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LOCAL SCOUR DOWNSTREAM OF AN APRON CAUSED BY SUBMERGED HORIZONTAL JET

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The experimental results on scour in uniform and nonuniform sediments downstream of an apron due to a submerged horizontal jet issuing from a sluice opening are presented. The equilibrium scour depth, related to the sediment size relative to the sluice opening, decreases with increase in sediment size and sluice opening. On the other hand, the equilibrium scour depth increases with increase in densimetric Froude number. The dependency of equilibrium scour depth on tailwater depth indicates that a critical value of tailwater exists corresponding to a minimum value of equilibrium scour depth. The effect of sediment gradation on scour depth is pronounced for nonuniform sediments, which reduce scour depth considerably due to formation of armor-layer in the scour hole. The characteristic parameters affecting equilibrium scour depth are identified based on the physical reasoning and dimensional analysis. Equation of maximum equilibrium scour depth obtained empirically agrees satisfactorily with the experimental data.

1 Introduction

The safety of an apron downstream of a sluice gate is threatened by the erosive action of the fluid jets due to scour downstream of an apron. Scour downstream of an apron was studied by many investigators, and a comprehensive state-of-the-art review on the investigations done on scour due to jets was given by Sarkar and Dey (2004). Breusers (1965) studied the time variation of downstream scour by the flow over and under an estuary closure structure. Chatterjee and Ghosh (1980), Hassan and Narayanan (1985), and Chatterjee et al (1994) measured the velocity distributions of submerged jets issuing from a sluice opening over an apron followed by a scour hole in noncohesive beds; whereas Dey and Westrich (2003) detected the flow characteristics of submerged jets over the apron and in the equilibrium scour hole in cohesive beds.

The present study aims to investigate the scour in noncohesive sediments (uniform and nonuniform) downstream of an apron due to a submerged horizontal jet issuing from a sluice opening. The study reports an experimental investigation, whose findings are used to describe influences of various parameters on scour depth. Attempt is also made to derive the equation of equilibrium scour depth empirically using the dimensional analysis.

2 Experimentation

Experiments were performed in a glass walled flume of 0.6 m wide, 0.71 m deep and 10 m long. A sediment recess of 0.3 m deep and 2 m long having a width of the flume was constructed. A sediment trap was constructed adjacent to the downstream wall of the sediment recess to trap the scoured sediments. Six sands and two gravels were used in the experiments. The characteristics of the sediments used in the experiments are furnished in Table 1. The apron was made of perspex sheet over which a vertical sluice gate was fixed (Fig. 1). The different sluice gate openings *b* (12.5 mm and 15 mm) were achieved by adjusting the gate vertically; and the gate was moved horizontally to vary the distance *l* (0.4 m and 0.5 m) from the edge of the apron. A tailgate downstream of the flume controlled the tailwater depth in the flume. The water discharge at the inlet, controlled by an inlet valve, was measured by a calibrated V-notch weir. In all the experimental runs, the jets issuing from the sluice opening were well submerged by the tailwater.

Table 1. Characteristics of sediments used in the experiments.

Type	Median size d_{50} (mm)	Relative density s	Geometric standard deviation σ_g	Angle of repose ϕ (degree)
Sand	0.26	2.65	1.21	29
	0.49	2.65	1.13	29.5
	0.8	2.65	1.3	30
	1.86	2.65	1.27	31.5
	2.54	2.65	1.06	33
	3	2.65	1.19	34
Gravel	4.1	2.65	1.13	35.5
	5.53	2.65	1.1	37

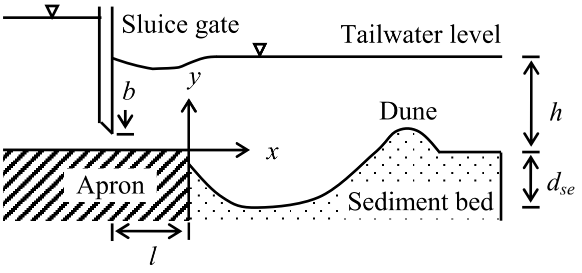

Figure 1. Schematic view of scour hole downstream of an apron.

