Study on hydrodynamic forces on submersible groins in series

H. Kawaguchi
Hiroshima University, Higashi Hiroshima City, Japan

S. Fukuoka
Hiroshima University, Higashi Hiroshima City, Japan

ABSTRACT: Groins are used as structures against bank erosion in curved channels. The arrangement of groins has been studied by the statistical, experimental, and numerical methods. Recently, they are also focused as structures making a favorable environment in rivers. The arrangement of groins should be thought by the function of groins. For this purpose, the numerical model, which represents flow and bed deformation around groins, is needed. Considering the practical use, we have studied on quasi three-dimensional numerical model. We introduced groin arrangement and hydrodynamic forces in this model to estimate the effects of groin. The result shows the general features of the flow and bed deformation. Drag coefficient C_D and lift coefficient C_L of hydrodynamic force has been determined without measuring hydrodynamic force. In this paper, we have made clear the characteristics of the hydrodynamic force on the submersible groin in series with the various groin arrangements by measuring forces directly and flow around the groin, and obtained drag coefficients C_D and lift coefficients C_L.

1 INTRODUCTION

Groins are used in curved channels against bank erosion and for maintenance of a navigation route. Use of groins has been investigated through experimental analyses, numerical calculations and observations in rivers. Recently, in addition to these functions of groins, they have been expected as structures to make a riverine environment favorable because of variation of flow and bed topography. Groins must be arranged in river to fulfill various purposes from technical reasons. In other words, flow and bed topography must be understood for various groin arrangements using longitudinal and cross-sectional bed profiles, and hydraulic conditions.

An appropriate groin arrangement can be obtained through many experimental data analysis only for a particular purpose like protection of bank erosion. A method is needed for design of groin arrangement, considering several purposes like functions and costs of groin. For this reason, groin arrangement design method by a numerical calculation, which supplements experiments, is seems to be important.

Fukuoka, S. et al. (1992) presented the design method of groin arrangement using quasi-three-dimensional numerical model that reduced outside erosion in the curved part of rivers. In that model, effects of groins against flow were represented by the improvement of bed topography.

After that, the numerical model was improved by the addition of hydrodynamic forces on groins in series to momentum equation (Fukuoka, S. et al., 1998). This model is effective in the analysis of flow and bed topography in some set up of groin arrangements of a straight channel (Fukuoka, S. et al., 1998). But the drag and lift coefficients (C_D=5.0, C_L=0.1) of the hydrodynamic forces in that model were not verified directly.

