

Sediment re-suspension by turbulent jet in an intake pond

Remise en suspension de sédiments par un jet turbulent dans une prise d'eau

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ABSTRACT

Modern thermal or nuclear plants need cooling water from river or sea. Therefore an intake pond for the water delivery system is a requisite component where sediment frequently deposits. An impinging jet is a functional measure for sediment re-suspension and a precaution against sediment deposition. This paper predicts the consequences of this new measure using theoretical analysis and laboratory experiments. The jet diffusion discharged into an ambient flow field, and the jet velocity at bottom, are predicted by the governing equations using an integral method. Equilibrium scour is obtained after the process of scour asymptotically finished for a limited depth sand layer. The non-dimensional equation derived can predict well the particle re-suspension. Critical jet condition is obtained for the sediment re-suspension by experiments. The effect of the jet angle and jet height on sediment re-suspension is also included and discussed. The results obtained for the scour to a limited sand bed by an impinging jet through cross flow is especially significant to the engineering design of intake ponds and culverts etc.

Key words: Jet in Cross Flow; Jet Diffusion; Scour Hole; Sediment Re-suspension

RESUME

Les centrales modernes, thermiques ou nucléaires, requièrent de l'eau de refroidissement des rivières ou de l'océan. Pour cela, un réservoir de prise pour le système de distribution d'eau est un élément indispensable mais dans lequel les sédiments se déposent généralement. L'introduction d'un jet plongeant dans le réservoir est une mesure pratique pour la remise en suspension des sédiments, prévenant ainsi le dépôt de ceux-ci. Cet article prédit les conséquences de cette nouvelle disposition à l'aide d'une analyse théorique et d'essais en laboratoire. La diffusion du jet plongeant au sein d'un champ d'écoulement environnant et la vitesse du jet contre le radier peuvent être prédites à partir des équations adéquates en utilisant une méthode de résolution intégrale. L'érosion à l'équilibre se calcule comme l'asymptote du processus d'érosion d'une couche finie de sable. L'équation adimensionnelle correspondante peut prédire convenablement la remise en suspension. Les conditions critiques du jet pour la remise en suspension sont données par les expériences. Les effets de l'angle d'attaque et de la hauteur du jet sur cette remise en suspension sont également discutés. Les résultats obtenus sur l'érosion d'une couche limitée de lit sableux sous l'effet d'un jet plongeant à travers un écoulement sont spécialement significatifs pour la conception de réservoirs de prise d'eau et de pertuis.

Introduction

Sediment deposition usually produces unfavorable consequences. In the water delivery and utility system, for example, a quantity of sediment falling down in a local region leads to volume reduction of the water container. The intake pond is a requisite component of thermal or nuclear power plant. In the intake pond, where the flow section is suddenly expanded, sediment frequently deposits due to the reduction of the flow kinetic energy. With water continuously coming in and sediment constantly depositing, the siltation is thickened and, consequently, the pump intake becomes blocked up, which leads to pump failure. In consideration of this case, Chen et al. (1997) achieved a significant new measure by conducting a laboratory experiment; normal impinging jet was employed in a power plant in China to prevent the sediment at the bottom of the intake pond from depositing. However, a little attention has been paid to the mechanism of this practical case. Research into the mechanics of the turbulent jet impact on sediment re-suspension is essential to the increasingly application of this measure to the engineering.

In the past 50 years or more, laboratory measurements of scour depth under various flow conditions and structure configurations have been conducted. From the early 1930's, Rouse (1939) pioneered research work in this field. Since then, many more other scholars have contributed their studies to the scour by jets. Laursen (1952), Tarapore (1956), LeFeuvre (1965), Altin-

bilek(1973) reported their studies on erosion by two-dimensional submerged jets. Some of the significant contributions on the erosion by submerged circular impinging turbulent jets include Doddiah et al. (1953), Poreh and Hefez (1967), Rajaratnam (1977, 1981), Bormann and Julien (1991), Chiew and Parker (1994), Aderibigbe and Rajaratnam (1996). All of these researches were in accordance with the sufficient bed material and pure jet without cross flow. Uniquely, this paper accounts for the cross flow effect on jet stream and pays more attention to the erosion effect of jet impinging on a limited depth of the sediment bed. The study case of this paper is significant to the engineering design of sediment dredging in the intake pond and any other water delivery system where insufficient bottom sediment exists.