3 Influence of Different Parameters on Scour Depth

Fig. 2 shows the variation of nondimensional equilibrium scour depth $\tilde{d}_{se}$ (= d_{se}/b) with sediment size - sluice opening ratio $\tilde{d}$ (= d_{50}/b) for different apron length - sluice opening ratios $\tilde{l}$ (= l/b) and jet Froude numbers F_u [= $U/(gb)^{0.5}$, where U = issuing velocity of jet; and g = gravitational acceleration]. It is observed that $\tilde{d}_{se}$ decreases with increase in $\tilde{d}$, which indicates that d_{se} is less for relatively coarse sediment and larger sluice opening. To be more precise, with the development of scour hole, the bed shear stress acting on the scour hole reduces. Thus, for coarser sediments that need relatively more critical bed shear stress to initiate motion, the equilibrium scour reaches at a reduced scour depth d_{se}. On the other hand, U decreases with increase in b. Therefore, for larger b, U possesses lesser scour potential. The most interesting feature of the curve is that $\tilde{d}_{se}$ decreases sharply for $\tilde{d} < 0.1$. Then, the rate of reduction of $\tilde{d}_{se}$ falls down considerably, becoming independent of $\tilde{d}$ for $\tilde{d} > 0.3$. However, for a given value of $\tilde{l}$, $\tilde{d}_{se}$ increases with increase in F_u.

The dependency of nondimensional equilibrium scour depth $\tilde{d}_{se}$ on densimetric Froude number F_o [$= U/(\Delta g d_{50})^{0.5}$, where $\Delta = s - 1$; and s = relative density] for different $\tilde{l}$ and d_{50} is shown in Fig. 3. Here, $\tilde{d}_{se}$ increases with increase in F_o and with decrease in d_{50}. The rate of increase of $\tilde{d}_{se}$ is more for lower F_o, but for higher F_o ($F_o > 12$), it falls down becoming almost independent of F_o.

Fig. 4 depicts the nondimensional equilibrium scour depth $\tilde{d}_{se}$ as a function of tailwater depth - sluice opening ratio $\tilde{h}$ ($= h/b$, where h = tailwater depth) for different F_o and apron length - sediment size ratios $\tilde{l}_d$ ($= l/d_{50}$). The variation of $\tilde{d}_{se}$ with $\tilde{h}$ is sagging in nature. It means that a critical value of tailwater exists corresponding to a minimum value of $\tilde{d}_{se}$. It is pertinent to point out that for a given value of $\tilde{l}_d$, the critical value of tailwater depth shifts towards the right with increase in F_o in Fig. 4. But, the sagging nature of the curves $\tilde{d}_{se}$ versus $\tilde{h}$ becomes almost straightened with increase in $\tilde{l}_d$. However, for a given value of F_o, $\tilde{d}_{se}$ increases with increase in $\tilde{l}_d$.

The experimental data of scour depth for different sediment gradations of nonuniform sediments, tested for $b = 0.15$ m and $l = 0.5$ m, are used to plot Fig. 5(a) that presents the variation of $\tilde{d}_{se}$ with geometric standard deviation σ_g of sediments, given by $(d_{84}/d_{16})^{0.5}$. The sediment gradation has a pronounced influence on the scour depth. According to Dey et al. (1995), the sediment becomes nonuniform, when σ_g is greater than 1.4. Nonuniform sediments ($\sigma_g > 1.4$) consistently produce lower scour depths than that in uniform sediments. A drastic reduction in scour depth that occurs for widely graded sediments is evident in Fig. 5(a). The equilibrium scour depth $d_{se}(\sigma_g)$ in nonuniform sediments can be estimated as

$$\tilde{d}_{se}(\sigma_g) = K_\sigma \tilde{d}_{se} \qquad (1)$$

where K_σ = coefficient due to sediment gradation. It is defined as the ratio of d_{se} in nonuniform sediment ($\sigma_g > 1.4$) to that in uniform sediment. The dependency of K_σ on σ_g is given in Fig. 5(b). It is evident from the mean curve drawn through the experimental data that $\tilde{d}_{se}$ in nonuniform sediment having $\sigma_g = 4$ is drastically reduced to 54 percent of $\tilde{d}_{se}$ in uniform sediment. However, the reduction of $\tilde{d}_{se}$ for $\sigma_g > 4.5$ is almost independent of the nonuniformity of sediments. In nonuniform sediments, a process of armoring in the scour hole takes place resulting in an exposure of coarser particles due to washing out the finer fraction. The armor-layer gradually increases the effective critical bed shear stress that limits the development of scour hole.

