Studies on the Scour from Flows Downstream of an Outlet

By Takashi SAITOU*, Hirofumi OHNARI**
and Nobuyoshi AKASHI***

(Received July 16, 1979)

Abstract

Though the local scour take rise by change of sediment transported through each section, generally, it is so complex phenomenon that the change of flow charactor in scour hole is closely related to progress of scour, and the development of scour is defined by changed flow charactor.

According to investigation on the sediment motion and the flow character by observations with moter-drive camera, on the scour mechanism, the progress of local scour from submerged plane jets are distinguished in three stage; i.e., initial, interium and progressive. In initial stage, the scour take rise in the sediment transport depends on the location from plane wall-jet. After the scour change to interium, the flow separate from sand surface at an inclined plane downstream of scour hole. The scour change into progressive stage, in addition to the separation of flow, the intermittent collapse of a slope downstreams of scour hole becomes occour.

In this paper, the author describes the results of some experiments on the scour from submerged plane jet, and suggest the method analysed the development of scour hole. As a results of analysis, it becomes clear that the separation of flow and the intermittent collapse are important in order to explane the mechanism of the local scour from submerged plane jet. The experimental results can be analysed sufficiently by the method proposed here.

1. Introduction

Studies on the local scour from submerged plane jets have been done for long times as one of fundamental probrem concerned with local scour. However the theoretical studies are limited by reason of complexity that the local scour is closely related to the change of flow character in scour hole accompanying the progress of scour and the development of scour is defined by changed flow character.

The study of Laursen[1]; a comparatively rough consideration were done by applying the equation of continuity for river bed material, Tsuchiya & Iwagaki[2]; the development of boundary layer in wall jets was considered in the equation of river bed variation, and Tsuchiya[3]; the scour mechanism in initial stage was considered on the basis of the character of wall jet and non-equilibrium sediment transport. Those three works are a typical example of theoretical investigation on the local scour from submerged plane jets. In those studies, the scour mechanism were considered on the basis of a jet flow along the flat smooth plate. The investigation in consideration of the change of flow character accompanying with the development of scour has never been performed.

* Department of Civil Engineering
** Tokuyama Technical College
*** Nishinippon Institute of Technology

In this study, following experiments on the scour from submerged plane jets were made.

1. A change of river bed and the motion of sand grain were traced by using motor-drive camera.
2. A detailed measurements have been made of velocity and state of flow in scour hole.

We will describe the character on a scour progress. In the very beginning of scour, a jet flow spouted from an outlet flows away straightly along a river bed, and a scour take in the sediment transport depends on the location. Instantaneously, a jet flow curves to a direction of a scour hole by roller growed up at a vicinity downstream of an outlet. Thereby, a scour become progress to direction of depth, and a slope downstream of scour hole become steep gradually. A grade of this slope become reaches to rest angle of sand in water, then unstable parts of this slope become collapse intermittently in correspondence to sway of a curved jet. As a results of this phenomenon, the similarity on the shape of a scour hole are mainted almostly, a scour take rise in the sediment carried over a sand heap downstream of a scour hole.

From the fact descrived above, on the basis of the scour mechanism, it can be distinguished the scour progress in three stages, initial; a variation of a river bed are very small and a jet flow from an outlet flowes away straightly, interium; the scour in derection of depth owing to the reattached wall-jet from curved jet distinguish, and progressive stage; the scour progress as keeping a similar shape of a scour hole.

The scour mechanism in the initial stage has been fairly maked clear. With that, in this study, we have a thing as an object to investigate the scour mechanism in interium and progressive stage.

It is necessary to clear the character of flow in the neighbourhood of the sand surface which were closely related to the sediment transports, namely, to clear the distribution of a shear velocity along a sand surface in a scour hole depends on the location and times. Simplifying a flow along a sand surface in a scour hole, it can be considered as wall-jet issuing parallel to a flat plate.

In accordance with the flow model descrived above, a variation of flow characters, which change every times, are expressed by the maximum scour depth depend on times.

In this paper, at the first place, the author describes the results and special characteristic of some experiments on the scour from submerged plane jet, and then, deduce the equation of continuity for river bed variation based on the non-equilibrium sediment transtorts, and analyse the progress of scour to introducing the separation of flow from a sand surface in interium stage and the intermittent collapse of a unstable slope downstream of scour hole in progressive stage. Further, in the case that the water depth downstream of an outlet is shallow, since the typical phenomenon that the direction of curved-jet changes upside or under-side in connection with the water depth, the maximum scour depth and the configuration of scour hole occurs, the experiments on the effect of this phenomenon were performed.

This phenomenon are quantitatively explained by the limiting condition on the flow direction of curved-jet.

2. Experimental Apparatus and Method

The schematic diagram of the experimental apparatus, which are composed of steel frame and acrylic grasses, and the typical notation used in this paper are shown in Fig. 1. The jet generator at upstream and the movable weir at downstream are set up.

Fig. 2 shows a grain size accumulation curve of sand used in this experiments. The sand character are arranged in tabuler form at the lower part in Fig. 2.

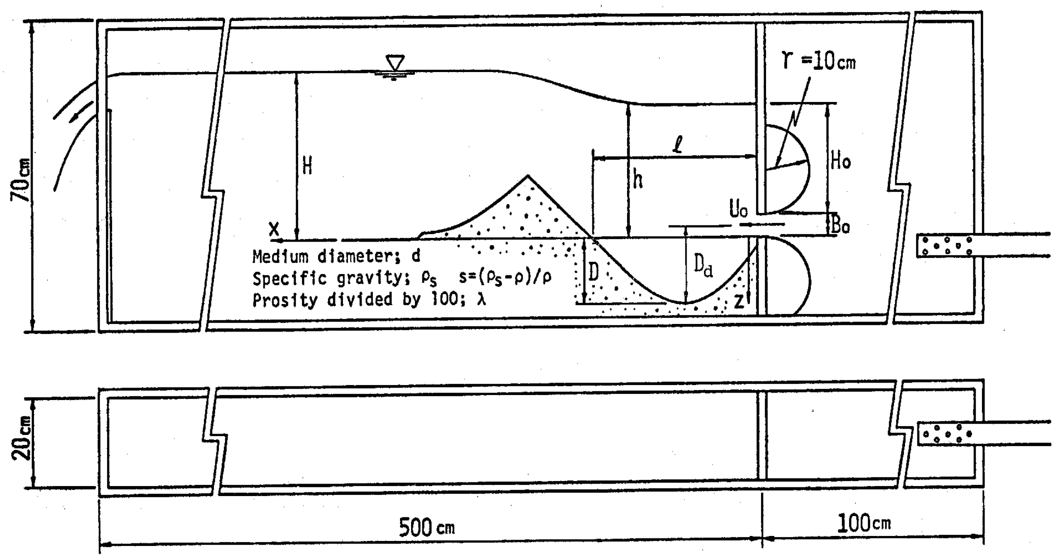
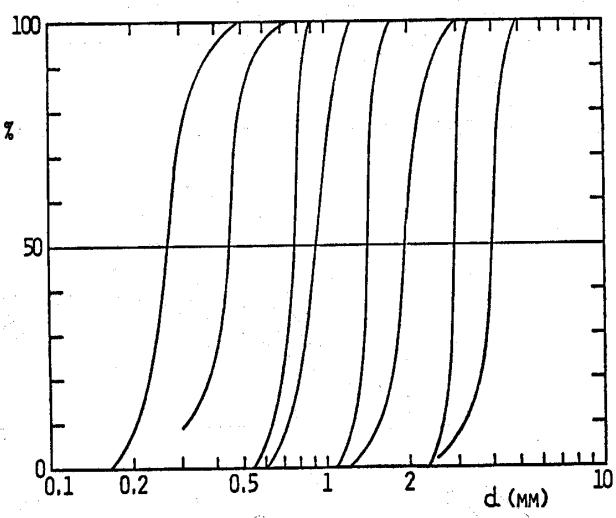


Fig. 1 Schematic diagram of experimental apparatus and typical notation.



d (cm)	0.027	0.045	0.077	0.092	0.141	0.192	0.290	0.395	0.435
Wo (cm/s)	3.59	5.52	8.33	9.33	12.3	14.4	18.2	19.9	21.3
$\sqrt{sgd}$ (cm/s)	6.61	8.53	11.2	12.2	15.1	17.6	23.6	25.3	26.1
U_{*co} (cm/s)	1.56	1.72	2.06	2.25	2.92	3.62	4.85	5.65	5.93

Fig. 2 Grain size accumulation curve and characters of sand grains.