A jet expands in the cross flow with turbulent entrainment. An important parameter is the ratio of the jet velocity to the cross flow velocity. In the intake pond or other similar water utility system, sediment deposits on the bottom due to the rate of the flow energy decay. Sediment dredging by jets has been a useful measure in this field. The fixed bottom will be exposed if a relatively strong jet is issued. The phenomenon of the scour by jet in this case differs from the case of a sufficient sediment depth at the bottom. In this study the cross flow effect on the jet motion, such as on jet trajectory and jet width growth, is predicted by mathematical calculation. A flume investigation is used to validate the sediment re-suspension equation derived

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theoretically based on the Shields criterion. The effect of the jet angle and the jet height on the volume of re-suspended sediment has also been studied experimentally. It is significant in obtaining an optimum engineering design.

Theoretical considerations

Jet Trajectory and Diffusion

In order to predict the impact of the jet on sediment local re-suspension in cross flow, one must first predict the characteristics of this flow phenomenon. There are many papers on jets in cross flow, which are concerned with environmental problems. Among them an interesting one was written by Hirst (1971) who studied the characteristics of round, turbulent and buoyant jets discharging to flowing stratified ambient fluid in a "natural" coordinate system. One of the authors had studied the sediment-laden jet in cross flow (Fujisaki et al., 1995, 1996). As an extreme case of the work, the present paper now predicts the trajectory of neutrally buoyant jet with free of sediment, in cross flow using this mathematical model in a natural coordinate system.

Consider the jet impinging structure sketched in Fig. 1. As the jet flow downstream from the nozzle enters the cross flow, it forms a neutrally buoyant jet with an initial issuing velocity V_j and an initial nozzle diameter D_j . The jet stream diffuses along its trajectory in the s streamwise direction. As the jet stream section gradually expands, the velocity reduces due to the effect of the turbulent mixing and entrainment. The problem considered here involves the dynamics of a neutrally buoyant jet discharged from a round diffuser. The jet density is assumed to be the same as that of the cross flow. It is assumed also that the flow is steady and fully turbulent and the fluid properties are constant. The motion of the jet is determined by the initial conditions at the diffuser exit and the cross flow conditions, such as exit velocity, outlet orientation, diffuser diameter, as well as the ambient velocity. The basic equations of this case are (1) conservation of mass and (2) conservation of momentum. These equations, written in natural coordinate system, are:

$$\frac{\partial u}{\partial s} + \frac{1}{r} \frac{\partial}{\partial r}(rv) = 0 \quad (1)$$

$$\left(u \frac{\partial u}{\partial s} + v \frac{\partial u}{\partial r}\right) \cos \theta = -\frac{1}{r} \frac{\partial}{\partial r}(ru'v') \cos \theta - \frac{q^* \sin \theta}{R} \quad (2)$$

$$\left(u \frac{\partial u}{\partial s} + v \frac{\partial u}{\partial r}\right) \sin \theta = \frac{q^* \cos \theta}{R} - \frac{1}{r} \frac{\partial}{\partial r}(ru'v') \sin \theta \quad (3)$$

where,

$$q^* = u^2 - \frac{r}{4} \left(\frac{\partial v^2}{\partial r} + \frac{\partial v'^2}{\partial r} \right) \quad (4)$$

and

$$R = -\frac{ds}{d\theta} \quad (5)$$

The meanings of other symbols are shown in Fig. 1.

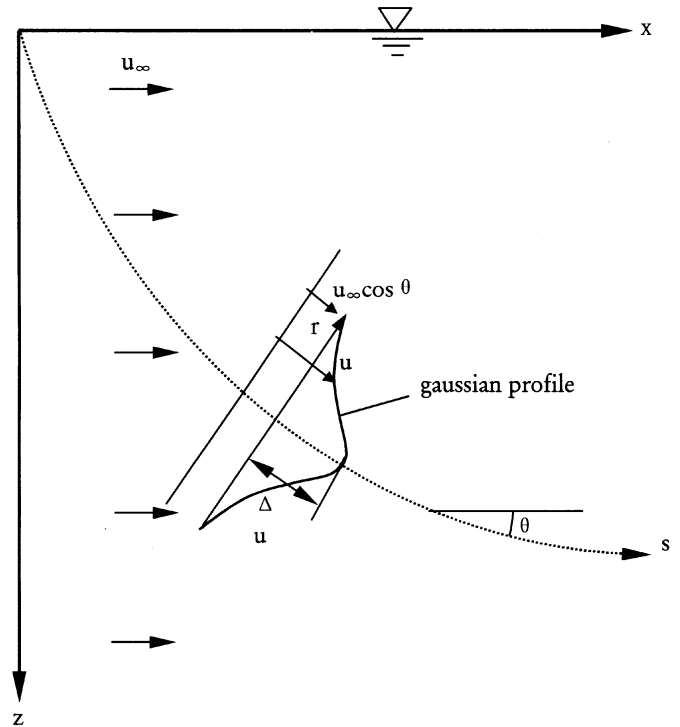


Fig. 1. Definition sketch for jet motion in cross-flow.