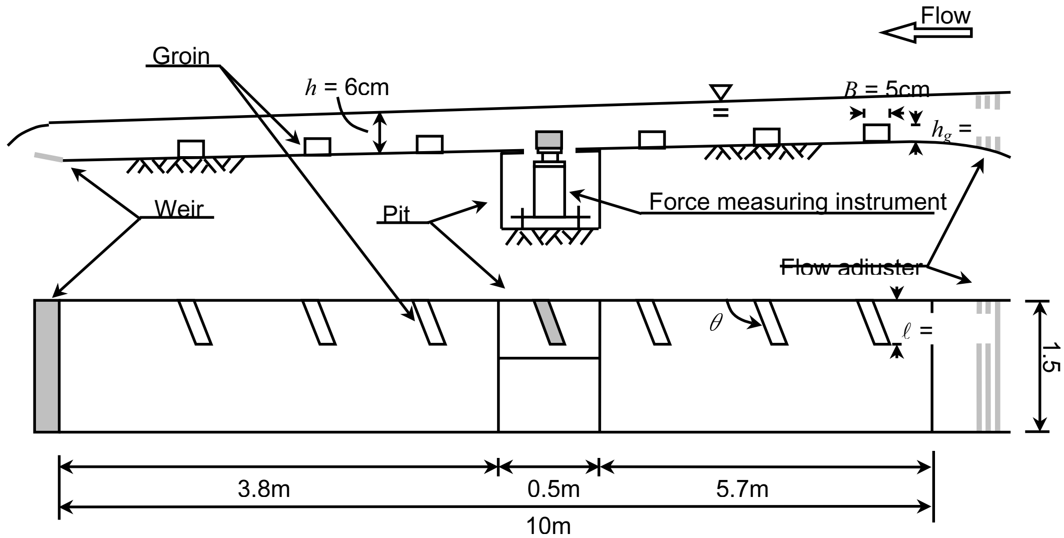


Figure 1 : Experimental setup

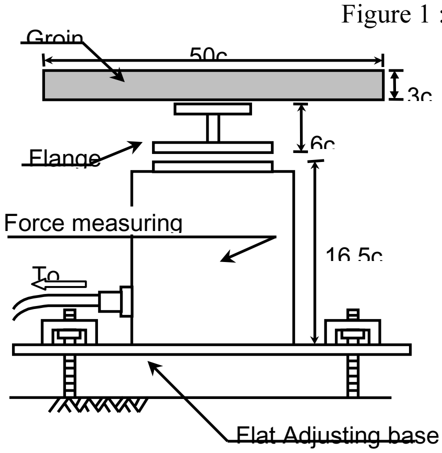


Figure 2 : Force measuring instrument with groin

In this paper, we make clear the relationship between the hydrodynamic forces on the groins and the flow around the groins. The flow and the hydrodynamic forces are measured for some groin arrangements with the various intervals between two groins and angle of the groins against the main flow. We also show drag and lift coefficients of the hydrodynamic force acting on the groin.

2 EXPERIMENTAL CONDITION AND METHOD

The experimental straight channel with fixed bed was 10m long, 1.5m wide and 1/500 slope (Figure 1). There was a pit at the center of the channel to measure the hydrodynamic forces. The pit was 0.5m×1.5m size and 0.5m deep, which is shown in Figure 2. The hydrodynamic forces acting on the groin is measured by force measuring instrument.

Table 1. Experimental condition

Discharge Q	30.67 *l/s*
Average depth h	6 cm
Slope i	1/500
Groin width B	5 cm
Groin length ℓ	50 cm
Groin height h_g	3 cm
Groin interval s	0.5, 0.75, 1.0, 1.5 m
Ratio of s/l	1, 1.5, 2, 3
Groin angle θ	75°, 90°, 105°

Hydraulic conditions of the experiments are shown in Table 1. The experiments were performed with the variation of the interval between two groins and the groin angle against the main flow. Considering the statistical results (Akikusa et al., 1960), total 12 numbers of experiments were performed. In these experiments, the ratio of the groin interval to the groin length (s/ℓ) were 1, 1.5, 2 and 3, and the groin angles were 75°, 90° and 105° measured from the left bank. To investigate the hydrodynamic force due to the flow around groin, the flow field is measured only for the 3 experimental cases (s/ℓ=2.0). The velocity of flow was measured by the electric and magnetic instrument.

3 EXPERIMENTAL RESULT

3.1 The hydrodynamic forces

The hydrodynamic force F, the drag force D, the lift force L acting on groin and the directional angles of the hydrodynamic force are shown in Figure 3. The drag force is defined as the longitudinal component of the hydrodynamic force. On the other hand, the lift force is defined as the lateral component of the hydrodynamic force. The directional angle of the hydrodynamic force is considered as the angle measuring from the longitudinal direction of flow.

The results of the measured drag and lift forces for the different ratio of the groin interval to the groin length (s/ℓ) are shown in Figure 4. The positive direction of the drag force is towards downstream along the longitudinal direction. The direction of the lift force is from the right bank to the left bank.

The drag force is larger for the higher value of s/ℓ. In these experimental conditions, the magnitude of the drag force varies from 60 to 110 gf. It is seen that the drag force is not correlated with the groin angle.

