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PREVENTION OF LOCAL SCOURING AT RIVER-BEND BY IOWA VANES

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SYNOPSIS

At a river-bend, the centrifugal force develops secondary flows, which cause local scouring along the outer bank. Iowa Vanes have been recently developed as a method to reduce secondary flows. The vanes are set at a river-bend for the purpose to cause a lift force which generates a torque to offset secondary flows.

In the present study, further investigations are done on Iowa Vanes and their effectiveness is attested. The applicability to real rivers is also discussed.

INTRODUCTION

Strong secondary flows at a river-bend cause local scouring along the outer bank. Bank protection and spurdikes have been used so far to prevent these phenomena. However, it can be said that they are rather passive methods because they aim only to weaken the influence of secondary flows.

Meanwhile a research is undertaken on a new and inexpensive method to reduce directly secondary flows themselves which are the cause of local scouring. Experimental and qualitative investigations are being carried out at the Public Works Research Institute in Japan as well as at the Moscow Institute of Hydromelioration in Soviet Union. Photo.1 is an example from Moscow and its characteristics lie in the fact that the top of the vanes is above water level. Abe and Suzuki (1) of the Public Works Research Institute are doing research on vanes in super critical flows and propose shorter vanes (which resemble blocs). The top part of their vanes is also above water level.

Recently Odgaard and Kennedy (3)(4) of the Institute of Hydraulic Research, The University of Iowa, advance an original research on vanes and prove their effectiveness theoretically. One of the characteristics of the Iowa Vanes is that they are submerged in case of the expected discharge.

Photo. 1 Experiment of vanes in Moscow

THEORY OF ODGAARD-KENNEDY

Odgaard and Kennedy (3)(4) explained theoretically the effects of vanes in the following manner.

Flows at a river-bend can be considered as a part of rotary movement. When a unit volume of density ρ rotates at velocity V and at radius of curvature r, the centrifugal force F is

$$F = \rho\frac{V^2}{r} \tag{1}$$

Fig.1 is a sketch of a bend flow and it indicates that the velocity distribution is not uniform. The centrifugal force expressed by Eq.1 shows a distribution profile as presented in Fig.2. As a result, the torque shown in the figure occurs inside the flow. When the radius of curvature is r and the water depth is h, the torque ΔT_f in bend flow of the angle ϕ (the length of the bend is expressed as $r\phi$) is expressed as follows,

$$\Delta T_f = r\phi\int_0^h \rho\frac{V^2}{r}(z-\frac{h}{2})dz = \rho\phi\int_0^h V^2(z-\frac{h}{2})dz \tag{2}$$

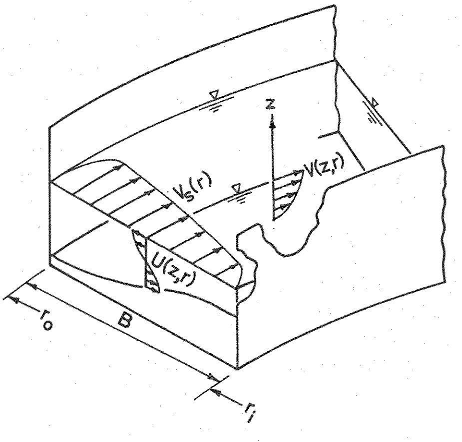

Fig. 1 Schematic illustration of a bend flow

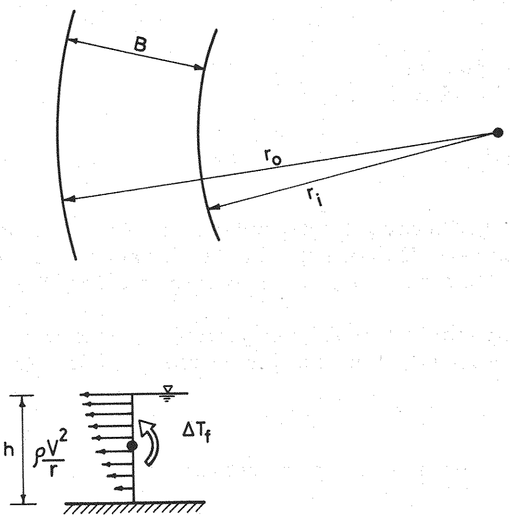

Fig. 2 Definition sketch for the calculation of the torque produced by a bend flow

where z = height from the bed.