These equations are still not easy to solve. To simplify the problem, integration of these equations over the jet cross section is performed. It is assumed that the profiles of the velocity in the s -axis are axially symmetric and similar, that is, the shape of the profile is invariant with s , the streamwise coordinate. Gaussian velocity profiles are used, which can be written as (6)

$$u = \Delta u_m \exp\{- (r/b)^2\} + u_\infty \cos \theta \quad (6)$$

Herein b is spreading width of jet flow velocity, Δu_m , the maximum velocity of the jet and u_∞ , the uniform cross flow velocity. Referring to the turbulence in the flow field, the concept of entrainment is applied. Using these assumptions and integrating equations (1) to (5) yields the following system of ordinary differential equations:

$$\frac{1}{2} b^2 \frac{d\Delta u_m}{ds} + v^* b \frac{db}{ds} - b^2 u_\infty \sin \theta \frac{d\theta}{ds} = E \quad (7)$$

$$\frac{1}{2} v^* b^2 \frac{d\Delta u_m}{ds} + \frac{v^{*2} b db}{2 ds} - v^* u_\infty b^2 \sin \theta \frac{d\theta}{ds} = E u_\infty \cos \theta \quad (8)$$

$$\frac{d\theta}{ds} = \frac{(u_\infty \sin \theta)^2 C_d \frac{b}{\sqrt{2\pi}} - E u_\infty \sin \theta}{\frac{1}{4} (b^2 v^{*2} - E^2)} \quad (9)$$

$$\tau_c = \rho u_c^2 = C\rho \frac{u_c^2}{2} \quad (18)$$

where C is friction factor, u_c is the critical flow velocity for incipient motion and ρ is the fluid density. Aderibigbe and Rajaratnam (1996) simplified the expression of the critical shear velocity u_{*cs} for the particle incipient motion based on Shields curve:

$$u_{*cs} = C_c \sqrt{g \frac{\Delta\rho}{\rho} D_{50}} \quad (19)$$

where C_c is an another coefficient, g is the gravitational acceleration and $\Delta\rho$ is the difference between the particle density and the fluid density. Chiew and Parker(1994) proposed the following equation to account for the effect of bed slope on the Shields critical shear velocity as:

$$\frac{u_{*c}}{u_{*cs}} = \sqrt{\cos\phi \left(1 - \frac{\tan\phi}{\tan\beta}\right)} = K \quad (20)$$

herein ϕ is the bed slope and β is the repose angle of the particle submerged in water and K is a constant.

Under equilibrium scour conditions, the maximum scour length L_j is obtained when u_b is equal to u_c , x_1 is equal to $L_j/2$. Combining equation (17), (18), (19) and (20) the following formula can be obtained:

$$\frac{L_j}{2H_j} = C_s \frac{u_{bj}}{\sqrt{g \frac{\Delta\rho}{\rho} D_{50}}} \quad (21)$$

where C_s is a synthetic coefficient.

Discussion

Numerical Solutions of Jet Movement

Assuming an entrainment coefficient $E_0 = 0.05$, the jet trajectory can be obtained by solving equations (7) to (10). Fig. 3 shows the variation of the jet trajectory with different initial jet velocity. In that figure the ratio of jet exit velocity to cross flow velocity V_j/u_∞ denotes the non-dimensional jet intensity. The jet trajectory for $V_j/u_\infty = 25, 50, 100$ and 200 are plotted in the Figure 3 in non-dimensional coordinate axis z/D_j versus x/D_j . The decay of the jet central line velocity can be seen from Fig. 4. An expected reasonable trend is provided in varying ratio of jet exit velocity to cross flow velocity. As described above, from the calculation result Δu_m in Fig. 4, one can estimate the mean jet velocity near the bed u_{bj} by equation (14). The development of jet width b is mainly dominated by the jet turbulent entrainment. The deviation of b in the far field is distinct for different jet velocities, which is shown in Fig. 5.

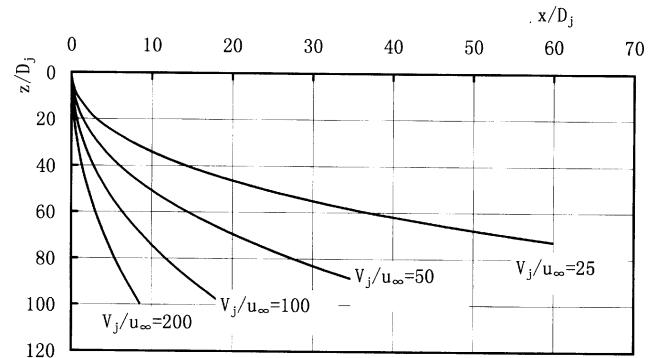


Fig. 3. The variation of jet trajectory.