On the other hand, the absolute value of the lift force is not subjected to the ratio of s/ℓ. The lift forces in the right angle cases are small compared to the drag forces. Therefore, their values are ignored. The lift forces in the 75° groin angle cases are from –30 to -20 gf acting from the left bank to the right bank. The lift forces in the cases of 105° angle are 20～30 gf acting from the right bank to the left bank, which are working just in the opposite direction to the lift forces in the 75° angle cases. Their values are about 1/3～1/4 of the value of the respective drag force.

The directions of the hydrodynamic forces on the groins are shown in Figure 5. The

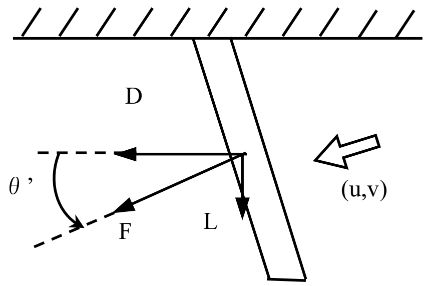


Figure 3 : Definition of hydrodynamic force F, drag force D, lift force L and angle of hydrodynamic force θ'

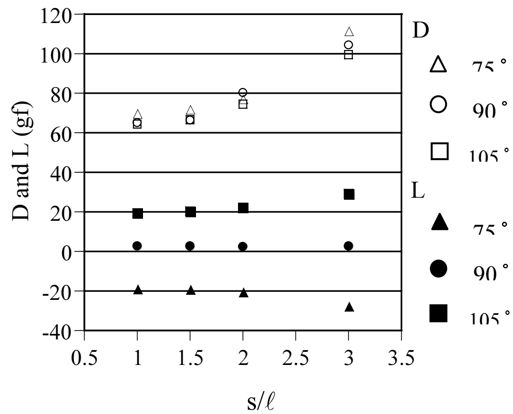


Figure 4 : Drag forces D and lift forces L

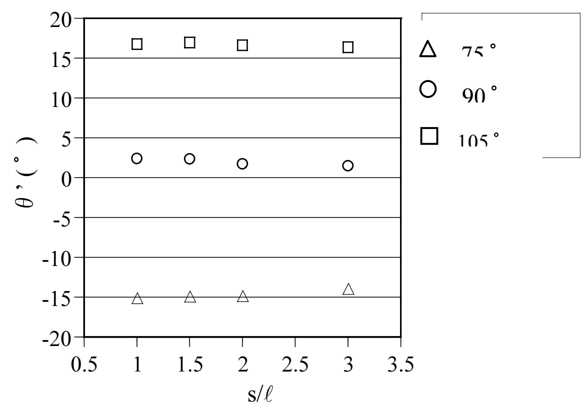
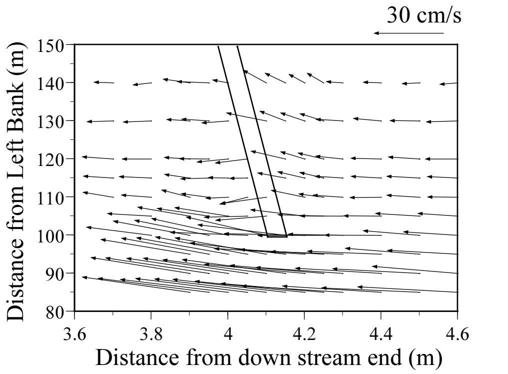
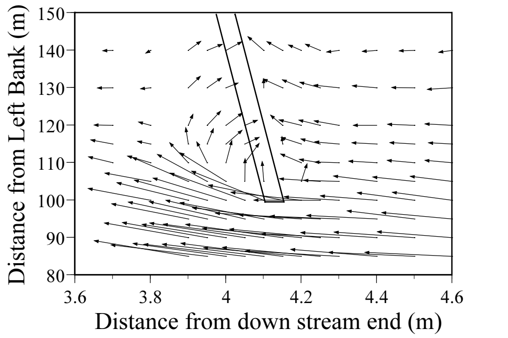