The vertical distribution profile of the longitudinal velocity V expressed in Eq.2 is shown in Fig.1. Strictly speaking, it is different from that in case of a straight flow. But the difference between the velocity distribution in a bend flow and that in a straight flow is supposed to be so small that the velocity V can be represented in the following form

$$V = \frac{n+1}{n}\left(\frac{z}{h}\right)^{1/n}\overline{V} \tag{3}$$

where n = velocity-profile exponent; and $\overline{V}$ = depth-averaged flow velocity.

By substituting Eq.3 into Eq.2,

$$\Delta T_f = \frac{1}{2n}\frac{n+1}{(n+2)}\rho\phi\overline{V}^2 h^2 \tag{4}$$

Therefore, when the inner and outer radiuses of the curvature of the bend are r_i and r_o, respectively, the torque T_f is,

$$T_f = \int_{r_i}^{r_o} \Delta T_f dr$$

$$= \frac{1}{2n}\frac{n+1}{(n+2)}\rho\phi\int_{r_i}^{r_o}\overline{V}^2 h^2 dr \tag{5}$$

For the integration of Eq.5, it is necessary to know the lateral distribution profiles of the water depth h and the mean velocity $\overline{V}$ which are functions of the radius of the curvature r. However, according to Zimmermann-Kennedy (6), the influence of the distribution profile of $\overline{V}$ on Eq.5 is so small that it can be neglected, thus the following approximation is made possible under the assumption that the lateral bed slope I_ℓ is small,

$$\int_{r_i}^{r_o} \overline{V}^2 h^2 dr = (r_o - r_i)\overline{V}^2 h^2 = B\overline{V}^2 h^2 \qquad (6)$$

where B = width of the channel.

Using Eq.6, Eq.5 is simplified,

$$T_f = \frac{1}{2n}\frac{n+1}{(n+2)}\rho\phi B\overline{V}^2 h^2 \qquad (7)$$

At a river-bend the torque T_f expressed by Eq.7 causes secondary flows and thus causes local scouring. Therefore, if the torque can be offset by any means, local scouring will be prevented. Vanes shown in Fig.3 were developed for this purpose.

According to the Kutta-Joukowski theorem (2), when a vane of a length L and a height H is set in an uniform flow, it generates a lift force F_ℓ,

$$F_\ell = \frac{1}{2}C_L \rho v^2 HL \qquad (8)$$

where C_L = lift force coefficient; v = uniform velocity; and C_L for an angle of incidence α is theoretically given by,

$$C_L = 2\pi \sin\alpha \qquad (9)$$

If the uniform flow velocity v is assumed to be approximated by the mean velocity $\tilde{V}$ averaged over the height of the vane, the lift force F_ℓ is expressed as follows,

$$F_\ell = \frac{1}{2}\beta C_L \rho \tilde{V}^2 HL = \pi\beta\rho \sin\alpha \tilde{V}^2 HL \qquad (10)$$

where β = ratio of actual to theoretical value of C_L; and the mean velocity $\tilde{V}$ is given as follows by means of Eq.3,

$$\tilde{V} = \frac{1}{H}\int_0^H \frac{n+1}{n}\left(\frac{z}{h}\right)^{1/n}\overline{V}dz = \overline{V}\left(\frac{H}{h}\right)^{1/n} \qquad (11)$$