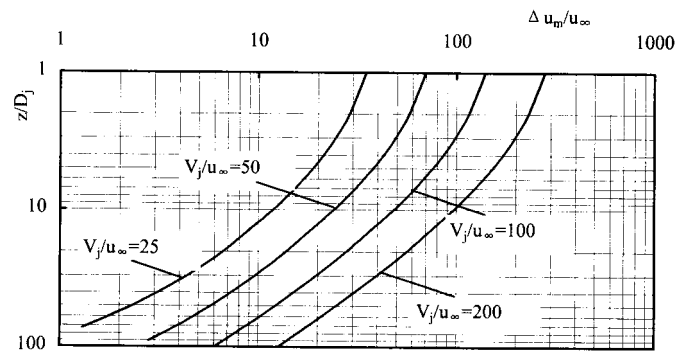


Fig. 4. The decay of jet velocity.

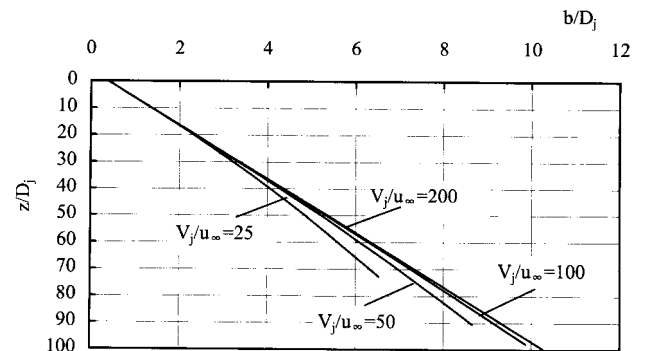


Fig. 5. The variation of jet width

For non-dimensional expression of jet characteristics, a more simplified treatment is possible using the idea of virtual origin, for example, taking momentum length as a length scale. In this paper, however, the finite jet nozzle diameter D_j is taken as a length scale for practical application.

Experimental Investigations

The purpose of the experiments is to decide the coefficient C_s in equation (21) and to obtain an experimental equation estimating the particle re-suspension quantity for practical application. Using dimensional analysis, the relationship between the sediment re-suspension volume \bar{V} and the ratio of jet flow dynamic force to particle friction force can be obtained. In addition, the optimum jet angle and height are also studied by experiment.

The particle re-suspension induced by the same jet in quiescent water is also included herein to extend the application scope. The experiment apparatus is sketched in Fig. 6. The relative density of the particles adopted in the experiment is $\gamma_s = 2.56$. Two kinds of particle with different diameter of $D_{50} \approx 0.5\text{mm}$ and 0.7mm are employed respectively. A round jet nozzle with internal diameter of 2mm is mounted in a fixed frame. The sand layer is 2.5cm thick to simulate the limited deposition on the bed. The experimental flume is 22cm wide, 30cm high and 150cm long. A right triangle weir installed in the flume tail measures the discharge of the cross flow.

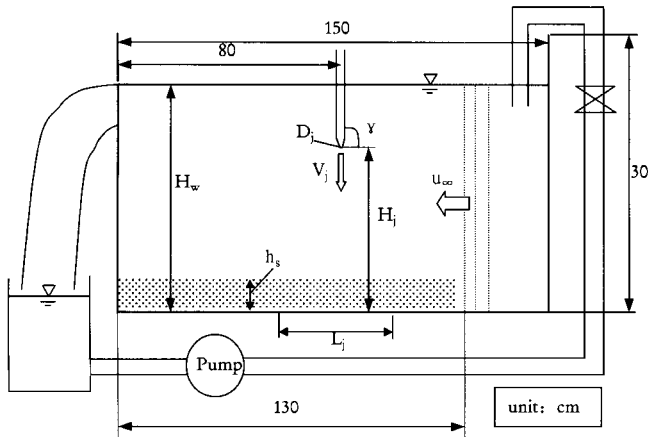


Fig. 6. Experimental setup.

The experimental data set contains 40 tests, which are summarized in Table 1. In addition, Table 1 contains the case of the impinging jet in quiescent water. For each case the cross flow velocity is controlled to keep the hydrodynamic condition under the sediment movement condition.

