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Comparison of Flow-Boundary Effects on Critical Submergence of an Intake†

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ABSTRACT

In this study, the effects of canal bottom and dead-end wall on the critical submergence of a single rectangular or circular intake are investigated and compared. In order to find the functional relationship involving the critical submergence and the influencing dimensionless variables, dimensional analysis is utilized. Experiments were conducted on a rectangular or circular intake sited with different positions in a uniform canal flow. Experimental results have indicated that the flow boundaries considerably affect the critical submergence. The effect of the boundary cutting the free surface on the critical submergence is much larger than that of the sub-surface boundary not cutting the free surface.

Keywords: *Intake, vortex, submergence, critical submergence*

1. INTRODUCTION

For various purposes (irrigation, energy, domestic use, industry etc.) water is taken from rivers and lakes by means of intakes. The vertical distance of the intake center to the free surface is called the "submergence". When the submergence of the intake is not sufficient, air enters the intake through the air-core vortex that develops at the water surface above the intake. Air-entrainment to intakes causes some hydraulic problems such as discharge reduction, vibrations, and loss of efficiency in turbines, pumps, and water conveying structures. Therefore, determination of the parameters affecting the air-entrainment to intakes is important for designing intake structures.

The submergence at which the tip of the air-core vortex reaches the intake is called "critical submergence". If the submergence of the intake is below the critical submergence air enters the intake and causes aforementioned problems (Fig. 1).

The flow boundaries affect the air-entraining vortex or the critical submergence of an intake. Herein, the effects of dead-end wall and canal bottom on the critical submergence of a rectangular or pipe intake located in a uniform canal flow were investigated and compared.

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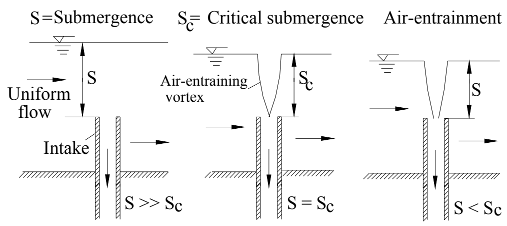

Figure 1. Submergence, critical submergence, and air-entrainment

2. PREVIOUS STUDIES

Extensive research has been conducted on air-entraining vortices. Yıldırım and Jain [1] investigated the effect of the surface tension on the critical submergence. Posey and Hsu [2] examined the effect of the air-entrainment to an intake on discharge coefficient. Iversen [3] analyzed the effects of the flow boundaries and showed that the clearances of an intake to a dead-end wall and canal bottom should be D/4 – D/2, and D/2 respectively, to avoid the stimulating effects of the sharp corners on air-entraining vortex (D = internal diameter of the pipe intake). Denny [4] investigated the effect of the air-entrainment on the efficiency of centrifugal pumps. Markland and Pope [5] found a relationship between intake velocity and intake submergence by experiments. Gulliver and Rindels [6] experimentally showed that the angle of approach flow relative to canal axis is effective on air-entrainment. Odgaard [7] considered the air-entrainment to an intake in still-water as the combination of a free vortex and line sink. Hite and Mih [8] studied the shape and velocity distribution of a free vortex. Jain et al. [9, 10] experimentally examined the effects of viscosity and imposed circulation on critical submergence. Yıldırım and Kocabaş [11] predicted the critical submergence for a single pipe intake using potential flow. Flow toward a pipe intake is approximated as a point sink. The potential flow solution for the combination of a point sink and a uniform flow is available, and is known as a Rankine ovoid. In the critical situation, the water surface level above the intake just matches the upper surface of the Rankine ovoid, and the critical submergence is equal to the radius of the Rankine ovoid at the intake. The critical submergence for a pipe intake is equal to the radius of a "Critical Spherical Sink Surface (CSSS)" that has the same center and discharge as the intake. Velocity at CSSS is a constant for a given flow and geometry. Yıldırım and Kocabaş [12] proved that "CSSS" can be used to find the critical submergence of a pipe intake in still-water. Yıldırım et al. [13, 14] investigated the "blockage effects", which was defined as the loss of surface area from a CSSS, of the flow boundaries on critical submergence. Kocabaş and Yıldırım [15] demonstrated that imposed circulation increases the critical submergence. Yıldırım [16], and Eroğlu and Bahadırlı [17] obtained the critical submergence for a rectangular intake by potential flow solution.