Where, d; medium particle size,
w_0; rate of sedimentation calculated by Rubey formula,
U_{*c0}; critical shear velocity calculated Iwagaki formula.

The experiments were performed under following condition.

$B_0 = 0.97\text{–}2.60$ cm, $U_0 = 35\text{–}200$ cm/sec,
$d/B_0 = 0.03, 0.05, 0.10,$
$U_0/sgd = 15, 60, 200.$

The variation on the configuration of a scour hole and the maximum scour depth with time were measured with moter drived camera.

In the typical experiments, to grasp the relationship between a sand movement and a flow situation in scour hole, the intermittent flows of a colouring matter were photographed with 8 mm movie camera. Further, the velocity distribution in a few movable and a few fixed scour hole were measured. For the measurement of velocity, we used a pitott tube which were made a stainless pipe with the inside diameter 1.8 mm and the outside diameter 2.2 mm. The direction of pitott tube and a colouring matter flow were arranged in the same.

3. Experimental Results and Considerations

(1) The configuration of scour hole

The dimensionless parameter which define the configuration of scour hole will be writen as follows.

$$Z/B_0 = f_1(X/B_0,\ U_0t/B_0,\ U_0^2/sgd,\ \sqrt{sgd}\cdot d/\nu,\ d/B_0,\ H/B_0,\ s) \quad \cdots\cdots\cdots(1)$$

Lets us carry on the reserch on each dimensionless parameter in the above equation, exclusive of the effect of downstream depth H/B_0 which are investigate later.

The configuration of scour hole which are written the dimensionless form with the maximum scour depth D and the length of scour hole l are shown in Fig. 3(a),

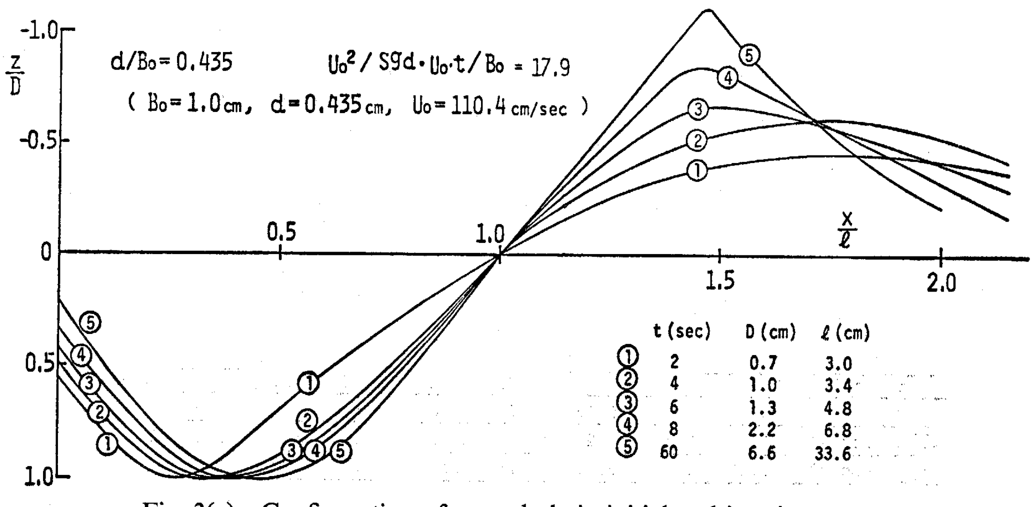


Fig. 3(a) Configuration of scour hole in initial and interium stage.

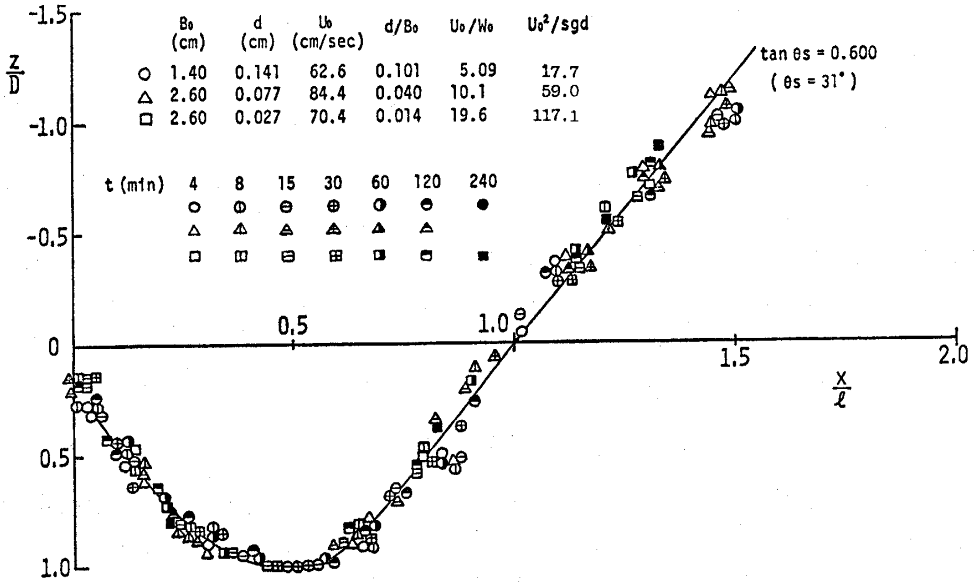


Fig. 3(b) Configuration of scour hole in progressive stage.

(b). As is seen in Fig. 3(b), it may be quite all right to consider that the similitude in the configuration of scour hole are applicable in the progressive stage, but the configurations in the initial and the interium stage depends remarkably on times as is seen in Fig. 3(a).

The relationship between the maximum depth D and the scour length l which are used to make the dimensionless configuration of scour hole are shown in Fig. 4. In the range of $D/B_0 \geq 2$, it can be considered that there is no effect of roughness expresion d/B_0 on l/B_0, another, in the range of $D/B_0 \leq 2$, the value of l/B_0 depends strongly on d/B_0. For caution's sake, a curve in Fig. 4 are a calculated value which are described later.

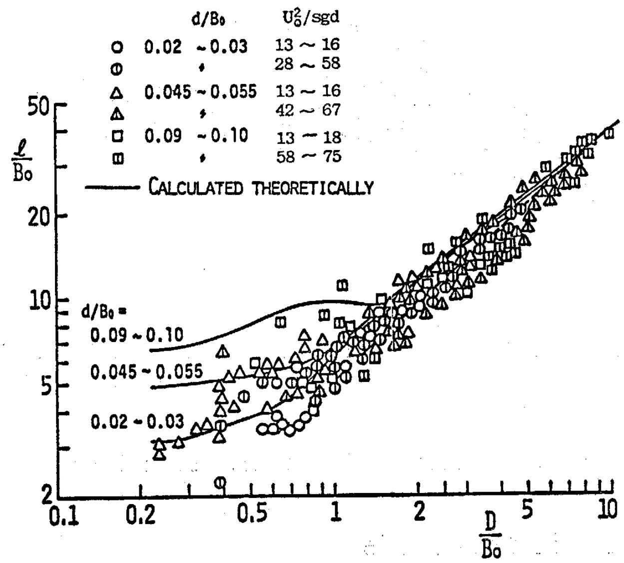


Fig. 4 Relationship between the maximum scour depth and scour length.

(2) A variation of maximum scour depth with time

As mentioned above, it became clear that the similitude of the configuration of scour hole are applicable in a progressive stage, and it can be expressed the dimensionless form with one standard length. Therefore, in the consideration on the progress of scour depth, we carry on the research on the maximum scour depth.

The specific gravity of sand grain in water s does not very much change, and, as a results of experiment, the sand grain Raynould's number $\sqrt{sgd}\cdot d/\nu$ have not strongly effects upon the scour. Then, if we neglect those effects, in the case of that the depth downstream of an outlet are enoughly deep ($H/B_0 \to \infty$), equ. 1) is rewrite as follows.

$$D/B_0 = f_2(U_0^2/sgd,\ d/B_0,\ U_0\cdot t/B_0) \qquad \cdots\cdots\cdots(2)$$

Dependeng on the equation of river bed variation which is described in later section, the development of scour are defined by the dimensionless time $\tau=(U_0^2/sgd)^{m-0.5}\cdot U_0\cdot t/B_0$. It is satisfactory to consider the sediment transport as a contact or saltation load. Consequently, in take of the exponent of the bed-load function for sediment transportation with an exponential form $m=3/2$, a variation of the maximum scour depth with time are shown in Fig. 5. A tendency of experimental values change at $\tau=0.5\times10^3$ $(D/B_0=0.5)$ and $\tau=0.7\sim2\times10^4$ $(d/B_0=1\sim2)$, each point are the criteria of an initial and an interium stage of scour.