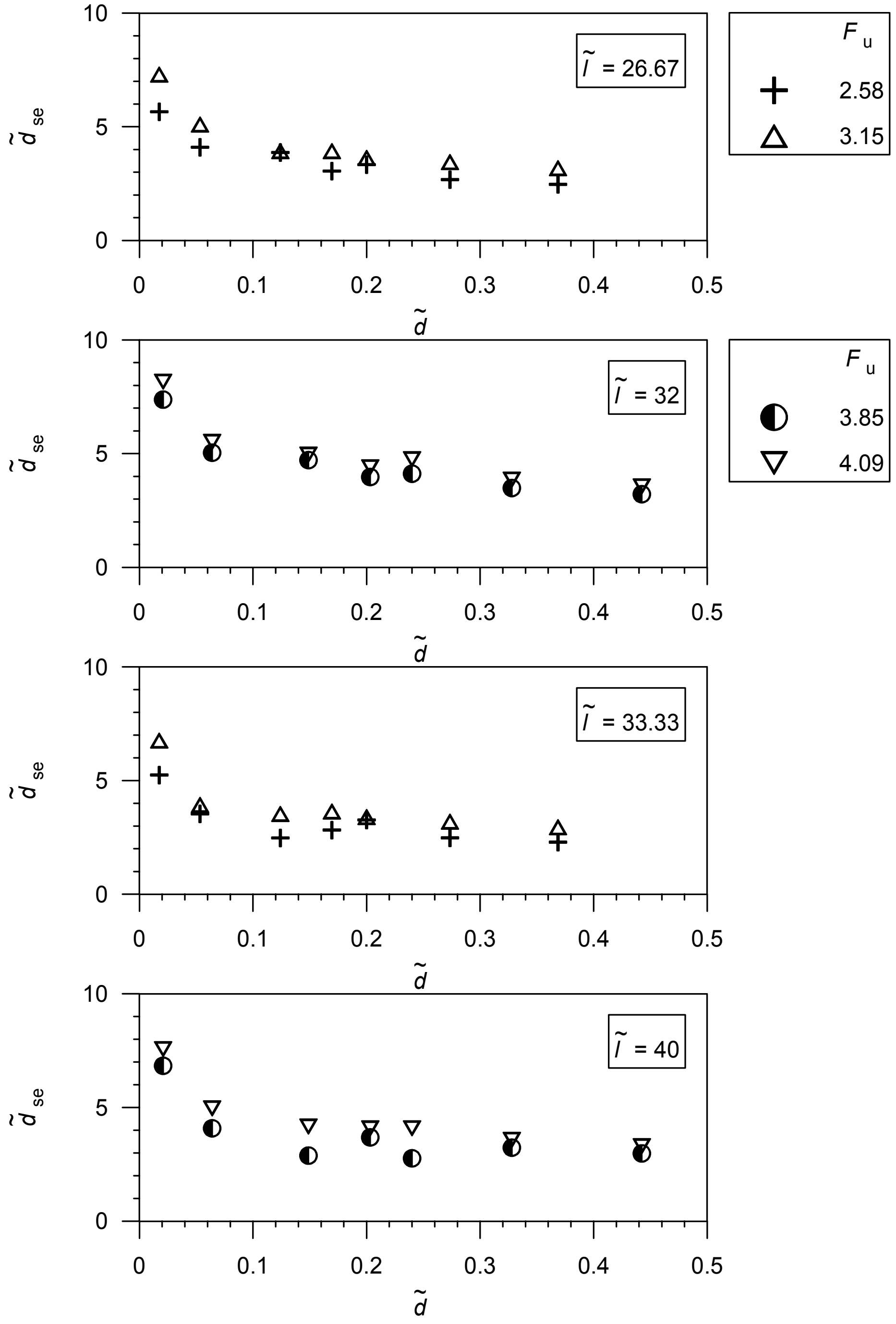

Figure 2. Variation of $\tilde{d}_{se}$ with $\tilde{d}$ for different $\tilde{l}$ and F_u.