In this study the effects of dead-end wall and canal bottom on the critical submergence are compared. Since the analysis of air-entrainment to an intake by means of free vortices is analytically very complex, herein dimensional analysis is utilized.

3. DIMENSIONAL ANALYSIS

In this study the effects of dead-end wall and canal bottom are investigated for both a pipe and a rectangular intakes. The explanation of dimensional analysis for a rectangular intake is as follows (similar dimensional analysis for a pipe intake is presented later).

Consider a rectangular intake located in a horizontal rectangular canal (Fig. 2). Parameters affecting the critical submergence are:

$$S_{cd} = f_1\left(V_d, U_\infty, \rho, \mu, \Gamma, \sigma, g, b, a, c_d, b_{1d}, b_{2d}, l_d, e_d\right) \tag{1}$$

in which, S_{cd} = critical submergence for rectangular intake, V_d = average flow velocity at the rectangular intake, U_∞ = average approach flow velocity, ρ = density of the fluid, μ = dynamic viscosity of the fluid, Γ = imposed circulation, σ = surface tension of the fluid, g = gravity acceleration, *a* and b = length of the short and long sides of rectangular intake respectively, c_d = vertical distance between the intake and canal bottom, b_{1d} and b_{2d} = the distances between the points M_1 and M_2 and the right and left side walls of the canal respectively, l_d = horizontal distance of the rectangular intake to dead-end wall, and e_d = wall thickness of rectangular intake (Fig. 2).

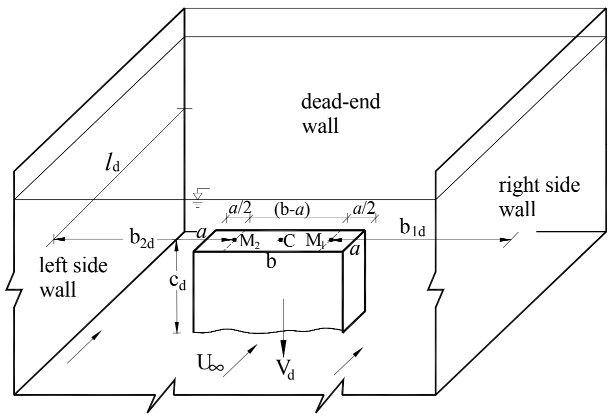

Figure 2.Parameters for a rectangular intake and its position

Dimensional analysis of the parameters in eq. (1) yields,

$$\frac{S_{cd}}{a} = f_2\left[\frac{V_d}{U_\infty}, \frac{b}{a}, W, K, R, F_d, \frac{c_d}{a}, \frac{b_{1d}}{a}, \frac{b_{2d}}{a}, \frac{l_d}{a}, \frac{e_d}{a}\right] \tag{2}$$

in which, $W = \rho a V_d^2/\sigma$ = Weber number for rectangular intake, $K = \Gamma/(V_d a)$ = circulation number for rectangular intake, R $= V_d a/\nu$ = Reynolds number for rectangular intake, $F_d = V_d/(ga)^{0.5}$ = Froude number for rectangular intake and $\nu = \mu/\rho$ = kinematic viscosity of the fluid. To suppress the effects of the canal side walls and thus to examine the effects of the canal bottom and dead-end wall on the critical submergence, intake was located on the canal axis without any boundary blockage caused by the canal side walls [the clearances of the intake to the side walls of the canal were kept larger than the maximum critical submergence. The maximum value of the critical submergence varies with geometrical and flow conditions. Experiments were conducted for the cases in which the critical submergence is less than b_{1d} and b_{2d}. For instance, for $b/a = 1$ ($b = 5$ cm, $a = 5$ cm) maximum critical submergence was 22.5 cm and $b_{1d} = b_{2d} = 25$ cm]. Therefore, the effects of the side walls on the critical submergence can be neglected and b_{1d}/a and b_{2d}/a can be dropped out from the eq. (2). Since the wall thickness of the intake was 3 mm, e_d/a is also sufficiently small and can be neglected [in this study e_d/a = 3 mm / 50 mm = 0.06 and for $V_d/U_\infty > 10$ the effect of the relative pipe thickness is less than 2% and can be ignored (Yıldırım, 2004, Fig.3)]. Furthermore, no circulation was imposed on the flow ($\Gamma = K = 0$). The previous studies [1, 6, 7, 8, 9, 10, 11] showed that, in practice, the effects of W and R on critical submergence can be ignored.