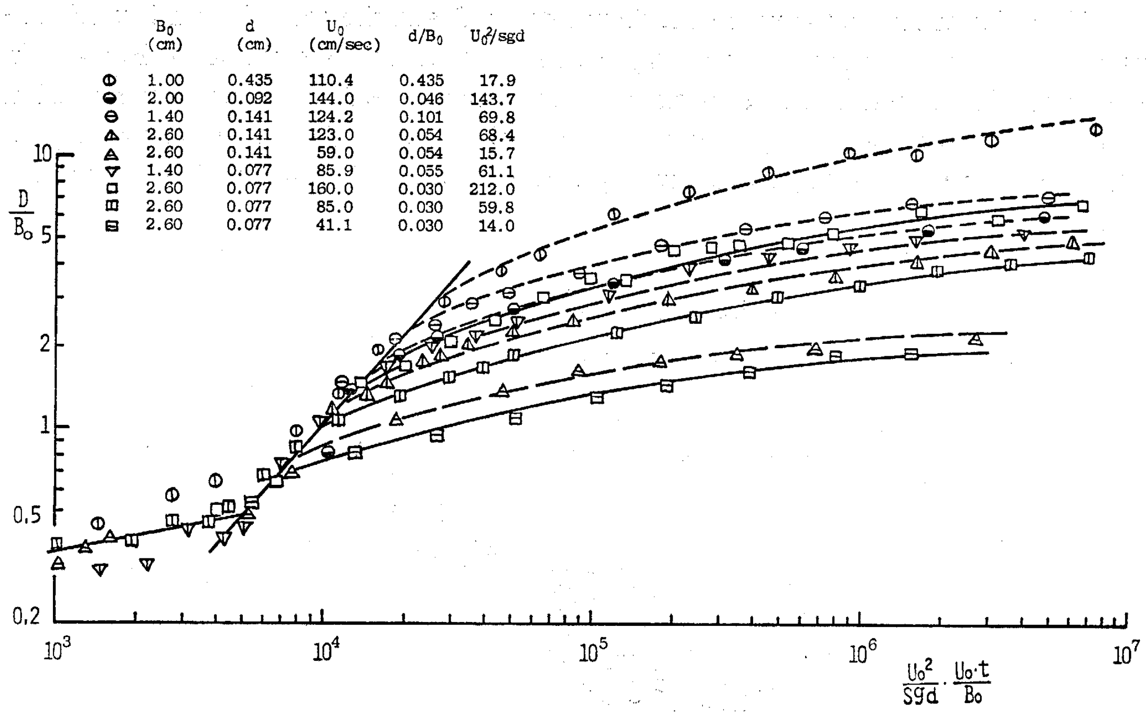


Fig. 5 Variation of the maximum scour depth.

(3) A states of flow in a scour hole

Fig. 6 shows the velocity contour line, which are described $z(cm)-x(cm)$ points along the constant velocity, in a fixed scour hole averaged in the progressive stage. The critical range of a wall-jet owing a curved-jet on a step boundary, whose height is equal to the maximum scour depth, are drawn to compare in this figure.

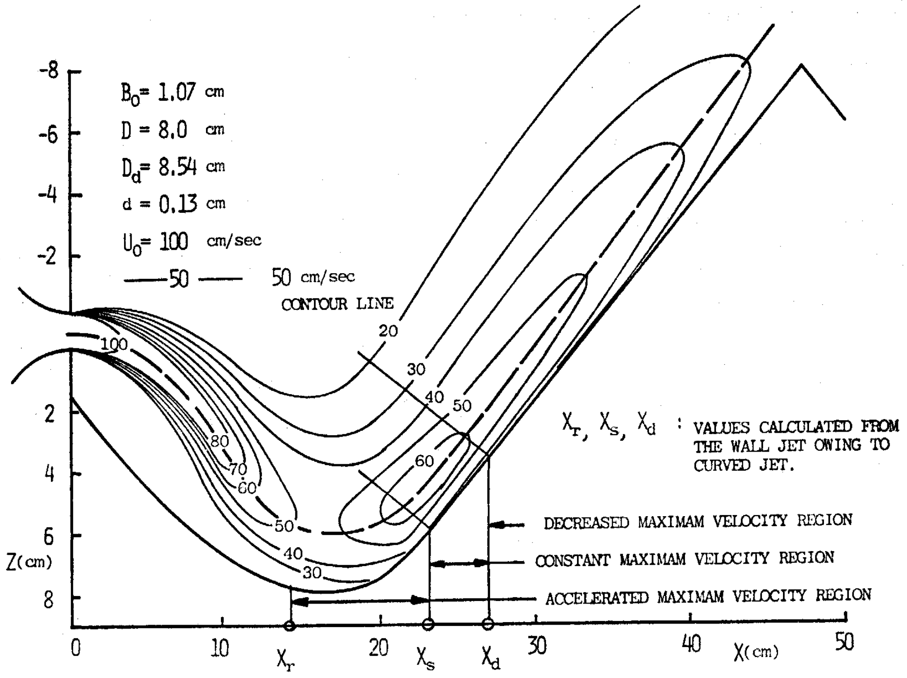


Fig. 6 Velocity contour line in fixed scour hole.

Fig. 7 shows the relationship between U_j/U_0 and D_d/B_0.
Where, U_j; velocity at outside edge of boundary layer in constant velocity region,
U_0; issuing velocity from an outlet,
D_d; height of step boundary from a center of an outlet.

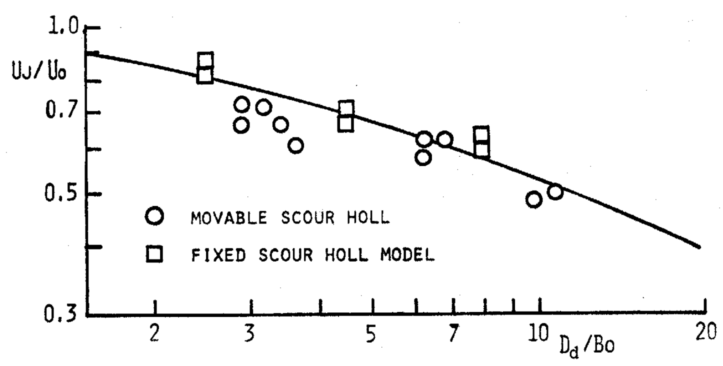


Fig. 7 Relationship between U_j/U_0 and $D_d/_0B$.

The experimental results on a wall-jet owing to a curved jet on a fixed step boundary, which is given a following equation, are shown as a curve in this figure[6].

$$U_j/U_0=\sqrt{3.5/(D_d/B_0+3.0)}, \quad D_d/B_0=D/B_0+0.5 \qquad \cdots\cdots\cdots(3)$$

4. The Equation of Continuity for Scour Based on Non-Equilibrium Sediment Transportation

One's way of thinking that the variation of river bed are caused by the sediment transport in stage of non-equilibrium has been applied to the probrem on the regime criterion for sand wave by the author[7] and the local scour downstream of an outlet by Tsuchiya[3] similtaneausly and independently. The bed load function for sediment transportation, which has been proposed by the two, was derived by making use of Einstein's model[8] with regard to sand removal.

The probability of removal P and the saltation length L of sand grains are decided by the character of sand grain and flows at vicinity of sand grain, accordingly, it can be possible to substitute those in state of equilibrium in stead of those in state of non-equilibrium. Taking the substitution as mentioned above and, introducing the dimensionless expression $\Phi_0 = q_{B_0}/\sqrt{sgd}$ and $\Phi = q_B/\sqrt{sgd}$, the equation of continuity for sediment transport is given in a form as follow.

$$\frac{\partial \Phi}{\partial \xi} = \frac{B_0}{L}(\Phi_0 - \Phi), \quad \xi = x/B_0 \qquad \cdots\cdots\cdots(4)$$

Integration of the equation under the boundary condition that $\Phi = \Phi_1$ at $\xi = 0$, yield

$$\Phi - \Phi_1 = \exp\left(-\int \frac{B_0}{L}\, d\xi\right)\int_0^{\xi} \frac{B_0}{L}\, \Phi_0 \cdot \exp\left(\int \frac{B_0}{L}\, d\xi\right) d\xi \qquad \cdots\cdots\cdots(5)$$

Since the bed load function in state of equilibrium, which is proposed by Einstein[8], has a complicated form, we adopt the following equation which employed the improvements for a slope of river bed Θ.

$$\Phi_0 = K(U_*^2/sgd(\sin(\Theta) + \mu\cos(\Theta))^m(I - U_{*co}^2/U_*^2) \qquad \cdots\cdots\cdots(6)$$

Where μ; coefficient of friction between sand grains,

U_*: shear velocity $\sqrt{\tau_0/\rho}$,

U_{*c0}; critical shear velocity for sand removal.