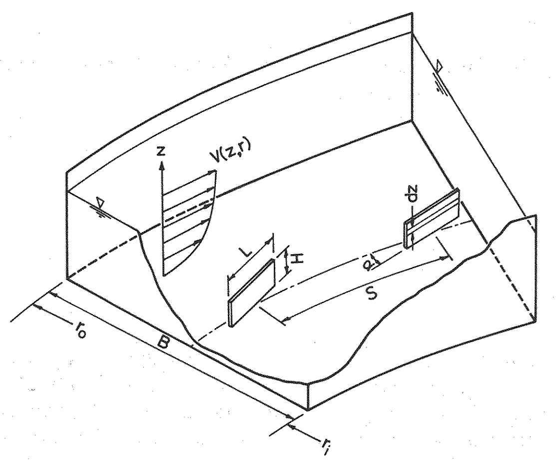

Fig. 3 Schematic illustration of Iowa Vanes

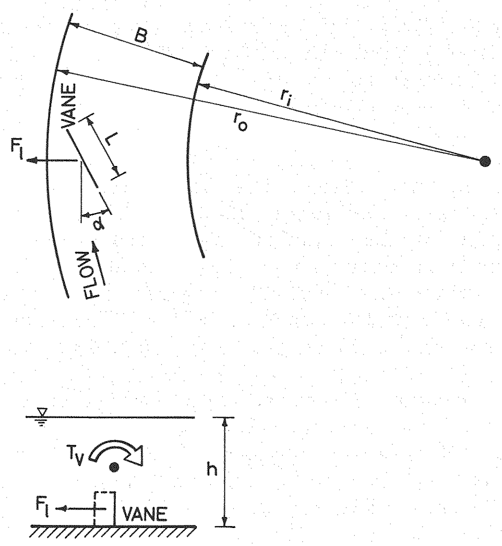

Fig. 4 Definition sketch for the calculation of the torque produced by Iowa Vanes

Therefore, as shown in Fig.4, the torque T_v produced by N_v identical submerged vanes around the center line is,

$$T_v = F_\ell \left(\frac{h}{2}-\frac{H}{2}\right) N_v$$

$$= \pi\beta\rho \sin\alpha \tilde{V}^2 HL \left(\frac{h}{2}-\frac{H}{2}\right) N_v$$

$$= \frac{1}{2}\pi\beta\rho \sin\alpha HLN_v \bar{V}^2 \left(\frac{H}{h}\right)^{2/n} (h-H) \qquad (12)$$

The ratio of Eq.7 to Eq.12 leads,

$$\frac{T_v}{T_f} = Cf\left(\frac{H}{h}\right) \qquad (13)$$

where

$$C = \frac{n(n+2)}{n+1} \frac{\pi\beta \sin\alpha LN_v}{B\phi} \qquad (14)$$

$$f\left(\frac{H}{h}\right) = \left(\frac{H}{h}\right)^{(n+2)/n} \left(1-\frac{H}{h}\right) \qquad (15)$$

Therefore, if the right member of Eq.13 becomes equal to 1, the torque at a river-bend is expected to be offset and thus secondary flows are reduced, and finally local scouring will be prevented. So the discussion should be directed to the adequate height H, length L, angle of incidence α and number of vanes N_v.

EXPERIMENT

Fig.5 is a brief description of equipments used in this investigation. The flume is 2.4 m wide and has a bend the radius of which is 12.9 m at the channel center line, and straight flumes which are 19.5 m long both in the upper and the lower streams. Uniform sands are used as bed materials and their mean diameter is 0.3 mm.

The lateral bed slope at the section 80 is shown in Fig.6 as an example. In this case, the discharge is 150 ℓ/sec. The bed near the outer bank is dug out while sands are piled up near the inner bank as time passes. Fig.7 shows the longitudinal characteristics of the lateral bed slope which are obtained by means of the least square method. A remarkable local scouring is recorded around the section 80 (at the point about 45° from the beginning of the bend) and the lower stream maintains about a half of the maximum slope. The unusual slope around the section 150 is due to a column of 20 cm in diameter which stands inside the flume near the right bank.

After the bed profile reaches a steady state, 42 vanes are set at the bend of the flume as shown in Fig.5 and Photo.2. Each vane is 35 cm long and set at an angle of incidence $\alpha = 15°$. The height of vanes H is determined to be one third of the mean water depth h, that is, $H/h = 1/3$, in which H and h are given on the basis of the expected river bed height (horizontal river bed).