Hence, eq.(2) can be rewritten as,

$$\frac{S_{cd}}{a} = f_3\left[\frac{V_d}{U_\infty}, \frac{b}{a}, F_d, \frac{c_d}{a}, \frac{l_d}{a}\right] \tag{3}$$

Similarly for a pipe intake (Fig. 3), dimensional analysis yields,

$$\frac{S_{cp}}{D} = f_4\left[\frac{V_p}{U_\infty}, F_p, \frac{c_p}{D}, \frac{l_p}{D}\right] \tag{4}$$

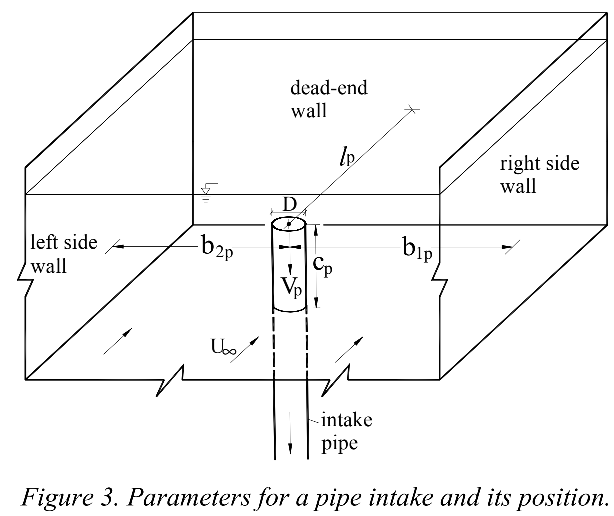

Figure 3. Parameters for a pipe intake and its position.

In Fig.3, S_{cp} = critical submergence for a pipe intake, V_p = average intake velocity in pipe intake, D = internal diameter of the intake, c_p = clearance of the pipe intake to the canal bottom, b_{1p} and b_{2p} = clearances of the intake to the right and left side walls of the canal, respectively, l_p = clearance of the intake to the dead-end wall, and $F_p=V_p/(gD)^{0.5}$ = Froude number for pipe intake (Fig. 3).

Because of its geometrical form, there are different alternatives for the position of the rectangular intake in the canal. To distinguish the positions and simplify the analysis of experimental results, four different cases are considered herein.

Case I: A rectangular intake whose long side is parallel to the canal bottom passing through the dead-end wall (LSHRI) (Fig. 4).

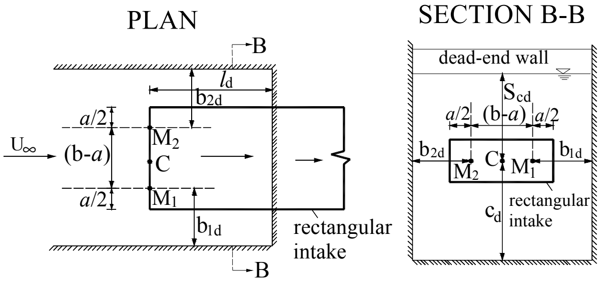

Figure 4. Case I (LSHRI)

Case II: A rectangular intake whose long side is normal to the canal bottom passing through the dead-end wall (LSVRI) (Fig. 5).