The equation of continuity for scour can be written as

$$\frac{\partial Z}{\partial t} = \frac{1}{1-\lambda}\frac{\partial q_B}{\partial x} \qquad \cdots\cdots\cdots(7)$$

Substituting Equ. (4) Equ (6) into Equ (7), the variation of river bed based on sediment transport in state of non-equilibrium can be expressed by

$$\frac{\partial \zeta}{\partial \tau} = \frac{K}{1-\lambda}\frac{d}{L}\left\{\Phi_{0*} - \Phi_{1*} - \exp\left(-\int \frac{B_0}{L}\, d\xi\right)\int_0^{\xi} \frac{B_0}{L}\, \Phi_{0*} \exp\left(\int \frac{B_0}{L}\, d\xi\right) d\xi\right\}$$

$$\cdots\cdots\cdots(8)$$

Where, U_m; velocity at outer edge of boundary layer,

$$\tau=(U_0^2/sgd)^{m-0.5}\cdot U_0 t/B_0,$$

$$\zeta=z/B_0,$$

$$\Phi_{0*}=((U_*/U_m)^2(U_m/U_0)^2/(\sin(\Theta)+\nu\cos(\Theta)))^m\cdot$$
$$(1-U_{*co}^2/sgd\cdot(sgd/U_0)^2(U_0/U_m)^2(U_m/U_*))^2$$

$$\Phi_{1*}=(\Phi_{0*})_{\xi=0}$$

Putting $L=\lambda_1 d$ simply, in the case that there is no sediment transport from upstream ($\Phi_1=0$), above equation is rewritten as

$$\frac{\partial\zeta}{\partial\tau}=\frac{K}{\lambda_1(1-\lambda)}\left\{\Phi_{0*}-\frac{\lambda_1 d}{B_0}\exp(-\xi)\int_0^{\xi}\Phi_{0*}\exp(\xi)\,d\xi\right\} \quad \cdots\cdots\cdots(9)$$

From the consideration described above, if we make it clear the distribution of U_m/U_0 and U_*/U_m along the sand surface in scour hole, Φ_{0*} in Equ. (8) and Equ. (9) can be calculated as a function of ξ, and the rate of a variation of a river bed at each times can be obtained by the use of Equ. (8) or Equ. (9), so that, we can momentarily trace the progress of scour.

5. Mechanism of Local Scour

It is the purpose of this section to make up the model for flows and sediment movement in scour hole at each stage of scour, and to consider on the method which analyze the development of scour based on it.

(1) The initial stage of scour

A river bed is not very much change and a jet flow spouted from an outlet flows away straightly along a river bed, then, in this stage, we can consider a flow along a sand surface to be wall jet spouted along a rough surface.

It can be devided a flow of wall jet into a zone of flow establishment in which the maximum velocity is constant and a zone of established flow in which the maximum velocity decrease in proportion to $\sqrt{x}$.

From the reference report 4), the distance X_e from an outlet to the border of the two zones is decided by the development of boundary layer and the diffusion of discontinuous velocity face, and is given in a following equation by the use of Manning-strickler's resistance low.

$$(X_e/B_0)/(1-0.248(X_e/B_0)(d/B_0)^{0.25})=14.44 \qquad \text{for} \quad X\geq X_e \quad \cdots\cdots\cdots(10)$$

and a shear velocity in this region is expressed as

$$(U_*/U_m)^2=0.00785(d/X)^{5/12} \qquad \cdots\cdots\cdots(11)$$

Next, it has been suggested following equations in the reference report 4) (for futher details, the reader should refer to it).

$$U_m/U_0=((X_e+X_0)/(X+X_0))^{1/2},\quad X_0/B_0=4.43 \qquad \cdots\cdots\cdots(12)$$

$$(U_*/U_m)^2=0.5(0.0128+0.103(d/B_0)^{1/2})\cdot$$

$$(X/B_0)^{-(0.237+0.15\exp(-100d/B_0))} \qquad \cdots\cdots\cdots(13)$$

Inserting the character of wall jet (Equ. (11) Equ. (13)) to Φ_{0*} in Equ. (8), and integrating Equ. (8) with respect to τ by giving initial condition, that is $z=0$ at $t=0$, then the configuration of scour hole is obtained as shown by solid curve schematically in Fig. 8. Refer to some experimental results and observations, the configuration of scour is modified as the dotted line in Fig. 8.

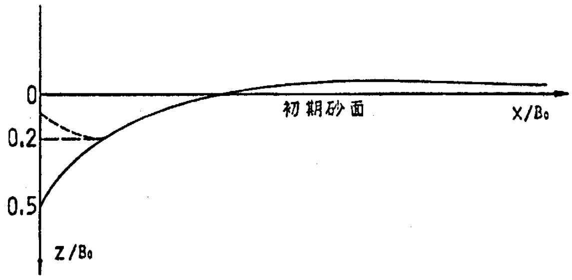


Fig. 8 Explanation figure on the initial stage scour.

(2) The interium and the progressive stage of scour

As descrived at the section 2(3), a flow along sand surface in scour hole at the interium and the progressive stage is approximated by the wall jet which is formed at downstream of reattached point of curved jet on step boundary of which the height is equal to the maximum scour depth.

An outline of wall jet flow, which was originated in a curved jet, are shown in Fig. 9, 10. From the reference report 4) and 5), we explain the quantities required the calculation of scour, which are the border of each range, the velocity at outer edge of boundary layer and etc., briefly in an ordinary manner.

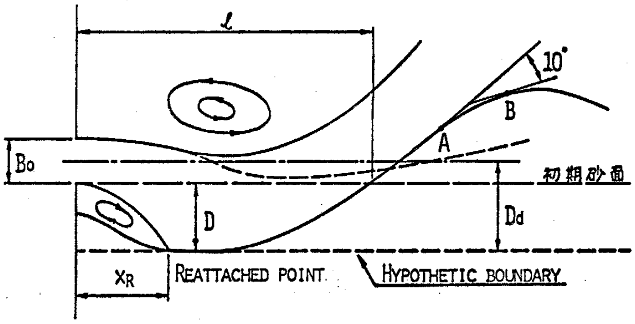


Fig. 9 Schematic figure of flow in scour hole.

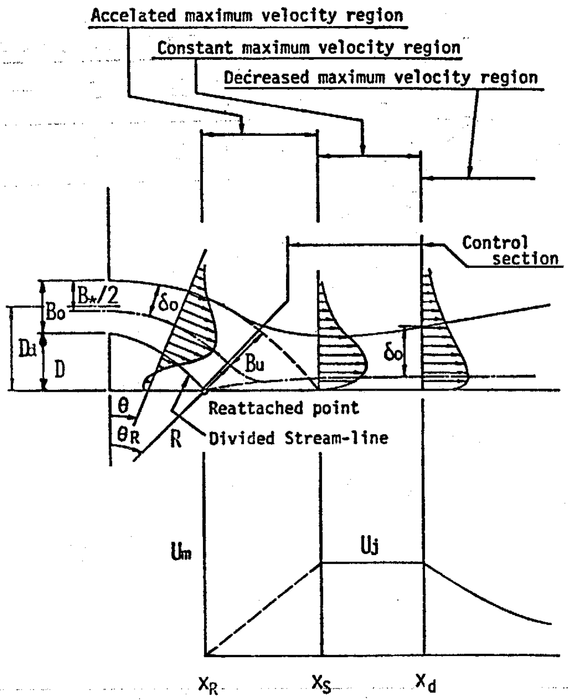


Fig. 10 Schematic diagram of wall jet owing to curved jet issuing parallel to step boundary.

(a) Reattachment point X_r

The position of reattached is decided by the diffusion and the curvature of jet flow and the height of step, although, X_r/B_0 is expressed by D/B_0 finally, the relation of the $X_r/B_0=f(D/B_0)$ is as shown in Fig. 11.

(b) Accelerated velocity region $X_r \leq X \leq X_s$

Since an acceleration of flow at vicinity of wall after reattachment is the result of a contraction of flow owing to a vertical component of flow, we consider that the border of accalerated velocity region have a correspondence to the intersection of line with the angle of reattachment Θ_r from the point of 1/10 maximam velocity and a step boundary surface. The results obtained are shown as broken line Fig. 11, and experimental results are determined from velocity distribution measured in movable and fixed scour hole.