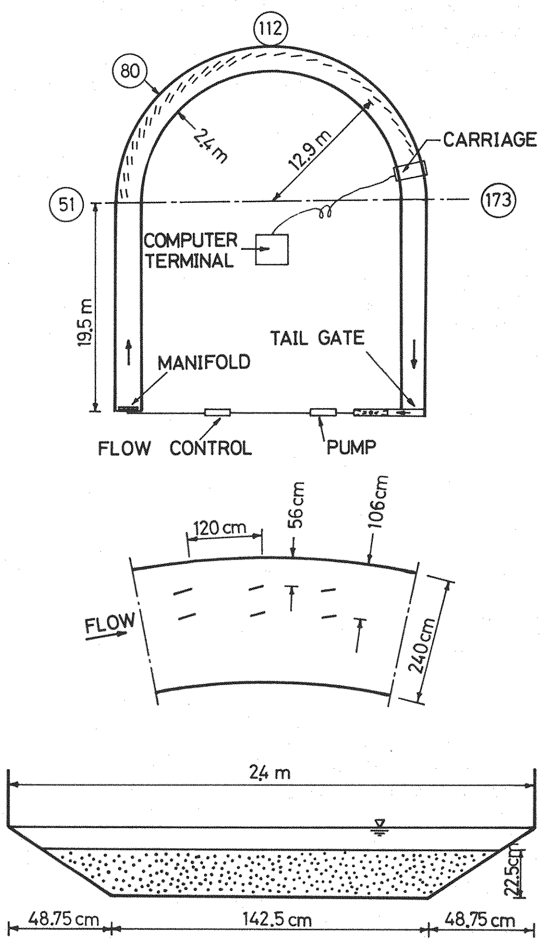

Fig. 5 Schematic illustration of experimental equipments

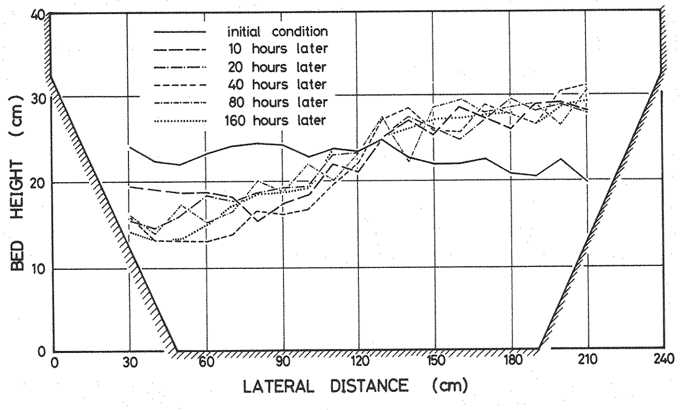

Fig. 6 Bed profiles at section 80 without vanes

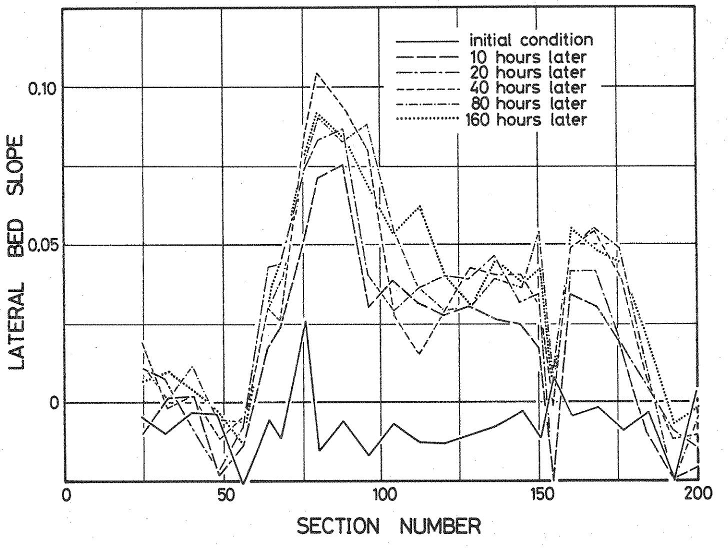

Fig. 7 Longitudinal distribution profiles of lateral bed slopes without vanes

Photo. 2 Experiment of Iowa Vanes

As shown in Fig.8 which presents the results at the section 80, the bed near the outer bank tends to be raised and the bed near the inner bank tends to be lowered by the effect of vanes. Consequently, the lateral bed slope approaches the horizontal. However, compared with Fig.6, these changes are smaller and slower than the local scouring which has already been developed before the setting of vanes.

The longitudinal characteristics of the lateral bed slope are presented in Fig.9 in the same manner as Fig.7. A remarkable effect can be seen around the section 80. On the other hand, around the section 100, the effect of vanes is