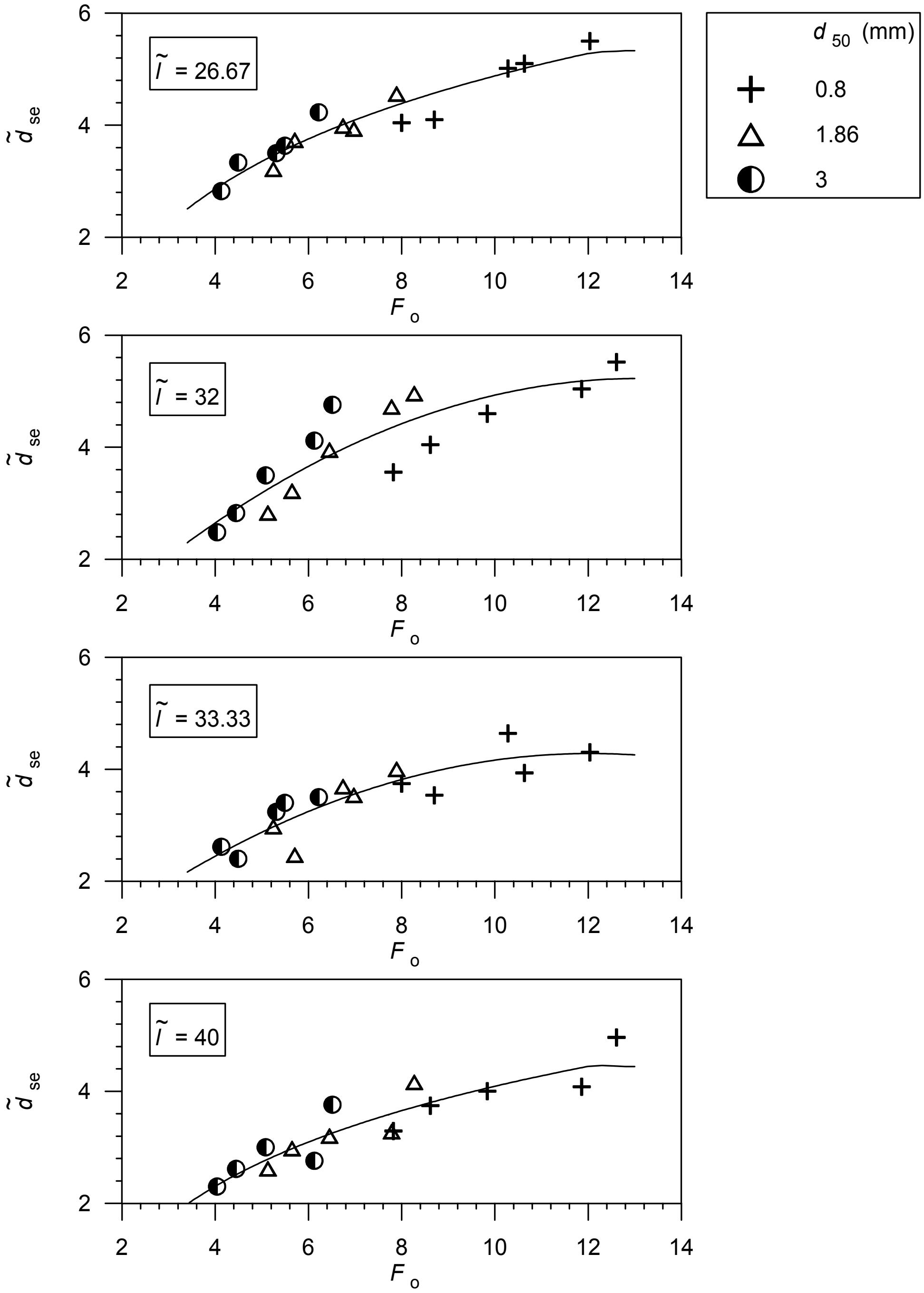

Figure 3. Dependency of $\tilde{d}_{se}$ on F_o for different $\tilde{l}$ and d_{50}