Table 1. Range of Experiments

Test Number (1)	Angle of impingement (ϕ) (2)	Jet height H_j (cm) (3)	Jet velocity V_j (m/s) (4)	Water depth H_w (cm) (5)	Cross flow velocity u_w (cm/s) (6)	Sand thickness h_s (cm) (7)	Particle diameter D_{50} (mm) (8)	Scour Length L_j (cm) (9)
1	46	12.5	2.37	19.0	0.0	2.5	0.7	7.14
2	46	12.5	3.10	19.0	0.0	2.5	0.7	5.06
3	72	12.5	2.37	19.0	0.0	2.5	0.7	8.80
4	55	12.5	3.03	19.0	0.0	2.5	0.7	10.20
5	90	12.5	3.14	19.0	0.0	2.5	0.7	12.60
6	67	12.5	3.10	19.0	0.0	2.5	0.7	14.20
7	78	12.5	3.12	19.0	0.0	2.5	0.7	13.90
8	90	15.8	4.22	22.3	8.7	2.5	0.7	18.80
9	90	20.0	5.62	21.4	0.3	2.5	0.5	21.00
10	46	12.5	5.31	19.0	0.0	2.5	0.7	18.00
11	67	12.0	4.22	19.0	0.0	2.5	0.7	19.80
12	70	18.0	6.37	22.3	0.6	2.5	0.5	24.40
13	58	12.5	5.31	19.0	0.0	2.5	0.7	22.00
14	45	17.0	10.32	19.0	0.0	2.5	0.5	26.80
15	90	17.0	9.65	22.6	0.6	2.5	0.5	31.00
16	90	17.5	10.42	21.0	0.2	2.5	0.5	36.00
17	90	12.5	2.37	19.0	0.0	2.5	0.7	12.30
18	60	12.5	2.37	19.0	0.0	2.5	0.7	7.82
19	90	12.5	3.12	19.0	0.0	2.5	0.7	12.80
20	90	12.5	4.26	19.0	0.0	2.5	0.7	19.50
21	81	12.5	4.26	19.0	0.0	2.5	0.7	19.10
22	47	12.5	4.22	19.0	0.0	2.5	0.7	18.40
23	90	14.6	4.22	21.1	3.3	2.5	0.7	25.40
24	90	17.2	4.22	23.7	13.5	2.5	0.7	18.20
25	46	17.5	10.50	21.2	2.6	2.5	0.5	27.20
26	70	17.8	10.55	21.3	0.3	2.5	0.5	29.80
27	90	18.0	5.40	22.1	0.6	2.5	0.5	22.70
28	75	12.5	5.31	19.0	0.0	2.5	0.7	22.50
29	90	12.5	5.31	19.0	0.0	2.5	0.7	22.60
30	90	12.5	2.38	19.0	0.0	2.5	0.7	13.60
31	90	18.0	2.38	19.0	0.0	2.5	0.7	7.60
32	90	12.5	2.38	19.0	0.0	1.3	0.7	13.10
33	90	12.5	2.38	19.0	0.0	0.5	0.7	13.30
34	90	10.0	2.38	19.0	0.0	2.5	0.7	12.00
35	90	6.0	2.38	19.0	0.0	2.5	0.7	12.80
36	90	3.0	2.38	19.0	0.0	2.5	0.7	10.60
37	90	12.5	0.11	19.0	0.0	2.5	0.5	0.00
38	90	12.5	0.18	19.0	0.0	2.5	0.5	0.00
39	90	12.5	0.24	19.0	0.0	3.0	0.5	2.0
40	90	12.5	1.68	19.0	0.8	3.0	0.5	6.40

That is to say, without the jet issuing, the sediment does not move. The experimental data show a weak effect of the cross flow on the particle re-suspension. Because of the large ratio of the jet velocity to cross flow in the experiment, the jet momentum is dominant for the particle re-suspension. The cross flow dynamics plays twofold roles: (1) transporting the particles suspended due to the jet impinging to a far distance and (2) changing the jet stream angle and therefore, the impingement position. Considering the practical application in engineering, some experiments for different jet exit angles, γ , are conducted. A special attention is paid, by the way, to the jet height effect on the scour in experiments of No. 33 to No. 36. Experiments of No. 37 to No. 40 are provided with lower jet velocities, which are used specially to explore the critical condition of the sediment re-suspension. Figs. 7-1 to 7-4 show the shape of the equilibrium scour hole at four kinds of jet velocity conditions. For each jet velocity four different jet angles are set. It is obvious that for the jet velocity equals to 2.37m/s and 3.1m/s , the scoured volume varies as the jet angle. When the jet velocity equals to 4.22m/s and 5.31m/s the effect of the jet angle on the scour hole volume is not obvious. It is found in the process of the experiment that the center point of the scour hole moves downstream with the jet angle γ enlarges. The maximum side slope of the hole α is approximately to 33° .