so excessive that even an adverse slope is formed, that is, the bed near the inner bank becomes lower than that near the outer bank. This effect influences the lower stream but can be diminished by improving the size, number and arrangement of vanes.

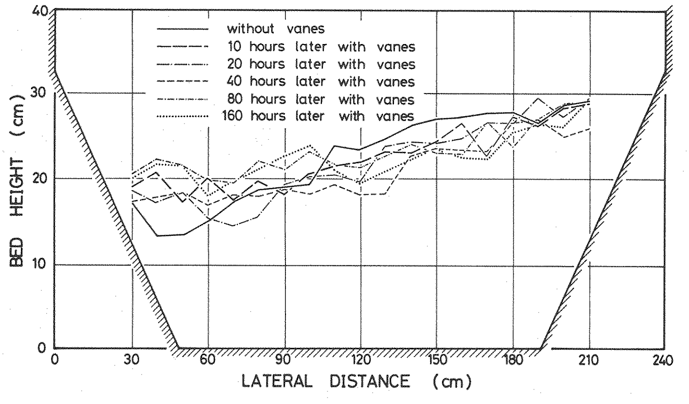

Fig. 8 Bed profiles at section 80 with Iowa Vanes

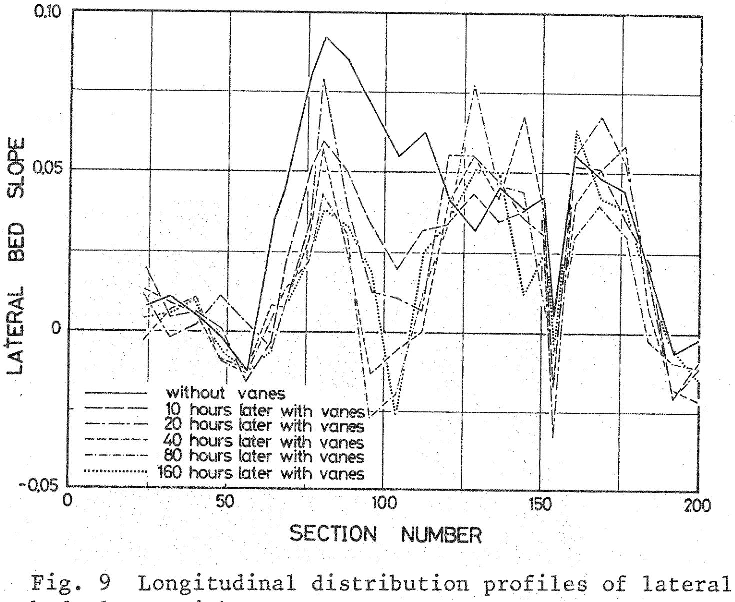

Fig. 9 Longitudinal distribution profiles of lateral bed slopes with Iowa Vanes

Fig.10 shows an effect of vanes through the investigation comparing the depth of local scouring (the difference between the mean bed height and the deepest bed height). It is understood from the figure that the depth of local scouring can be reduced to approximately a half around the section 80. After the experiment, the section 80 shows a local scouring only as one and a half as deep as those in sections without vanes, that is, the upper stream from the section 50 and the lower stream from the section 180.