Figure 5 : Angles of hydrodynamic forces

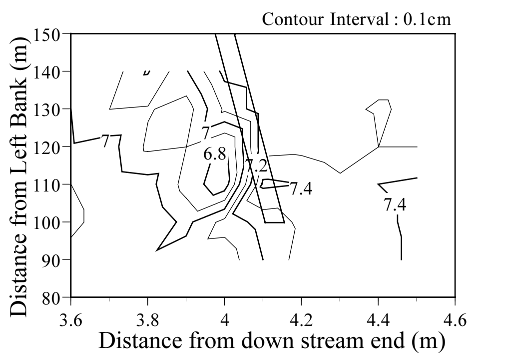
angles of the hydrodynamic forces are –14.7°, 2.0° and 16.7° for the cases with the groin angle 75°, 90° and 105° respectively. In



Flow velocity vector on the plane 3cm below the water surface



Flow velocity vector on the plane 5cm below the water surface

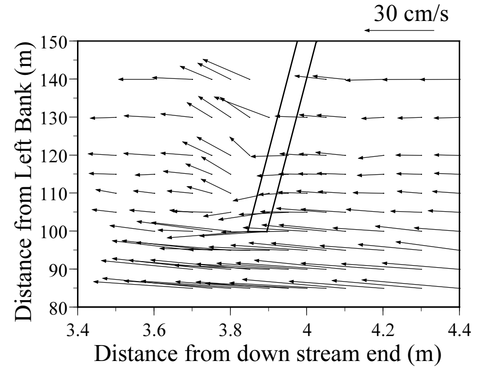


Contour of the water surface

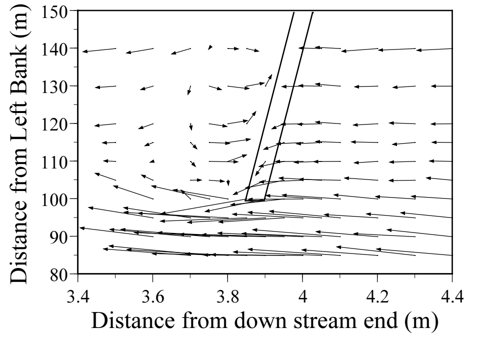
Figure 6 : Flow field in the case of the groin angle 105°

other words, the hydrodynamic forces act perpendicular to the direction of groin length.

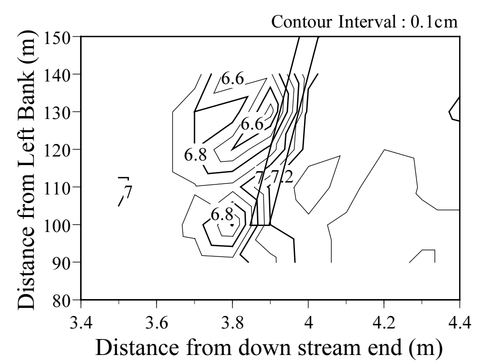
3.2 The flow around the groin



Flow velocity vector on the plane 3cm below the water surface



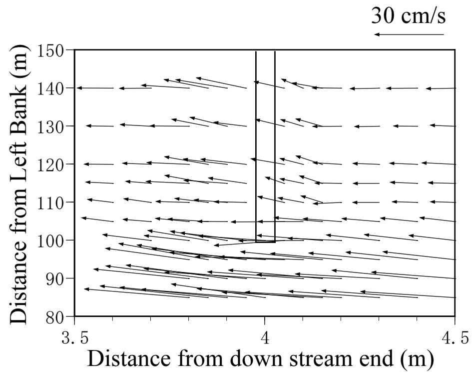
Flow velocity vector on the plane 5cm below the water surface