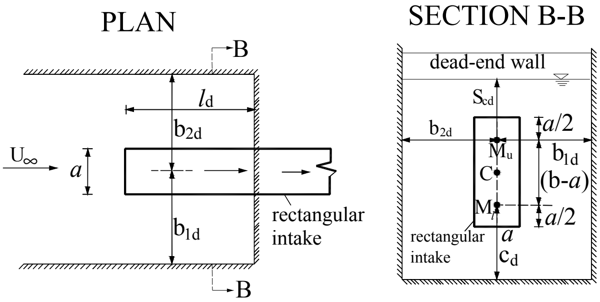

Figure 5. Case II (LSVRI)

Case III: A downward-flowing rectangular intake whose long side is normal to the approach flow direction (LSHRI) (Fig. 6)

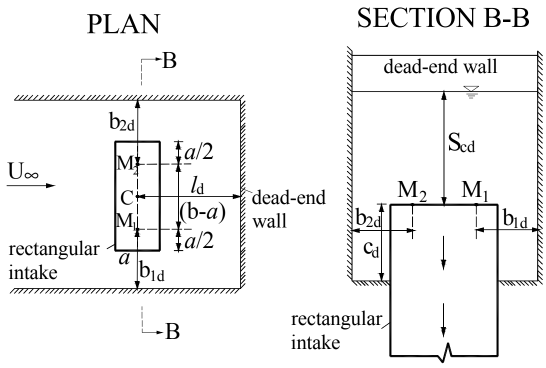

Figure 6. Case III (LSHRI)

Case IV: A downward-flowing rectangular intake whose long side is parallel to the approach flow direction (LSHRI) (Fig. 7)

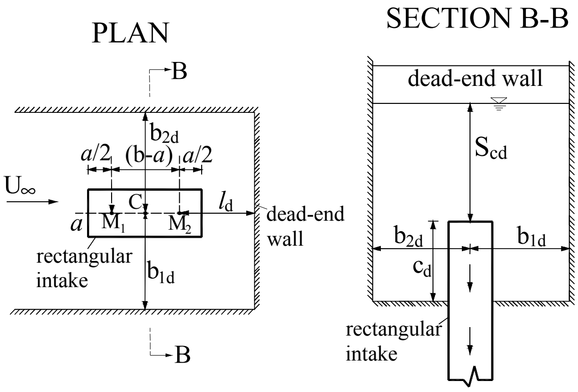

Figure 7. Case IV (LSHRI)

The points M_u and M_l represent the points M_1 and M_2 accordingly if the intake entrance is not on the horizontal plane (Figs. 4 to 7). The critical submergence or intake level are measured with respect to points M_1, M_2 or M_u and M_l and these points were analytically found by using the potential flow solution given in the studies of Yıldırım [16] and, Eroğlu and Bahadırlı [17]. It should be noted that if the intake entrance is on the vertical plane, although the air-core vortex enters the intake from top of it, the critical submergence for case I (Fig. 4) is taken as the distance between the water surface and the intake center, and for the case II (Fig. 5) the distance between the water surface and M_u (because as it is indicated before, the critical submergence for a rectangular intake is measured with respect to the center points M_1 or M_2 and M_u depending on its position in the canal).

4. EXPERIMENTAL SET-UP and EXPERIMENTS

To find the relationships in eqs. (3) and (4), experiments were conducted in a 10 m- long, 50 cm- wide and 50 cm-depth horizontal rectangular canal whose bottom and sides are made of glass. At the entrance of the flume there are energy dissipating screens and rafts, which make the flow as uniform and free of circulation as possible. The working section of the flume was 7.5 m. The intake was centrally placed at a distance of 2.5 m from the adjustable flapping gate at the end of the flume.

Steel rectangular and circular intakes of 2-3 mm wall thicknesses were used. The dimensions of the rectangular intake were a = 5 cm, b = 5-20 cm. Experimental procedure for a rectangular intake was as follows.

Intake was centrally located in the canal according to the predetermined distances of c_d and l_d. Since the main purpose of this study is to present only the effects of the dead-end wall and the canal bottom, clearances of the intake to canal side walls were kept sufficiently large (larger than the possible maximum critical submergence).