Therefore, it can be said that the Iowa Vanes are effective to prevent local scouring at a river-bend. However, the setting of vanes should be done carefully because the wrong number and arrangement may cause a new local scouring. In fact, in this experiment a local scouring also occurs along the inner bank around the section 100.

The local scouring around vanes can be neglected as shown in Photo.3 when the angle of incidence $\alpha \leqq 15°$.

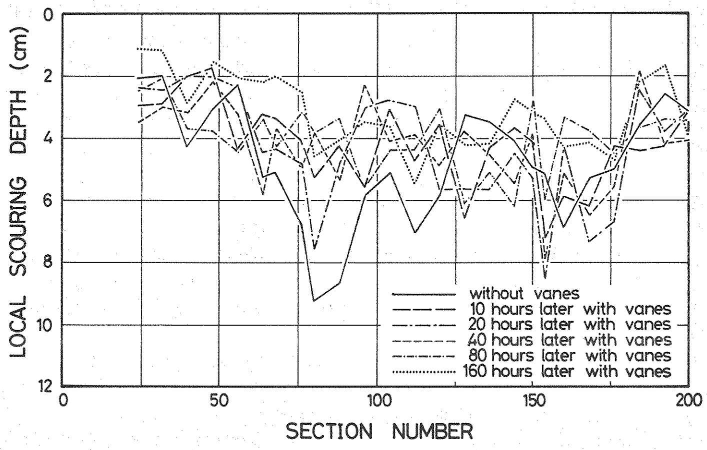

Fig. 10 Longitudinal distribution profiles of local scouring depth with Iowa Vanes

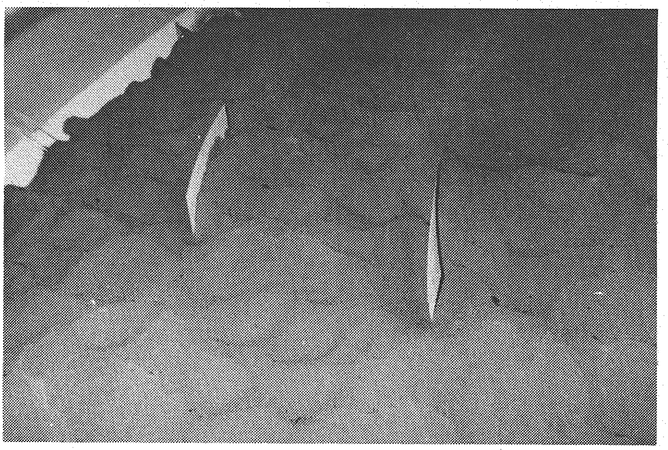

Photo. 3 Local scouring around Iowa Vanes

SOME PROBLEMS IN APPLICATION

There are some problems in determination of the size, number and arrangement of vanes on the basis of Eq.13.

Eq.13 can be also used for the investigation of the influence of the velocity distribution coefficient n. The terms concerning n in Eq.13 are as follows,

$$g(n,\frac{H}{h}) = \frac{n(n+2)}{n+1} f(\frac{H}{h}) \tag{16}$$

When $G(n)$ denotes the maximum value of $g(n,H/h)$ with variable H/h, the influence of n on $G(n)$ is shown in Fig.11. It is known that the velocity distribution coefficient n, that is, the roughness coefficient plays an important role in the evaluation of the effectiveness of vanes.

Secondary, a coefficient β of a lift force coefficient C_L for a single vane which is set in a uniform flow is well known and confirmed by experiments when the aspect ratio A_R of the height H to the length L of a vane is big. But if A_R is small like in this study, β is expected to be very small as shown in Fig.12. The values in the figure are evaluated from the experimental results (5) for A_R = 1,2,3,4,5,6,and 7 in uniform flows. Moreover, as a flow in a real river is a shear flow, it does not always have the same characteristics as an uniform flow. Specially when several vanes are located in a row, the characteristics of β become more complicated because of the cascade effect. For that reason, experimental investigations are necessary to determine the value of β and the size, number and arrangement of vanes.