The change of velocity along the outer edge of boundary layer, from in consideration of the condition that $U_m/U_0=0$ at $X=X_r$ and U_m/U_0 reduce to Equ. (3) at $X=X_s$, we assume a straight distribution as follow equation.

$$U_m/U_0=\sqrt{3.5/(D/B_0+3.5)}\cdot(X-X_r)/(X_s-X_r) \qquad \cdots\cdots\cdots(14)$$

(c) Constant velocity region $X_s \leq X \leq X_d$

The border of constant velocity region and decreased velocity region is given in the position at which the velocity in decreased velocity region agree with the velocity of constant velocity region.

$$X_d/B_0=4.4(K_{u1}\cdot K_{u2})^2(D/B_0+3.5)-5.9 \qquad \cdots\cdots\cdots(15)$$

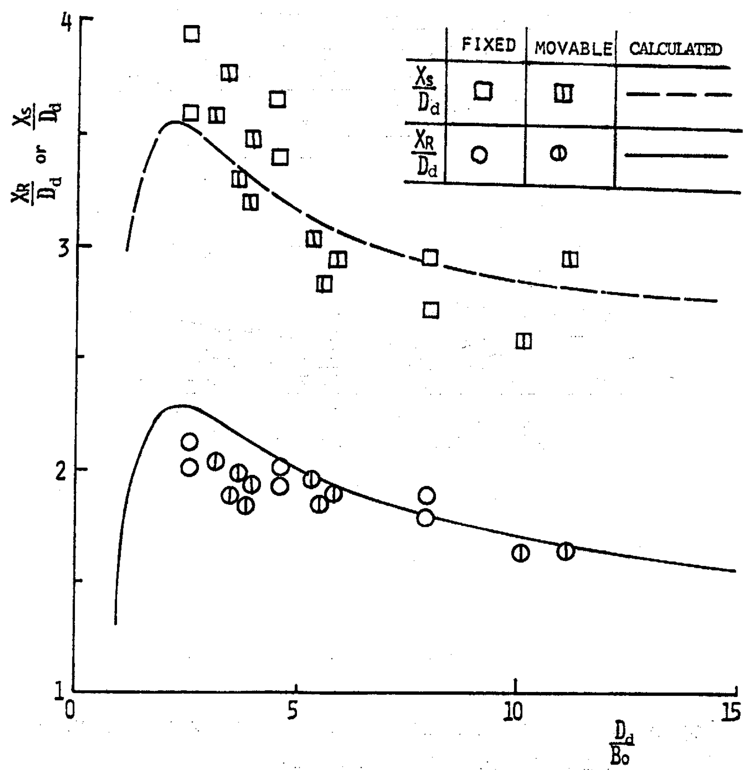


Fig. 11 Relation of D_a/B_0 and X_r/D_a, and D_a/B_0 and X_s/D_a.

(d) Decreased velocity region $X > X_d$

Standardizing a variation of the maximum velocity of wall jet along the horizontal smooth surface,

$$(U_m/U_0)_{h\cdot s} = \sqrt{15.4/(X/B_0+5.9)} \quad \cdots\cdots\cdots(16)$$

from experimental results on a step boundary with a smooth and rough surface, the result of introduction of the coefficient K_{u1} and K_{u2}, which express the effect of the step height D/B_0 and the roughness indication d/B_0, is following equation.

$$U_m/U_0 = K_{u1}\cdot K_{u2}\sqrt{15.4/(X/B_0+5.9)}$$
$$K_{u1} = (2.4/(D/B_0+1.9))^{1/8} \quad \cdots\cdots\cdots(17)$$
$$K_{u2} = (0.176\log(D/B_0)+0.553)^{(d/B_0)^2/4((d/B_0)^2+0.005)}$$

A variation of the maximum velocity measured in fixed scour hole and results calculated from Equ. (15) and Equ. (17) are shown in Fig. 12.

Fig. 13 shows the local friction coefficient of wall jet coused by curved jet. The calculation in this figure is the results which are analyzed in the reference report 6).

In order to simplify the calculation of scour, we make an approximation with a following equation which are given by a broken line in Fig. 13.

$$(U_*/U_m)^2 = 0.5(0.0145+0.103(d/B_0)^{1/2})(X/B_0)^{-(0.237+0.15\exp(-100d/B_0))} \quad \cdots\cdots\cdots(18)$$

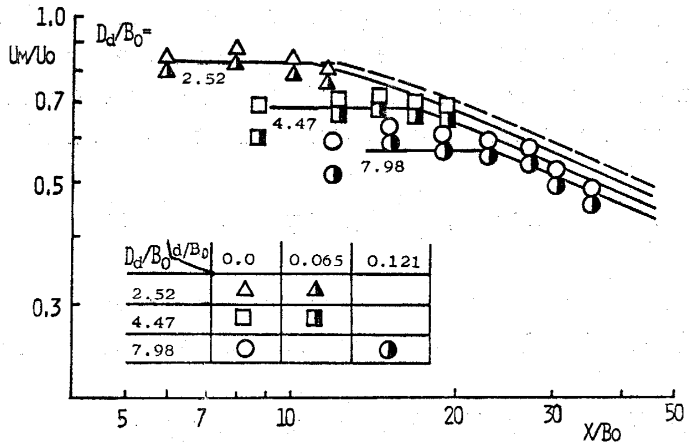


Fig. 12 Variation of velocity at outer edge of boundary layer.

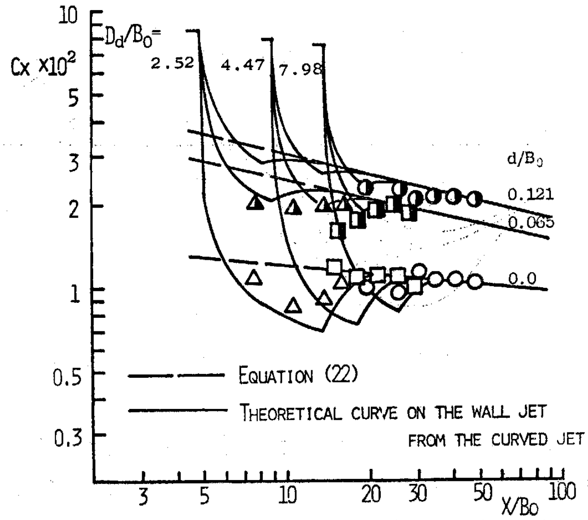


Fig. 13 Local friction coefficient of wall jet owing to curved jet.

(3) The method of calculation of scour in interium and progressive stage

As mentioned before, it was observed that the separation of flow at a slope downside of scour hole in interium stage and intermittent collapse of unstable slope downside in scour hole in progressive stage. We introduced those phenomenon into the calculation of variation of river bed as follow.

INTERIUM STAGE; On account of a fact that sand grains which start to move at downstream of a point, at where flow separate, is confirmed, we assume that the value of Φ_0/L in section between the point where the angle of slope is the largest (point A in Fig. 9, $X=X_a$) and the point where the slope gentle 10° compare to the largest (point B in Fig. 9, $X=X_b$) are as follows,

$$\Phi_0=(\Phi_0/L)_{X=Xa}(X_b-X)/(X_a-X_b) \quad \text{for} \quad X_a \leq X \leq X_b \qquad \cdots\cdots\cdots(19)$$

$$\Phi_0=0 \quad \text{for} \quad X \geq X_b$$

Substituting Φ_0 decided by above equations into the right hand of Equ. (9), and integrating this with respect to ξ, then we can obtained the rate of variation of river bed $\partial\zeta/\partial\tau$ and decided the variation of river be $\Delta\zeta$ in a time $\Delta\tau$ at each locations.

In this case, the rate of deposit at downstream of $\xi_b = X_b/B_0$ is given as follow,

$$\frac{\partial\zeta}{\partial\tau} = -\frac{1-\lambda}{K}\frac{d}{B_0}\exp(-\xi)\int_0^{\xi_B}\Phi_{0*}\exp(\xi)d\xi, \qquad \text{for} \quad \xi > \xi_b \quad \cdots\cdots\cdots(20)$$

This depostition decrease exponentialy as distance increase.

PROGRESSIVE STAGE; The intermittent collapse in this stage introduced as follows.

i) calculate U_m/U_0 and U_*/U_m along scour surface (curve AGH in Fig. 14) by the model of flow described at before section.