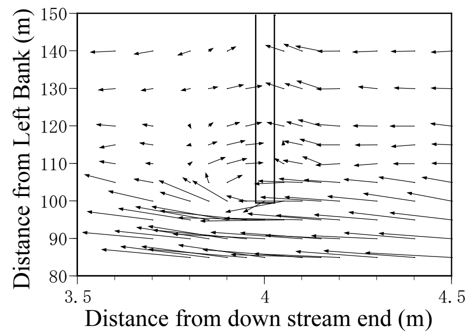
Contour of the water surface

Figure 7 : Flow field in the case of the groin angle 75°

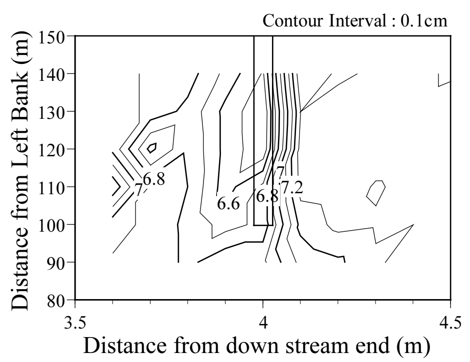
The flow field in the case of groin angle 105° (s/ℓ =2.0) is shown in Figure 6. It shows the vectors of the flow on the planes of 3cm and 5cm below the water surface, and the contour



Flow velocity vector on the plane 3cm below the water surface



Flow velocity vector on the plane 5cm below the water surface



Contour of the water surface

Figure 8 : Flow field in the case of the groin angle 90˚

of the water surface. The planes of 3cm and 5 cm below the water surface are selected as the plane of the groin height and the bed level respectively. Observing the vectors of the flow velocity around the groin, it is apparent that

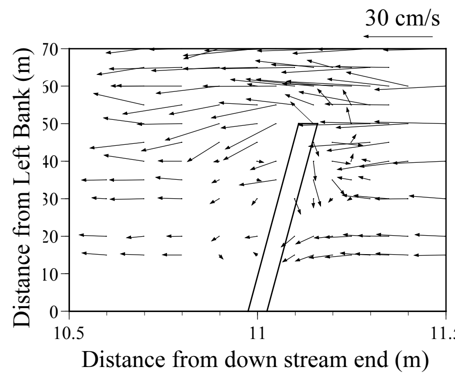


Figure 9 : Flow velocity near the movable bed under similar hydraulic conditions (groin angle 105˚)

the separation of the flow occurs in the downstream area of the groin. Because of the action of the hydrodynamic force on the groin, the flow in the upstream and downstream of groins is from the left bank to the right bank of the channel. From the contour of the water surface, it is understood that the rise of the water surface level is occurred by the force reacted from the groin, where the direction of the steepest slope represents the perpendicular direction from the groin length.

Similarly, Figure 7 and 8 show the flow fields around the groins for the cases of the groin angle 75˚ and 90˚ respectively, where the both has the ratio of $s/\ell = 2.0$. In the case of the groin angle 75 ˚, the flow in the upstream of the groin moves from the right bank towards the left bank due to the action from the groin. The separation of flow occurs in the downstream of the groin, due to the strong flow on the toe of groin. Therefore, the flow above the groin moves towards the separation area. In the case of the right angle groin, the flow around groin is directed to the longitudinal direction. The steepest water surface slope is the direction perpendicular to the groin length. From these fixed-bed experimental results, it is apparent that the groins control the flow.

For the movable bed, the flow field around the groin is affected by the scour hole around groin, and the separation area of the flow is decreased (Figure 9). Therefore, it is considered that the hydrodynamic force on a groin in a movable bed is smaller than that in a fixed bed.