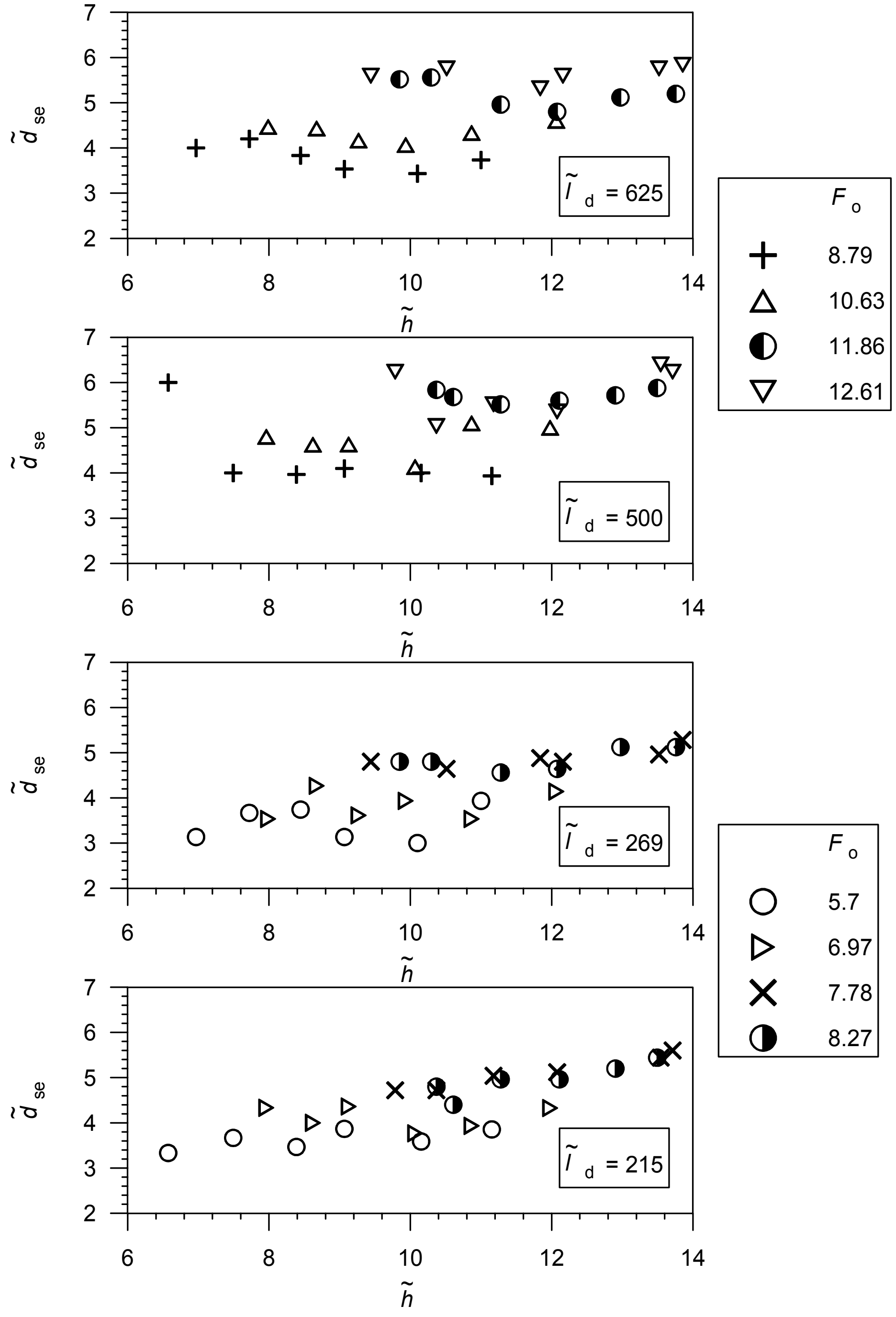

Figure 4. Variation of $\tilde{d}_{se}$ with $\tilde{h}$ for different $\tilde{l}_d$ and F_o.