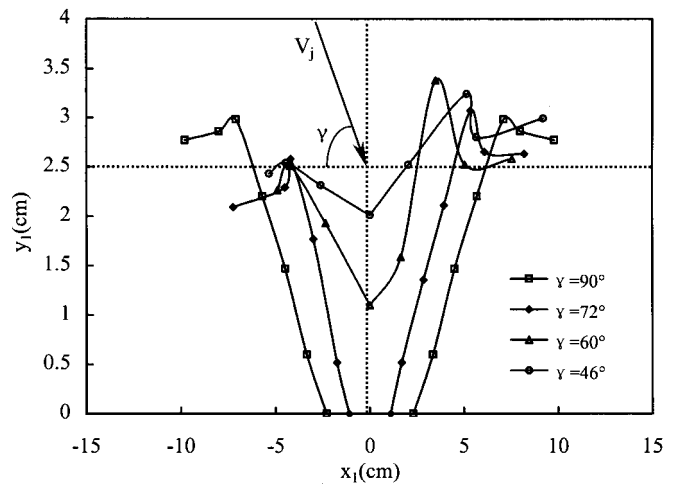


Fig. 7. 1) Variation of the scour shape with jet angle ($V_j = 237\text{ cm/s}$).

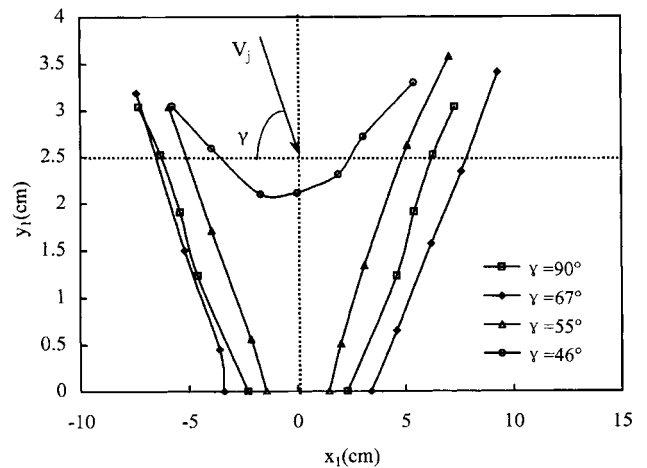


Fig. 7. 2) Variation of the scour shape with jet angle ($V_j = 310\text{ cm/s}$).

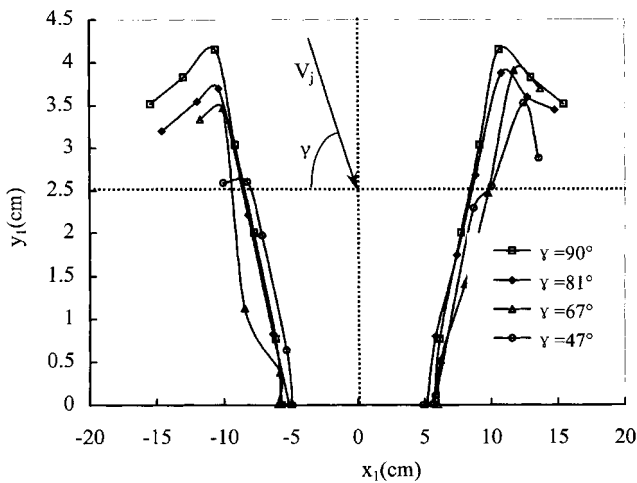


Fig. 7. 3) Variation of the scour shape with jet angle ($V_j = 422$ cm/s).

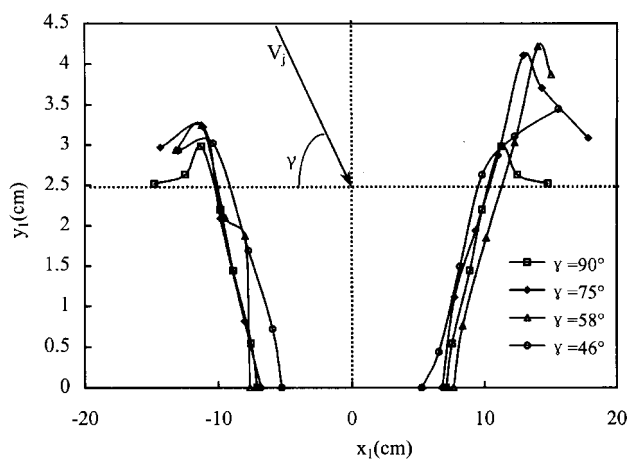


Fig. 7. 4) Variation of the scour shape with jet angle ($V_j = 531$ cm/s).