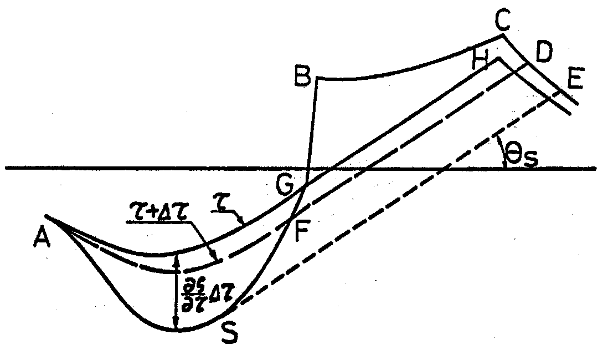


Fig. 14 Explanation figure on the progressive stage scour.

ii) substituting the result of i) into Equ. (9), calculate $\partial\zeta/\partial\tau$ from a reattachment point (point A in Fig. 14) to a section where $\partial\zeta/\partial\tau = 0$ (point G in Fig. 14).

iii) put $\Phi_0/L = 0$ at downstream of the separation point of flow (point G in Fig. 14), calculate deposition by the use of Equ. (10).

iv) the configuration which are shown as curve ASBCDE in Fig. 14 is obtained from the calculation of i) iii). A slope downstream of the point S, where a angle of slope equal to the rest angle of sand in water, is unstable.

v) draw a tangent, which touches the curve ASF at point S, and calculate the volume SBCE.

vi) fill up in proportion to $\partial\zeta/\partial\tau \cdot \Delta\tau$ in section between A and S in Fig. 14, forms a slope with constant angle Θ_s at downstream of the section S, then calculate the volume ASEDF.

vii) obtain the curve which satisfies the relation that the volume SGBCE = the volume ASEDF (or the volume ASF = the volume FBCD) by trial and error.

Finally, the curve AFD, which is obtained by above procedure, is the configuration of scour hole at $\tau + \Delta\tau$.

6. Numerical Considerations

By using the analytical model as described above, the variation of the maximum scour depth with time, the relation of the maximum scour depth and scour length and the configuration of scour hole are investigeted numerically. The average value of the property of sand grains used in experiments are as follow.

$s=1.65$; specific weight of sand grains in water,

$\lambda=0.4$; the value of porosity devide by 100,

$\Theta_s=31°$; rest angle of sand grains in water,

$\mu=1.0$[13]; coefficient of friction between sand grains.

Since a form of sand removal in scour hole is saltation, the exponent of the bed load function for sediment transportation in scour hole in the state of equilibrium $m=3/2$.

In ordinary circumstance, the coefficient, which decide the rate of sediment transportation, $K=4\sim20$[11], the average value of saltation length of sand grains $\lambda=80\sim300$, there is much left to study about those value.

We shall now describe the results on the numerical investigation, under the assumptions that $\lambda_1=100$ used for the study on the regime criterion for sand wave, and $K=30$ in consideration of the effect of main flow to boundary layer flow.

$D/B_0\sim l/B_0$ (Fig. 4); Both calculations and experinents of L/B_0 increases as the value of d/B_0 increases in the initial and interium stage of scour. In the progressive stage, the relation of D/B_0 and l/B_0 is linear with regardless of d/B_0. The physical meaning of this phenomenon is considered as follows. The configuration of scour hole in initial and interium stage are decided by relative rate of sediment transportation depended on the location, another, in progressive stage, a slope in downside of scour hole are maintained constant by the intermittent collapse.

Futhermore, U_0/sgd have nothing to do with this relation for this reason.

CONFIGURATION OF SCOUR HOLE IN PROGRESSIVE STAGE (Fig. 15);

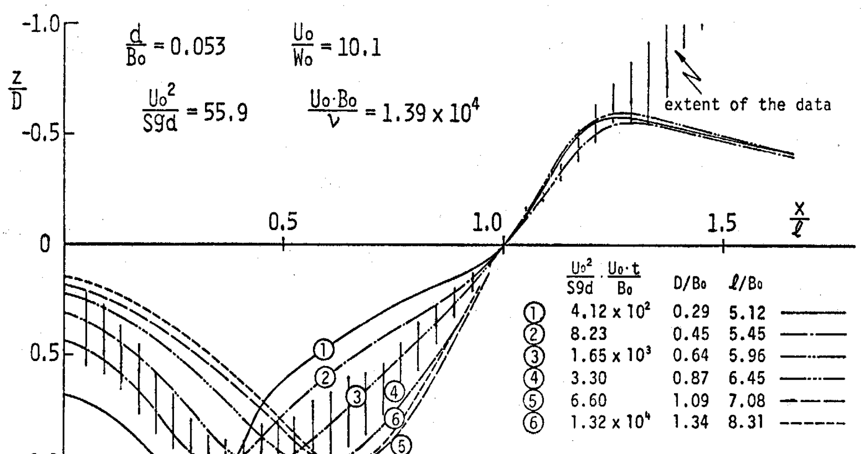


Fig. 15(a) Configuration of scour hole in interium stage.

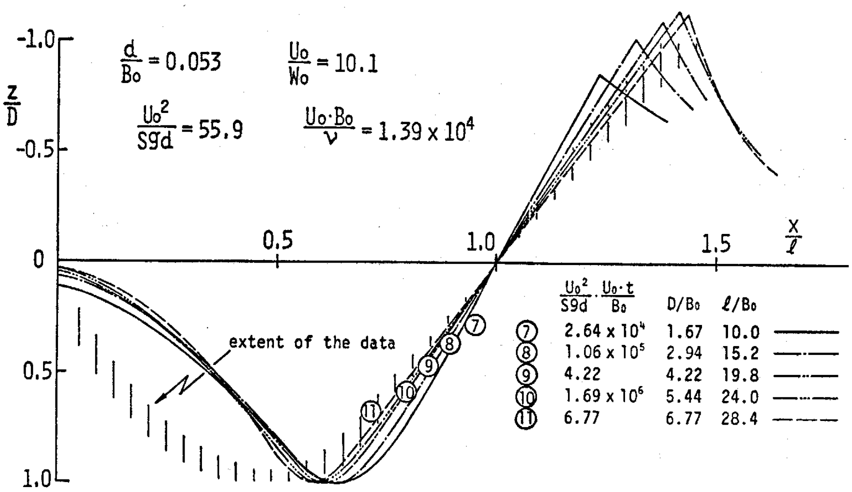
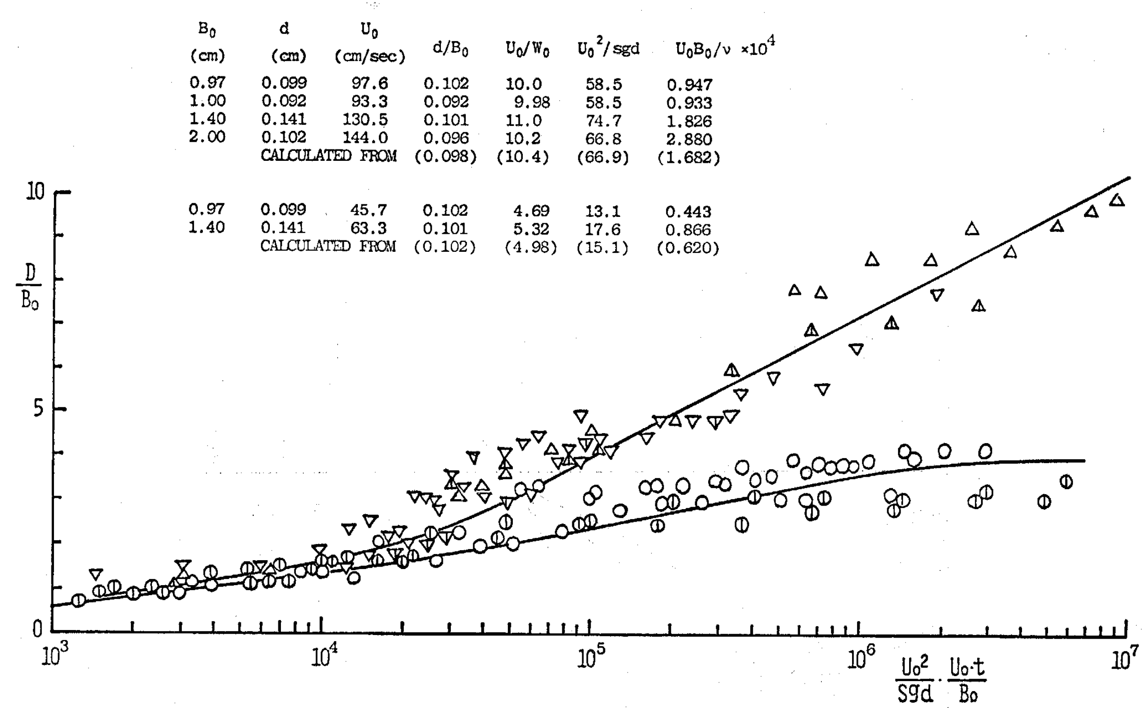


Fig. 15(b) Configuration of scour hole in progressive stage.

we take into no consideration of the scour taked rise by roller formed on scour surface downstream of an outlet, then, as compared with experimental results, the calculated depth of scour at a extent from an outlet to the maximum scour depth is fairly small.

