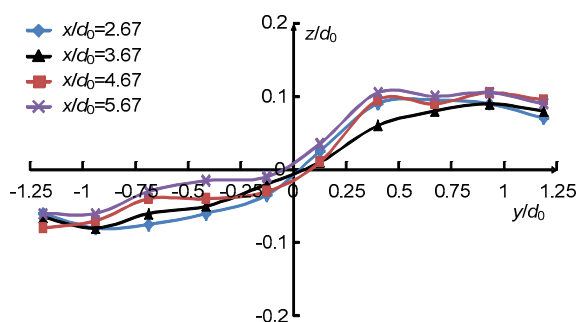


Fig. 10 Bed crosswise morphology for 603 K vane at different  $x/d_0$  values for  $T/d_0=0.7$ ,  $\alpha=10^\circ$

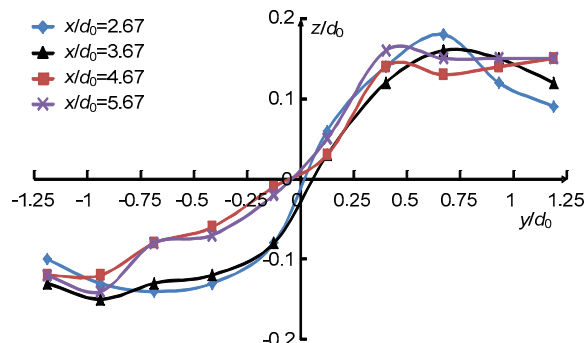


Fig. 11 Bed crosswise morphology for 603 K vane at different  $x/d_0$  values for  $T/d_0=0.7$ ,  $\alpha=20^\circ$

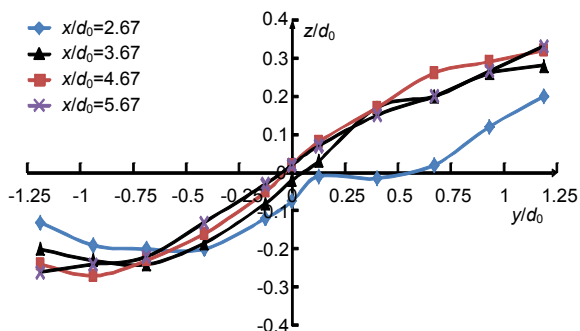


Fig. 12 Bed crosswise morphology for plane vane at different  $x/d_0$  values for  $T/d_0=0.5$ ,  $\alpha=20^\circ$

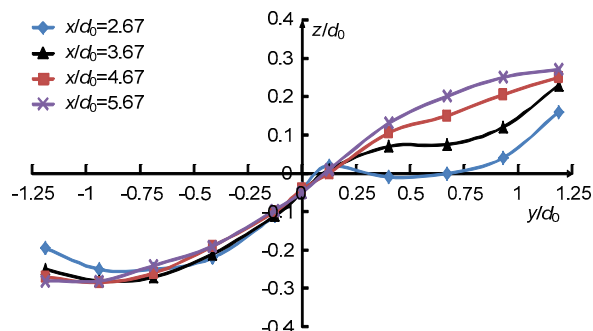


Fig. 13 Bed crosswise morphology for plane and 603 K vane for  $T/d_0=0.5$ ,  $\alpha=20^\circ$

### 4.3 Local scour

One of the main problems associated with the use of submerged vanes is the local scour phenomena close to the obstacle. The excavation at the foot of the vane is due to the action of different vorticity systems acting around the obstacle: the horseshoe vortex, the wake vortex, and the tip vortex. The local scour phenomena influence the structural stability of the vane. In fact, if the depth of the foundations is not adequate, the device can be removed by the incident flow. Sinha and Marelius (1997) showed that erosion at the foot of the vane increases when the angle  $\alpha$  increases.

To quantify the magnitude of such an excavation, and especially to compare the behaviour of the sheet-piling vane with respect to the thin plane one, the bed profile for both the obstacles was detected in the crosswise section at  $x/d_0=0$ , for different experimental configurations. In this section the local scour depth generally reaches its maximum value. In particular, the results for  $\alpha=10^\circ$  and  $\alpha=20^\circ$  and  $T/d_0=0.7$  are shown in Figs. 14 and 15. It is clearly noticeable that the excavation is always much more accentuated on the side of the vane directly impacted by the current (as seen on the right side of the section). On the exposed side of the vane, for the lower  $\alpha$  angular value, the plane vane produces localized effects smaller than the sheet-piling vane, with maximum depths that differ by 10%. When the angle of attack increases, both of the devices highlight

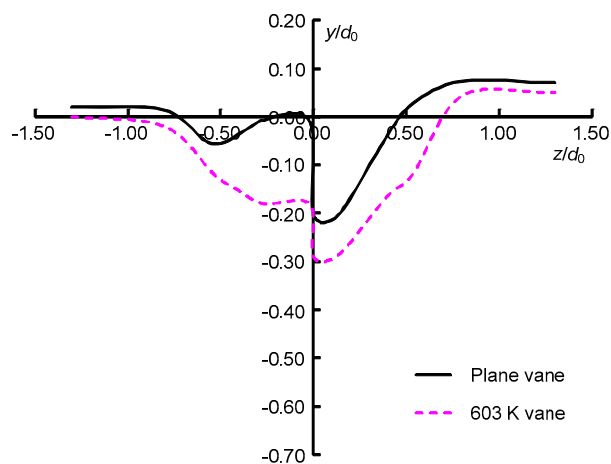


Fig. 14 Bed crosswise profile for plane and sheet-piling vane at  $x/d_0=0$ , for  $T/d_0=0.7$ ,  $\alpha=10^\circ$

significantly higher excavations, but the results for  $\alpha=20^\circ$  show that the thin plane vane produces deeper scour holes, approximately 30% more (Fig. 15). This result may be due to the more complex geometry of the sheet-piling vane which is able to pull in the sand locally eroded.