The effect of the jet height on the scour hole dimension is shown in Fig. 8. It is remarkable that the largest dimension of the hole does not correspond to the lowest location of the jet exit. It is observed in the experiment process of No.36 that when the state of equilibrium is reached for $H_j = 3$ cm numerous suspended particles could not move outside, only suspending inside the hole with the jet impinging turbulence. It is probably due to a decreased width of the impinging jet for a small jet height that provides little hydrodynamic effect beyond the scour hole, in this way the suspended particles cannot be carried out of the hole. Another extreme phenomenon is evident that the higher the exit of jet, the smaller the hole of scouring. There is an optimum jet height between $H_j = 12.5$ cm to $H_j = 18$ cm in this experiment range. With respect to a general equation for the optimum jet height, further investigations are required for the application of practical engineering.

Fig. 9 shows a critical condition for particle re-suspension. The critical value of relative intensity of the jet dynamic and particle resistance,

$$\frac{u_{bj}}{\sqrt{g \frac{\Delta \rho}{\rho} D_{50}}}$$

is approximately 1.5. In addition, the experimental observations show an approximate critical relationship between the jet velocity near bed u_{bj} and the particle fall velocity ω for the case of a small amount of sediment re-suspension, as follows:

$$u_{bj} \approx (5 \sim 7) \omega \quad (22)$$

In equation (22), ω is yielded by Stokes Formula:

$$\omega = \frac{1}{18} \frac{\Delta \rho g D_{50}^2}{\rho \nu} \quad (23)$$

in which ν is the fluid kinematic viscosity coefficient.

By regression method using the experimental results, the coefficient C_s in equation (21) is a constant in a certain region, expressed as:

$$C_s \approx 0.25, \quad \text{for} \quad \frac{u_{bj}}{\sqrt{g \frac{\Delta \rho}{\rho} D_{50}}} \geq 1.5 \sim 1.6 \quad (24)$$

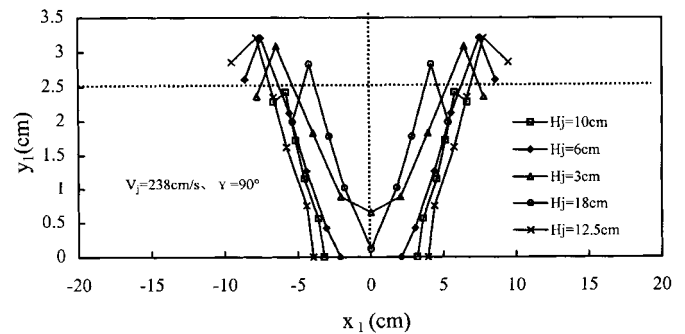


Fig. 8. Variation of the scour shape with jet height.

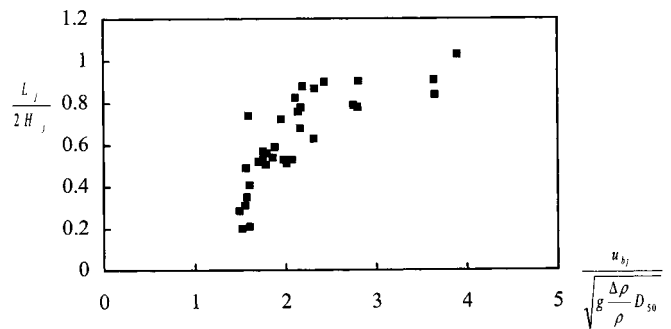


Fig. 9. Scour size for jet in cross flow.

In Fig. 10 the volume of particle re-suspension is estimated by experimental statistics using 15 sets of tests from No. 1 to No.15, the effects of jet angle and jet height are included herein. The relationship describing the jet effect on the bed particle re-suspension quantity is obtained by dimensional analysis and the coefficient is given by regression analysis, as:

$$\frac{\bar{V}}{D_j H_j h_s} = -34.5 \left(\frac{u_{bj} \sin \theta}{\sqrt{g \frac{\Delta \rho}{\rho} D_{50}}} \right)^2 + 255.2 \frac{u_{bj} \sin \theta}{\sqrt{g \frac{\Delta \rho}{\rho} D_{50}}} - 305.15 \quad (25)$$

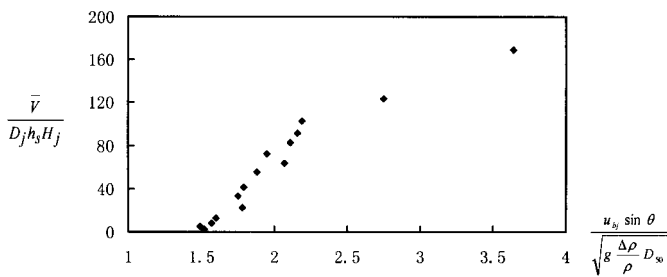


Fig. 10. Partial resuspension volume by impinging jet.