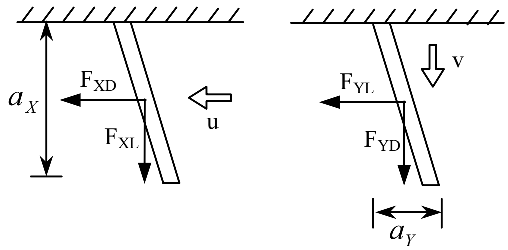


Figure 10 : The assumption of hydrodynamic forces estimated from components of approaching flow velocity vector

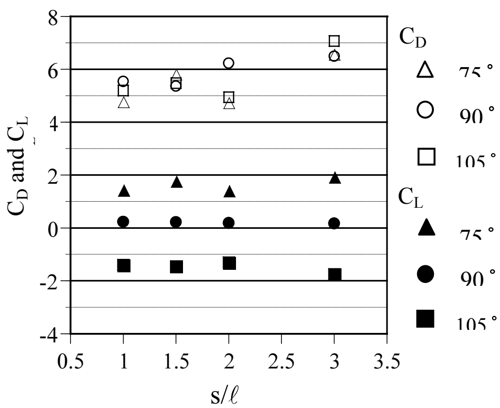


Figure 11 : C_D and C_L

4 DRAG COEFFICIENT C_D AND LIFT COEFFICIENT C_L

In this section, the relationship between the approaching flow velocity and the hydrodynamic force is studied by two methods. The approaching flow velocity vectors (u,v) are obtained from the average of the flow velocities, from the left bank to the toe of the groin and from the bed to the water surface level at 5cm upstream of the groin.

The first method for estimation of C_D and C_L is useful in the case where the cross-sectional component v is relatively large: the groin is not submersible or leaned against the main flow. It is considered that the drag and lift force are estimated from the components of the drag force and the lift force given by the longitudinal and cross-sectional component of the approaching flow:

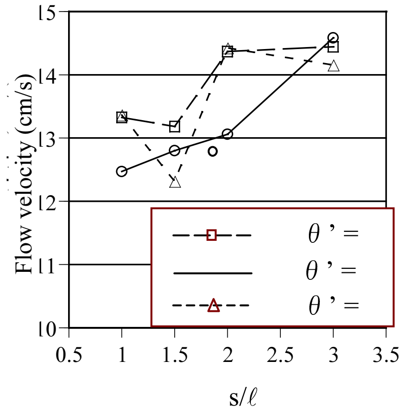


Figure 12 : Approaching flow velocity

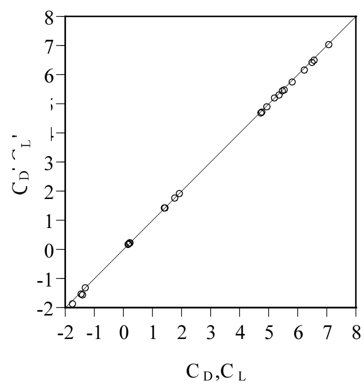


Figure 13 : C_D' and C_L' only from longitudinal component of flow velocity component

$$\begin{pmatrix} D \\ L \end{pmatrix} = \begin{pmatrix} F_{XD} \\ F_{XL} \end{pmatrix} + \begin{pmatrix} F_{YL} \\ F_{YD} \end{pmatrix} \qquad (1)$$

where D is the drag force, L is the lift force, F_{XD} is the drag force component and F_{XL} is the lift force component obtained from the longitudinal approaching flow velocity component. F_{YD} is the lift force component and F_{YL} is the drag force component obtained from the cross-sectional flow velocity component. The product of the velocity component and its absolute value is used instead of the squared component of the approaching flow velocity, in order to consider the relationship between the direction of the hydrodynamic force and that of the approaching flow velocity:

$$\begin{pmatrix} F_{XD} \\ F_{XL} \end{pmatrix} = \begin{pmatrix} C_D \\ C_L \end{pmatrix} a_X \frac{\rho(u|u|)}{2} \quad (2)$$

$$\begin{pmatrix} F_{YD} \\ F_{YL} \end{pmatrix} = \begin{pmatrix} C_D \\ C_L \end{pmatrix} a_Y \frac{\rho(v|v|)}{2} \quad (3)$$