For the determination of the height of vanes, it is necessary to presume the expected river bed height (the river bed height which is to be maintained) and the design water level. As a design water level, the level corresponding to the mean annual maximum discharge is chosen in case of a river with a single cross-section or the level corresponding to the height of the flood plane is chosen in case of a river with a composite cross-section, because it is considered to bring the biggest influence to local scourings at the section in question. However, if the water level does not correspond to the design water level, a local scouring also occurs.

Supposing that vanes are set to produce the intended effect in case of the expected depth h_0 (the difference between the expected river bed and the design water level). Fig.13 shows the effect of vanes when the water depth h is not the design depth h_0 (the physical conditions of vanes are determined to realize $T_f = T_v$, when $h = h_0$.

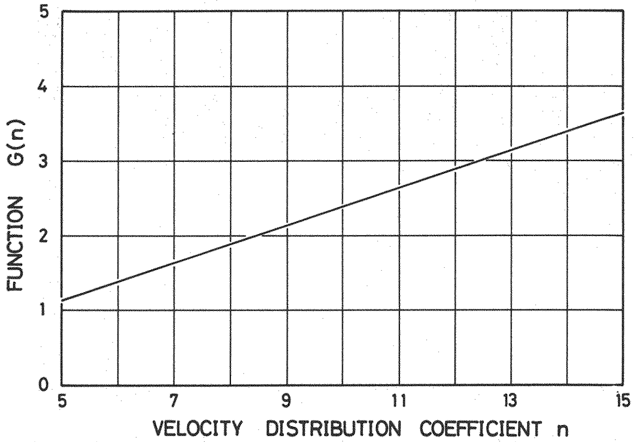

Fig. 11 Influence of the velocity-profile exponent n on the maximum value $G(n)$ of $g(n,H/h)$