But, the agreement of the two on the configuration downside of scour hole is fairly good. Accordingly, it became clear that the intermitted collapse, which is caused by shake of issuing flow, is closely related to the configuration of scour hole.

CHANGE OF THE MAXIMUM SCOUR DEPTH WITH TIME (Fig. 16); the maximum scour depth D/B_0 is described by the dimensionless time $\tau = U_0^2/sgd \cdot U_0t/B_0$ through the parameter d/B_0 and U_0^2/sgd. The agreement of experiments and



B_0 (cm)	d (cm)	U_0 (cm/sec)	d/B_0	U_0/W_0	U_0^2/sgd	U_0B_0/ν ×10⁴
0.97	0.099	97.6	0.102	10.0	58.5	0.947
1.00	0.092	93.3	0.092	9.98	58.5	0.933
1.40	0.141	130.5	0.101	11.0	74.7	1.826
2.00	0.102	144.0	0.096	10.2	66.8	2.880
	CALCULATED FROM		(0.098)	(10.4)	(66.9)	(1.682)
0.97	0.099	45.7	0.102	4.69	13.1	0.443
1.40	0.141	63.3	0.101	5.32	17.6	0.866
	CALCULATED FROM		(0.102)	(4.98)	(15.1)	(0.620)

Fig. 16(a) Change of the maximum scour depth with time ($d/B_0=0.1$).

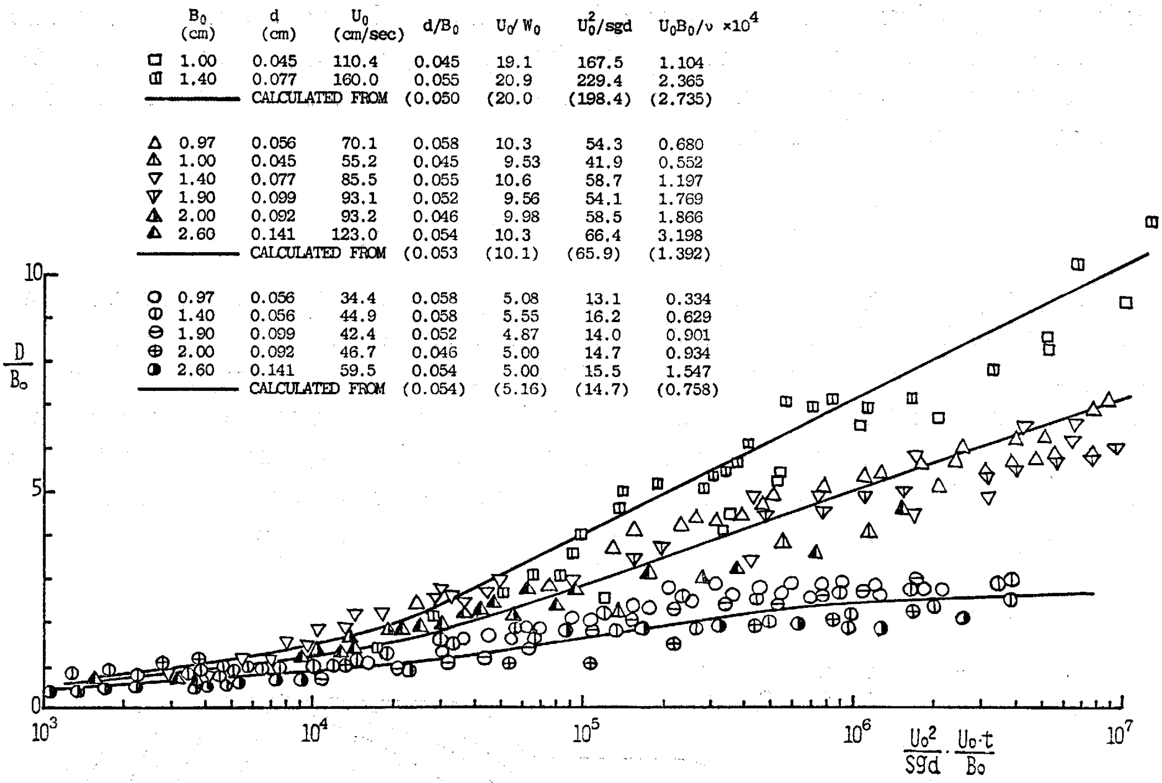


Fig. 16(b) Change of the maximum scour depth with time ($d/B_0=0.05$).

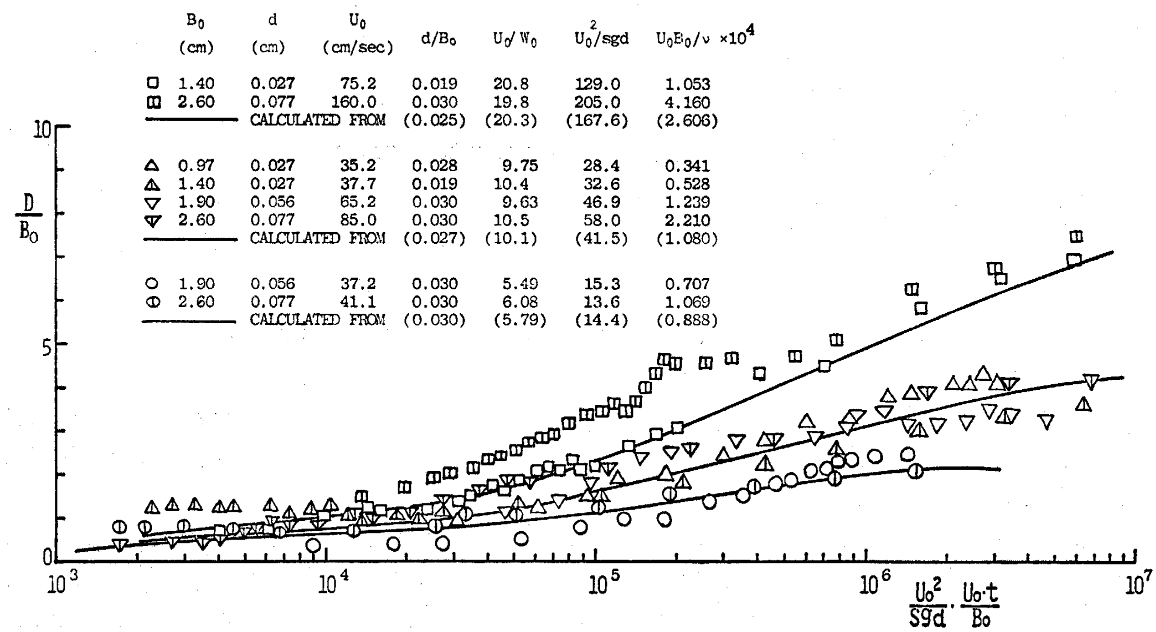


Fig. 16(c) Change of the maxmum scour depth with time ($d/B_0=0.03$).

calculations are fairly good.

The rate of sediment transport increase as the value of U_0^2/sgd increase, then, it can be estimated that D/B_0 increase as U_0^2/sgd increase. So that an increase in U_*/U_m

is larger than a decrease in U_m/U_0 as d/B_0 increase. D/B_0 increase as d/B_0 increase.

As mentioned above, experimental results can be explained well by the calculated results. It became clear that a bend of issuing flow in direction of scour hole plays an important role to the development of scour.

7. Experiments on the Intermittent Scour

In practical case, there are not little instance of shallow depth downstream of an outlet, and under such circumstance we fined the phenomenon that the direction of issuing flows turn from downward (reattachment flow) to upward (separated flow) in the development of scour. The auther called this phenomenon as intermittent scour.

Fig. 17 shows the configuration of scour hole. In this figure, the dotted line shows the configuration on the case that issuing flows are in state of reattachment flow, and the solid lines show the configuration in state of separated flows.