Fig. 11 compares the observed scour volume with the calculated scour volume from equation (25) using other experimental tests from No. 15 to No. 33. A good agreement between them under the jet condition $V_j \leq 10.5\text{m/s}$ is obtained, even though two sets of data depart from the predicted value. It should also be stated that some tests do not fit equation (25) for the case of smaller jet height.

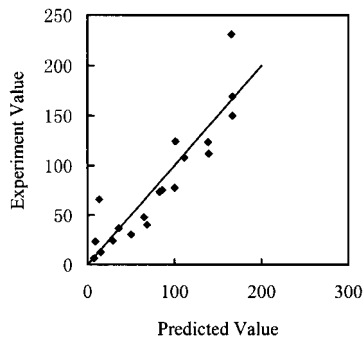


Fig. 11. Validation of the equation.

Conclusions

Local sediment re-suspension by the impinging jet in cross flow is examined theoretically and experimentally. The method of this paper proposed can be used to estimate or predict the sediment carrying capacity of the mixture flow of jet and uniform cross flow in an intake pond or any other water delivery system. The view of authors can be summarized as follows:

1. The set of hydrodynamic equations in natural coordinate system can be used to predict the jet motion in cross uniform flow.
2. An equation is derived which predicts well the equilibrium scour scale for limited depth of sand layer.
3. An equation to estimate the sediment re-suspension volume is obtained and validated.
4. The critical condition for the sediment re-suspension in this experiment investigation is

$$\frac{u_{bj}}{\sqrt{g \frac{\Delta \rho}{\rho} D_{50}}} \approx 1.5.$$

5. An optimum jet height exists for the bed particle re-suspension, which should be further studied.

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APPENDIX

Derivation of Equation (17)

Considering the case of jet impinging on the bed, the jet stream deflects around and transits as diffusion flow along the bed. Fig. 12 is the axial symmetric view of the structure of jet impinging flow. According to profile 1-1, approaching to the bed, and profile 2-2, momentum equations are written as:

$$M_{1-1} = u_{bj}^2 * \pi (\sqrt{2}b)^2 \quad (a)$$

$$M_{2-2} = u_b^2 * 2\pi x_1 y_0 \quad (b)$$

The momentum conservation is employed as:

$$M_{1-1} = M_{2-2} \quad (c)$$

Then, we have:

$$\left(\frac{u_b}{u_{bj}}\right)^2 = \frac{b^2}{x_1 y_0} \quad (d)$$

Considering the dimensional analysis of the jet flow:

$$b \propto z \quad \text{and} \quad y_0 \propto x_1 \quad (e)$$

and if z is set to $z = H_j$ when the jet stream approaches to the bed, the following relationship can be obtained:

$$\left(\frac{u_b}{u_{bj}}\right)^2 \propto \left(\frac{H_j}{x_1}\right)^2 \quad (f)$$

If a proportionality coefficient C_f is introduced, equation (17) is then obtained:

$$u_b = C_f \frac{u_{bj}}{x_1} \frac{H_j}{H_j} \quad (17)$$

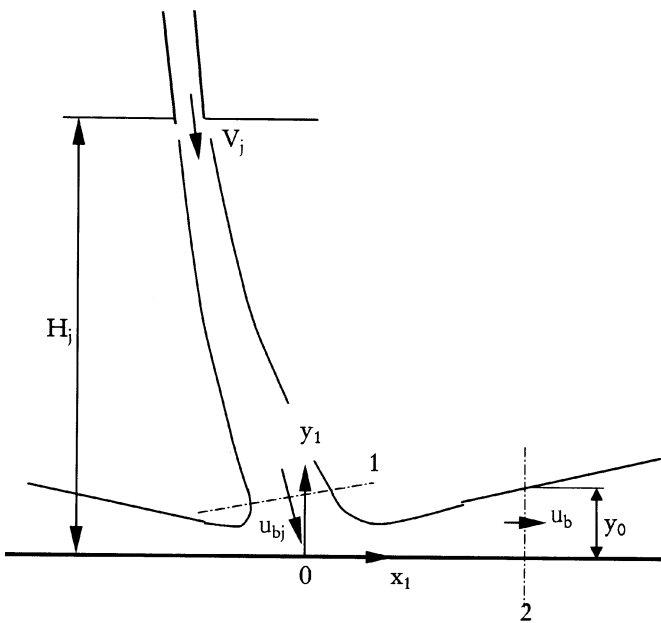


Fig. 12. Axial symmetry view of the impinging jet.