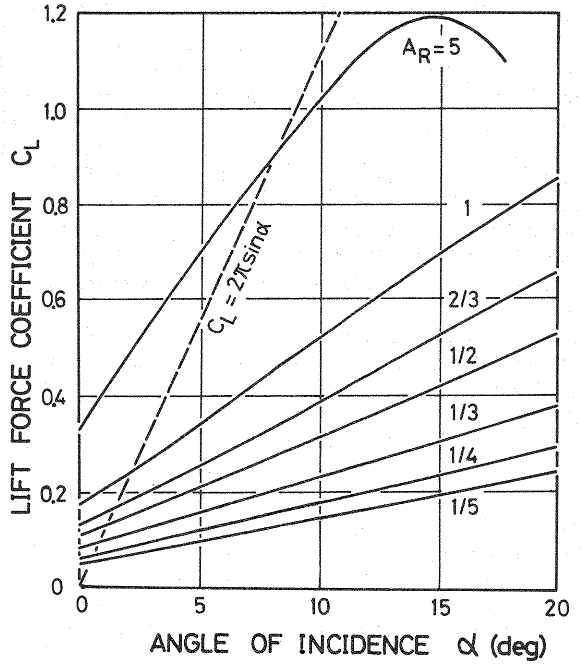

Fig. 12 Relation between angle of incidence α and lift force coefficient C_L

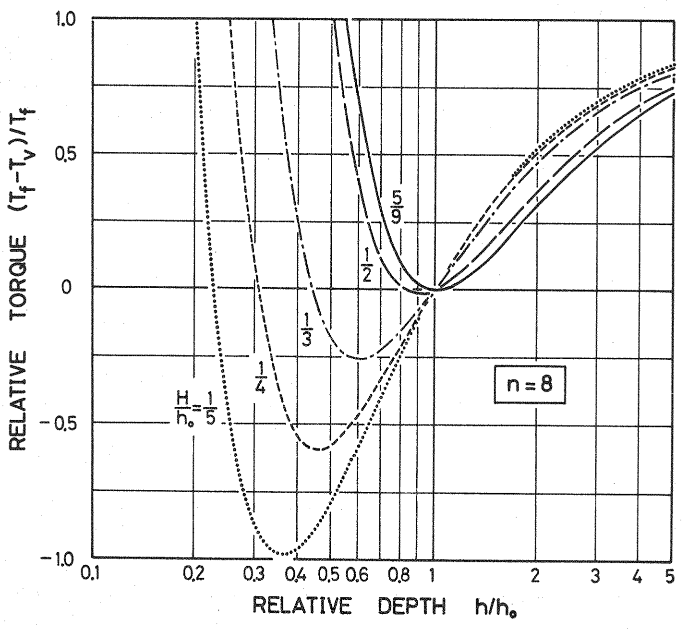

Fig. 13 Relation between relative depth h/h_0 and relative torque $(T_f - T_v)/T_f$ when n=8

Fig.13 is an example under the condition that velocity coefficient n = 8 and shows the effect of vanes of H in height. In this case, if the height of vanes is determined to satisfy H/h_0 = 5/9, the torque produced by vanes does not exceed the torque of the original flow at any water level and brings effect always to reduce the torque of the flow. On the other hand, if the relative height of vanes is smaller than H/h_0 = 5/9 and in case of low discharge, that is, the water level is lower than the design water level, the torque of vanes T_v exceeds the torque of flow T_f and thus secondary flows are generated in the opposite direction. Such a phenomenon may cause a local scouring along the inner bank. In short, if the water level is very low or higher than the design water level, vanes reduce local scourings along the outer bank, whereas if the discharge is in-between, that is, in case of small floods, local scourings may possibly occur along the inner bank.

With decreasing in the relative height of vanes H/h_0, the range, in which T_v exceeds T_f, increases and the relative torque $(T_f - T_v)/T_f$ decreases. On the other hand, for small relative depth h/h_0, the difference between the torques $(T_v - T_f)$ is kept small because the torque of flow is also small. Therefore, even if a local scouring occurs along the inner bank, this may not bring about a serious problem.

However, the frequency of discharge has very important influence in case of the application to real rivers.

FINAL REMARKS

The Iowa Vanes were proposed for the first time in 1982 and a plan is now in progress to install them in the East Nishnabotna River in Iowa, U.S.A.

Sheet piles are mainly used for the Iowa Vanes in real rivers. But when they do not match the landscape, the use of stone masonry is suggested. In Japan also, they are worth to be considered seriously as an inexpensive contermeasure.

Following conditions should be taken into account in case of the installment in real river:

1) strength and safety of the structure used as Iowa Vanes;
2) local scouring around vanes;
3) change of flow direction;
4) effect of Iowa Vanes when the discharge does not correspond to the design discharge;
5) order of installment; and
6) influence on the landscape.

Especially the conditions 2),3) and 4) are closely related to the determination of the angle of incidence of vanes, and the conditions 3) and 4) influence their height. These problems will require more extended research in the future.

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APPENDIX-NOTATION

The following symbols are used in this paper:

A_R = aspect ratio;
B = width of channel;
C = constant given by hydraulic condition;
C_L = lift force coefficient;
f = function of ratio of H to h;
F = centrifugal force;
F_ℓ = lift force;
g = function of n and ratio of H to h;
G = maximum value of g;
h = depth of flow;
h_0 = design depth or expected depth;
H = height of vane;
I_ℓ = lateral bed slope;
L = length of vane;
n = velocity-profile exponent;
N_v = number of vanes;
r = radius of curvature; radial coordinate;
r_i = innermost radius of curvature;
r_o = outermost radius of curvature;
T_f = total torque produced by bend flow;
T_v = total torque produced by Iowa Vanes;
v = uniform flow velocity;
V = flow velocity;
$\overline{V}$ = depth-averaged flow velocity;
$\tilde{V}$ = flow velocity averaged over height of vane;
z = distance upward from stream bed;
α = angle of incidence of vane;
β = ratio of actual to theoretical value of C_L;
ΔT_f = torque produced by bend flow with unit width;
ρ = fluid density at distance z from stream bed; and
ϕ = bend angle.