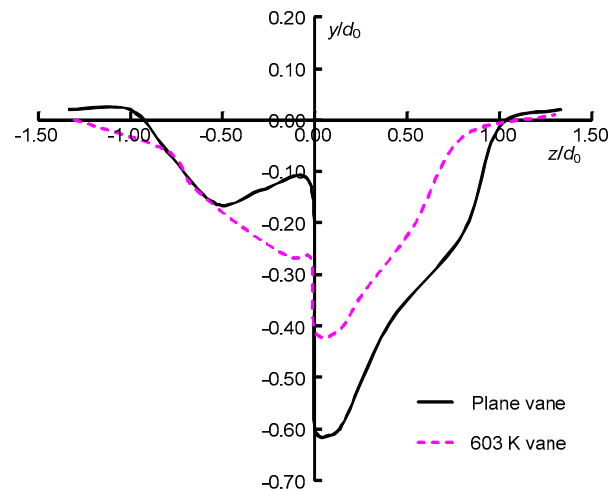


Fig. 15 Bed crosswise profile for plane and sheet-piling vane at  $x/d_0=0$ , for  $T/d_0=0.7$ ,  $\alpha=20^\circ$

## 5 Conclusions

In this study, experimental tests were carried out to compare sheet plane thin vanes and sheet-piling vanes reproducing steel sheet-piling Larssen 603 K (scale 1:20) within a straight water channel. In fact, while there are many studies on the use of thin plate vanes, there are no literature data on the effects of sheet-piling vanes. The experiments were focused on finding a possible loss in efficiency of sheet-piling vanes due to their non-hydrodynamic shape considering two different angles of attack with the incoming flow and four different shapes, which are plane vanes and sheet-piling vanes with two different values of the submergence parameter. All experiments were realized in conditions of incipient motion of the bed material.

The morphology of the river bed was investigated both close to the obstacle and in the area downstream which is not affected by local scour phenomena. The results showed that the effect of the submerged vanes on the morphology of the channel

bottom was significant only for short distances. Specifically, the area influenced by the action of these submerged structures does not extend to more than six times the water level. In particular, excluding the crosswise sections around the obstacle, where the local scouring effect due to the horseshoe vortex occurs, the maximum changes in bed morphology were localized between  $x/d_0=2$  and  $x/d_0=5$  downstream of the vane.

For the lower value of the submergence parameter  $T/d_0=0.5$  we observed that the bed morphology for the thin plane and sheet-piling vanes is very similar. Moreover, we can also notice a similar behaviour of the erosion profiles for the sheet-piling vane at different downstream sections.

For the submergence parameter of 0.7, the thin vane produces a more extended excavation area in the crosswise direction with higher depths of scour. Also, it produces more excavation in the area closest to the obstacle, especially with the angle of attack  $\alpha=20^\circ$ , as though the effect in the far field has a connection with the local scour hole. Obviously, with this submergence parameter, lower values of deposition and erosion rates are produced all over the crosswise section.

On the exposed side of the vane, for the lower angular values, the thin plane vane produces an excavation depth smaller by about 10% with respect to that formed by the sheet pile. When the angle increases, both devices change the channel bottom for a greater extension in the downstream direction. In particular the results for  $\alpha=20^\circ$  show that the thin plane vane produces deeper scour holes, approximately 30% more. This fact may be due to the more complex geometry of the sheet-piling vane which is able to pull in the sand locally eroded. The different behavior of the local scour with the increase of angle of attack for the two types of vane (thin plane and sheet-piling vane) can be justified by the interaction of the vortical structure with a horizontal axis (horseshoe vortex) with the surface of the obstacle. For small angles this vortex is very weak and the deeper erosion for the sheet-piling vane is probably due to the uneven surface of the structure. With the growth of the angle of attack the horseshoe vortex becomes stronger increasing its erosive capacity. By contrast, in this case the uneven surface of the sheet-piling vane mitigates the erosive strength of the vortex.

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## 中文概要

**题目:** 水下板桩叶片对移动河床的影响研究

**目的:** 比较板桩叶片和简单的平板叶片在控制河床沉积物再分配时的效率。

**方法:** 1. 在不受当地侵蚀现象影响的接近障碍物和下游区域的直线水道中研究河床的形态; 2. 使用不同的实验装置测试简单几何形状的平板叶片和复杂形状的 603 K 叶片的性能; 3. 在不同的叶片迎角和浸没参数下, 测试与其面积接近的结构和在远场中的河床形态。

**结论:** 1. 叶片的形状和迎角影响其对河床形态所产生的作用, 尤其是对于较大的淹没参数而言; 2. 平板叶片和板桩叶片对下游河床的重塑作用相似; 3. 随着迎角的增加, 平板叶片将造成更深的冲刷孔。这可能归因于与平板叶片相关的马蹄形涡流增加的侵蚀能力, 而板桩叶片的不均匀表面可减轻该涡旋的侵蚀强度。

**关键词:** 叶片; 沉积物; 冲刷; 河流水力学; 实验水力学