From Equation 1, 2 and 3, the drag and lift coefficient C_D and C_L are developed:

$$C_D = \frac{2\{a_X(u|u|)D/\rho - a_Y(v|v|)L/\rho\}}{a_X{}^2(u|u|)^2 - a_Y{}^2(v|v|)^2} \quad (4)$$

$$C_L = \frac{2\{a_X(u|u|)L/\rho - a_Y(v|v|)D/\rho\}}{a_X{}^2(u|u|)^2 - a_Y{}^2(v|v|)^2} \quad (5)$$

Figure 11 shows the value of the drag coefficients C_D and the lift coefficients C_L from Equation 4 and 5 respectively. Hydrodynamic forces are larger for the higher ratio of s/ℓ. The coefficients C_D and C_L are not correlated with the ratio of s/ℓ. The coefficient C_D is not also correlated with the groin angle, because of the approaching flow velocities as shown in Figure 12. So, C_D is about 5.6, which is not being affected by the ratio s/ℓ and the groin angle. The coefficient C_L is -1.6, 0.2 and 1.6 for the cases of the groin angle 75°, 90° and 105° respectively.

Generally, a cross-sectional component of an approaching flow velocity is much smaller than that of a longitudinal component. Equation 1 approximates the following equation.

$$\begin{pmatrix} D \\ L \end{pmatrix} = \begin{pmatrix} C_D' \\ C_L' \end{pmatrix} a_X \frac{\rho u|u|}{2} \quad (6)$$

Figure 13 shows the comparison of the drag and lift coefficients (C_D' and C_L') from Equation 6 with those (C_D and C_L) from Equation 4 and 5. It is observed from this result that the cross-sectional component of approaching flow velocity does not affect the hydrodynamic forces in all our cases.

In the second method, the s-n coordinate system is considered based upon the direction of the approaching flow velocity vector in

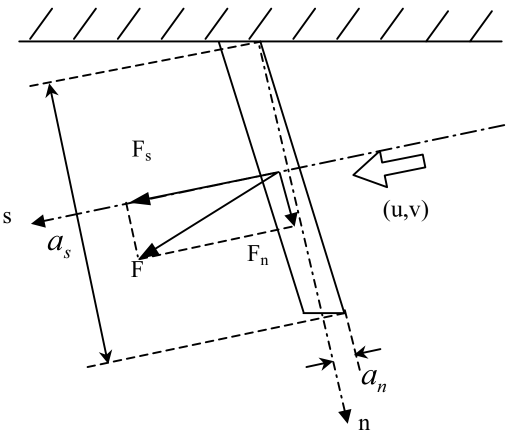


Figure 14 : The assumption of hydrodynamic force based upon direction of approaching flow velocity

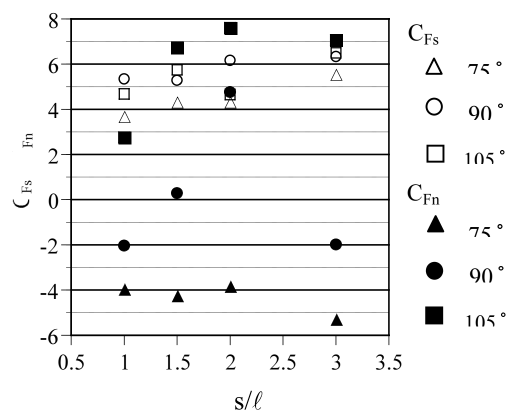


Figure 15 : C_D' and C_L' for the ration of s/ℓ

Figure 14. Then the relationship between the hydrodynamic force and the approaching flow velocity is expressed by the following equations:

$$F_s = C_{Fs} a_s \frac{\rho(u^2+v^2)}{2} \quad (7)$$

$$F_n = C_{Fn} a_n \frac{\rho(u^2+v^2)}{2} \quad (8)$$

where F_s and F_n are the s and n directional components of the hydrodynamic force respectively. On the other hand, a_s is the projected area of the groin in s direction and a_n is the projected area of the groin in n direction. C_{Fs} is the coefficient of Fs and C_{Fn} is the coefficient of F_n. Figure 15 shows the values of C_{Fs} and C_{Fn} obtained from Equation 7 and 8. It is apparent that the coefficients C_{Fs} are almost constant in every case. But the coefficients of C_{Fn} are different in the each case, because the direction of the hydrodynamic force is different from that of the approaching flow velocity vector. The second method is useful in the case where the flow is controlled by the structures like the houses in inundated areas.