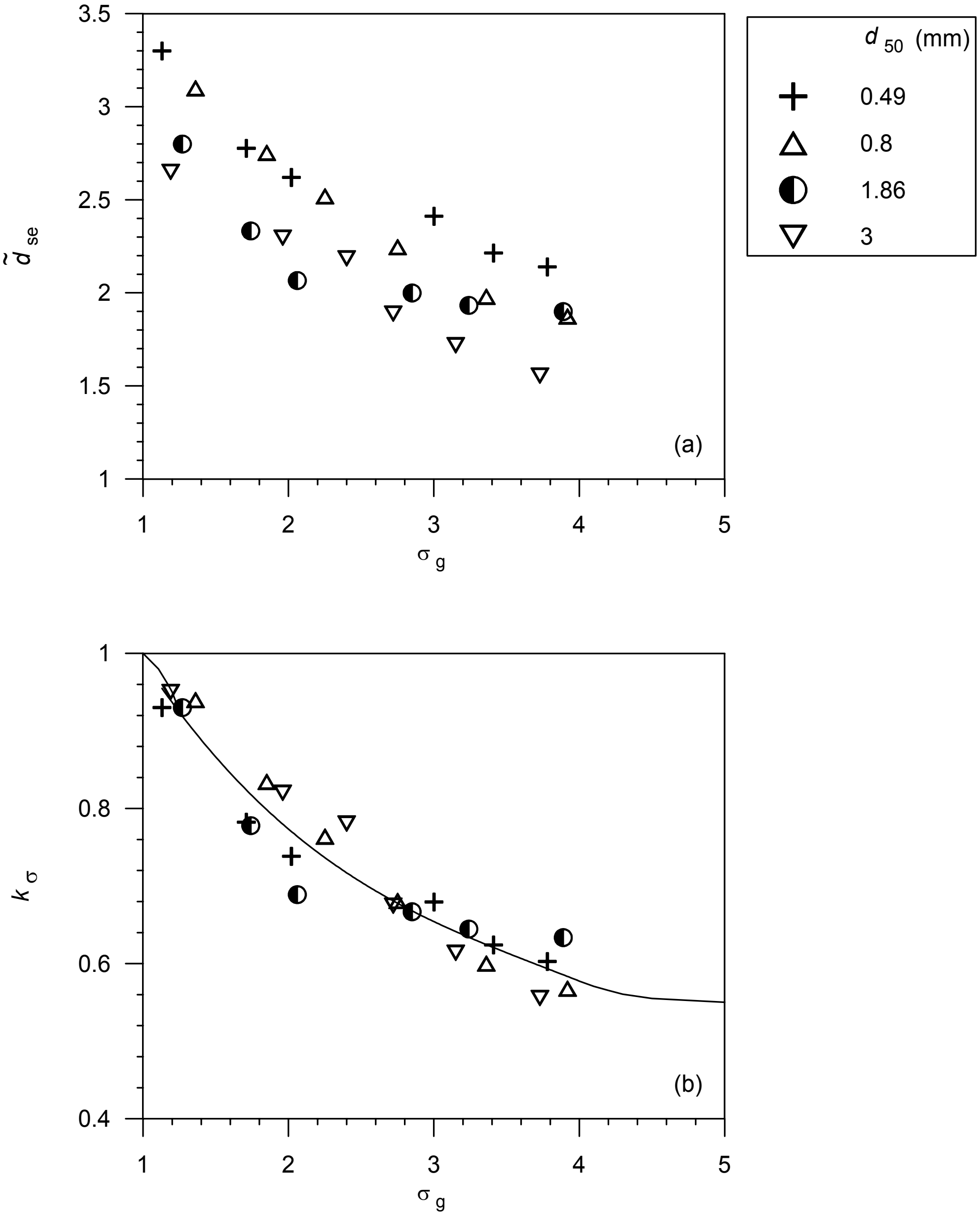

Figure 5. (a) Variation of $\tilde{d}_{se}$ with σ_g and (b) coefficient K_σ as a function of σ_g.

4 Equation of Equilibrium Scour Depth

Equilibrium scour depth downstream of an apron due to submerged jets issuing from a sluice opening may be given in following functional form:

$$d_{se} = f_1(U, \rho, \rho_s, g, \nu, b, l, h, d_{50}) \tag{2}$$

where ρ = mass density of water; ρ_s = mass density of sediments; and ν = kinematic viscosity of water. For sediment-water interaction, the terms g, ρ and ρ_s should appear as one independent parameter Δg. Hence, Eq. (2) becomes

$$d_{se} = f_2(U, \Delta g, \nu, b, l, h, d_{50}) \tag{3}$$

Using the Buckingham π-theorem, one can write

$$\tilde{d}_{se} = f_3(F_o, R_e, \tilde{l}, \tilde{h}, \tilde{d}) \tag{4}$$

where R_e = Reynolds number (= Ub/ν), which has a little influence on scour depth, when it is greater than 10^4. Therefore, Eq. (4) reduces to

$$\tilde{d}_{se} = f_4(F_o, \tilde{l}, \tilde{h}, \tilde{d}) \tag{5}$$

A regression analysis of the experimental data yields the following equation of nondimensional equilibrium scour depth:

$$\tilde{d}_{se} = 1.241 F_o^{0.85} \tilde{l}^{-0.19} \tilde{h}^{0.235} \tilde{d}^{0.193} \tag{6}$$

The regression coefficient between the experimentally obtained and the computed scour depths is 0.916, indicating that Eq. (6) agrees well with the experimental data. For nonuniform sediments, $\tilde{d}_{se}(\sigma_g)$ can be corrected using coefficient K_σ and σ_g [Fig. 5(b)].

5 Conclusions

The equilibrium scour depth decreases with increase in sediment size and sluice opening, and with decrease in densimetric Froude number. For higher densimetric Froude number, the scour depth is independent of densimetric Froude number. A critical value of tailwater exists corresponding to a minimum value of scour depth. The effect of nonuniform sediments on scour depth is significant, as the scour depth is reduced considerably.

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