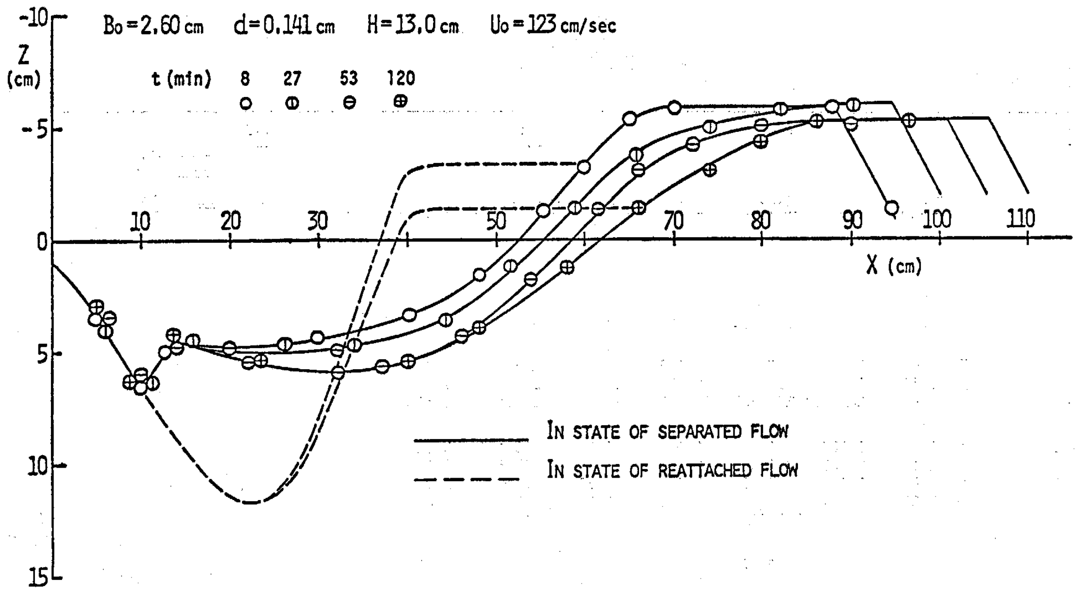


Fig. 17 Configuration of scour hole in the intermittent scour.

Fig. 18 shows the variation of the maximum scour depth with time. The rate of variation of the maximum scour depth decrease apparently in according with the occurrence of intermittent scour.

Fig. 19 shows the effect of intermittent scour on the maximum scour depth. The criterion for occurrence of intermittent scour are shown as the straight line in this figure. In the region of left side of this straight line, intermittent scour occur and the maximum scour depth D/B_0 decrease on comparing the case that the depth downstream of an outlet deep enoughly.

It is possible to decrease a scour depth by the use of this phenomenon in practical case.

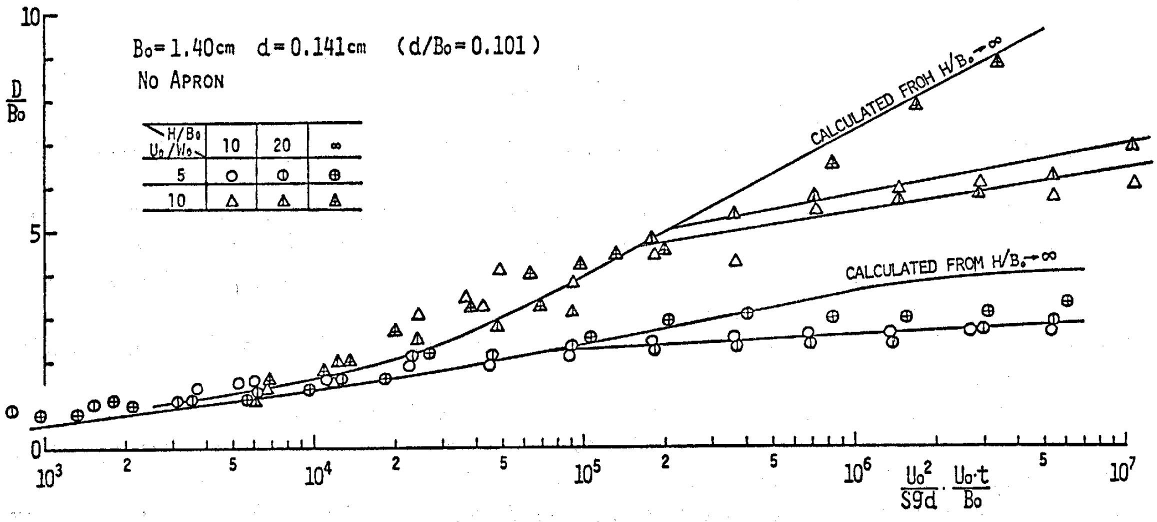


Fig. 18 Variation of the maximum scour depth in the intermittent scour.

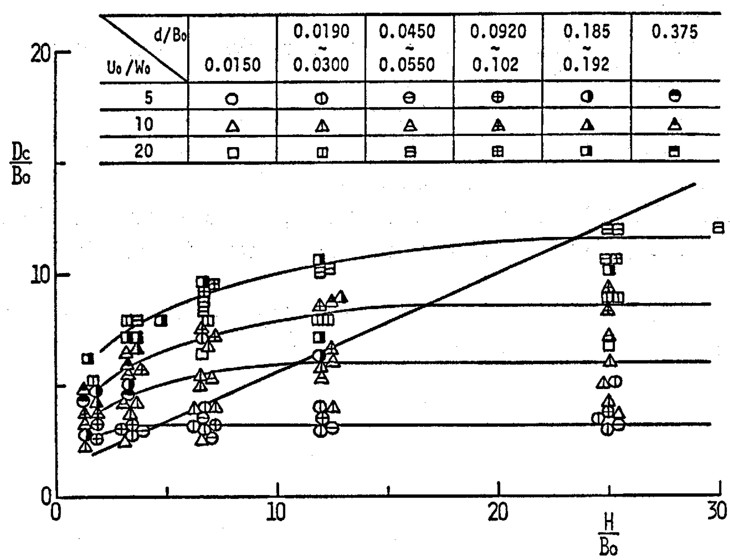


Fig. 19 Effect of intermittent scour phenomenon on the maximum scour depth.

9. Conclusion

The analysis on the development of scour mentioned above, involve comparatively rough assumptions on the effect of separation of flows on the sediment transportation and so, however, the theoretical results agree well with experimental results on the variation of the maximum scour depth, the configuration of scour hole and so on. It become clear that the bend of issuing flow in direction of scour hole after interium stage and the intermittent collapse at unstable slope of downside of scour hole play an important role to the development of scour. We hope the general idea on the mechanism of scour from plane submerged jet is evident.

Reference

1) Laursen E. M. "Observation of the nature of scour", Proc. 5th hyd. Conf., State Univ. Iowa, (1952)
2) Iwagaki Y., Tsuchiya Y. & Imamura M. "Studies on the local scour from flows downstream of an outlet", Disasater prevention research inst. annuals, Kyoto Univ., No. 8, 1965
3) Tsuchiya Y. & Iwagaki Y. "On the mechanism on the local scour from flows downstream of an outlet", Proc. 12th Congress of I.A.H.R., **3** (1967)
4) Saitou T. "The charactor of plane submerged jet inffluenced by boundary", Proc. J.S.C.E., No. 164 (1969)
5) Saitou T. "Stidies on the plane turbulent wall jet", Proc, J.S.C.E., No. 264 (1977)
6) Saitou T, Akashi N. & Kameda Y. "The wall jet owing to plane jet imping and reattachment", Memoires of the faculty of eng. Yamaguchi Univ., **28** [1], (1977)
7) Tsubaki T. & Saitou T. "Regime criteria for sand waves in erodible channel", Tech. Reports of Kyushu Univ., **40** [5], (1967)
8) Einstein H. A., "The bed load function for sediment transportation in open channel flows", United States Department of Agriculture coil Conservation service, Washinton, D. C., Tech. Bulletin No. 1026 (1950)
9) Tsubaki T. & Saitou T. "On the scour of a spur dike", Memoirs of the faculty of eng., Yamaguchi Univ., **13** [1], (1963)
10) Shinohara K. & Tsubaki T.; "A consideration on the mechanism of sand saltation", Bulletin of research institude for applied mechanics, Kyushu Univ., No. 10 (1957)
11) Hydrodynamic formal procesion; Japan society of civil eng. (1971)
12) Yano K., Tsuchiya Y. & Michiue M. "On the stochastic characteristic of transport mechanisn of sand in a stream", Disaster prevention reaseach institude annuals, Kyoto Univ., No 11 B, (1968)
13) Tsuchiya Y. "Studies on the critical tractive force of graded sand gravels", Disaster prevention research institude annual, Kyoto Univ., No. 6 (1963)