In our experimental cases, where the flow is almost in the channel direction, Equation 6 is more useful. It seems to be reasonable and proper to approximate $C_D = 5.0$ and $C_L = 0.1$ for numerical calculation. These values are verified by the investigation of the groin effects on the flow of the Shinano River (Fukuoka, S. et al , 2000).

5 CONCLUSIONS

On the recent days, use of groins is attracting attention. The arrangement of groins is needed to investigate much more, because of the use of the groins for various purposes. Flow field around a groin must be grasped and a hydrodynamic force must be estimated properly, in order to design arrangement in rivers to fulfill various purposes based upon technical reasons. In this paper, the relationship between the flow fields around the groin and the hydrodynamic forces acting on the groins became apparent. The drag coefficient C_D and the lift coefficients C_L are obtained in this analysis. The conclusions of this research are as follows.

(1) The drag force acting on the groin is not correlated to the groin angle. The lift forces acting on the groins in the cases of groin angle 75° and 105° are acting from the left bank to the right bank, and from the right bank to the left bank respectively.

(2) The flow field is regulated by the action of the hydrodynamic force acting on the groin.

(3) The drag and lift coefficients is almost constant for the ratio of the interval between groins and the groin length s/ℓ, using the method of the drag force and the lift force given by the longitudinal and cross-sectional component of the approaching flow. The drag coefficient C_D is about 5.6, which is independent of the ratio of s/ℓ and the groin angle. The lift coefficients are not also related to the ratio of the s/ℓ. The lift coefficients C_L are -1.6, 0.2 and 1.6 in the cases of the groin angle 75°, 90° and 105° respectively.

(4) It seems to be reasonable and proper to use $C_D = 5.0$ and $C_L = 0.1$ in the quasi-three numerical model, which are obtained from a fixed bed analysis. These values might also be considered for a movable bed.

REFERENCES

Akikusa,I., Kikkawa,H., Sakagami,Y., Ashida,K. and Tsuchiya,A. "Study on groin", Journal of Research, Public Works Research Institute, No.107, 1960.

Fukuoka,S., Takahashi,A and Watanabe,A. "Study on groin arrangement and scour protection effects of groin", Journal of Research, Public Works Research Institute, No.2640, 1988.

Fukuoka,S., Watanabe,A. and Nishimura,T., "On the groin arrangement in meandering rivers", Journal of Hydraulic, Coastal and Environmental Engineering, JSCE, No.443/Ⅱ-18, pp.27-36, 1992.

Yamamoto,K. "Groins in Japan", Sankaikdo, 1996

Fukuoka,S., Nishimura,T., Takahashi,A., Kawaguchi,A. and Okanobu,M. "Design method of submerged groins", Journal of Hydraulic, Coastal and Environmental Engineering, JSCE, No.593/Ⅱ-43, pp.51-68, 1998.

Fukuoka,S., Nishimura,T., Okanobu,M. and Kawaguchi,H. "Flow and bed topography around groins installed in a straight channnel", Annual Journal of Hydraulic

Engineering, JSCE, Vol.42, pp.997-1002, 1998.
Fukuoka,S., Abe,T. and Nishimura,T., "Control of bed variation at Ojiya-Koshiji District in Shinano River", Annual Journal of Hydraulic Engineering, JSCE, Vol.44, pp.347-352, 2000.