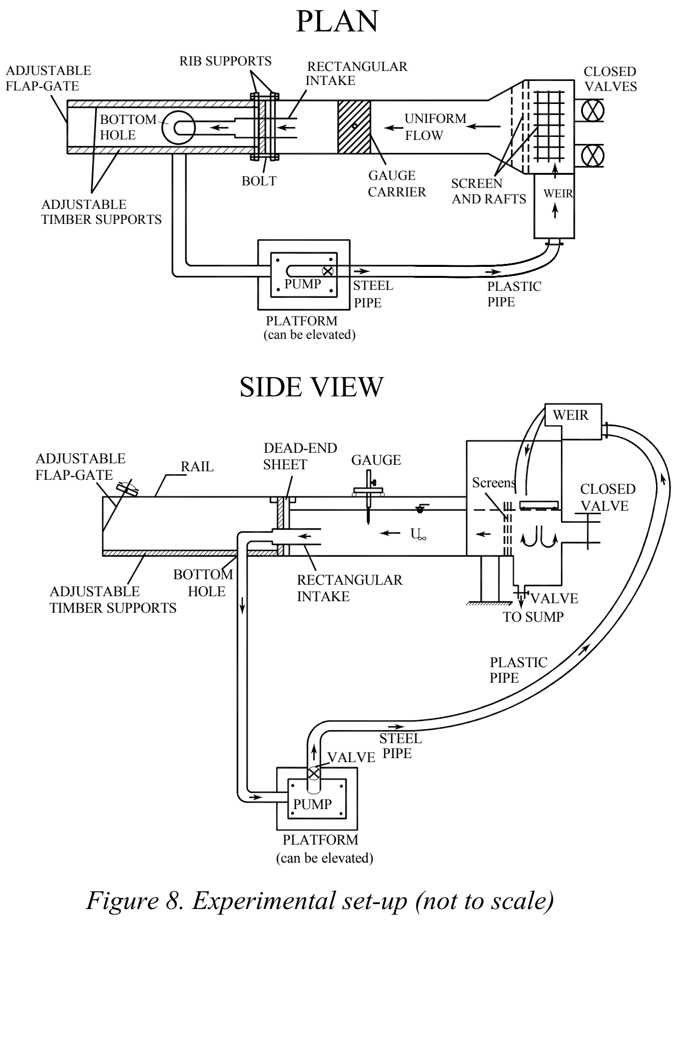

Figure 8. Experimental set-up (not to scale)

The end of the outlet pipe of the intake outside the canal was connected to a 7.5 kW centrifugal pump by 90° elbows and flanged couplings. The outlet of the pump was connected to a triangular (V-notch) weir, which was used for the measurement of intake discharge. There was a valve on the vertical section of the pipe after the pump. Water from the triangular weir was directed to the entrance of the canal. By means of a hose, the canal was filled with city water up to a sufficient depth. The pump was then started and the valve was opened to pass a selected discharge through the intake and to recirculate water. There was an initially closed valve on a small drain pipe at the beginning of the canal. Observations were made over 1-2 h to see whether or not a free air-core vortex developed. If no air-entrainment occurred during this time, the valve on the drain pipe was opened a small amount (i.e., submergence was decreased). When the water level in the canal reached the desired level, the draining was stopped to keep the water level constant. These steps were repeated carefully until an air-entraining vortex developed. When the air-entraining vortex developed, the measurements related to intake discharge, critical submergence and flow depth in the canal were made. Approach flow and intake velocities were computed from the continuity equation. Similar procedure was also followed for a pipe intake (D = 5.32 cm).

5. ANALYSIS OF EXPERIMENTAL RESULTS

The variations of the critical submergences for a pipe and a rectangular intake with "F_d and F_p" are presented in Figs. (9) and (10) [the numbers (I), (II), (III) and (IV) in Fig. 9 represent the cases I, II, III and IV respectively]. The effect of the dead-end wall on the critical submergence is shown in Fig. 9(a) (for all cases bottom clearances are identical, c_d/a=2). As it is seen from this figure, as the distance between the intake and the dead-end wall decreases, critical submergence also decreases. Especially when the intake entrance is level with the surface of the dead-end wall (l_d/a = 0) a fully developed air-entraining vortex cannot occur because the boundary surface of the dead-end just passes through the theoretical center of the vortex expected to occur. Thus, the vortex weakens and quickly disappears. Also, the velocity at the dead-end must be zero (no-slip condition). Due to this reason, the velocity at the tip of the air-core vortex (dimple) to be developed is zero. Therefore, a surface depression (dimple) cannot develop and elongate downward at the dead-end. In this case, when the submergence is decreased well below the expected critical submergence, air enters the intake with extremely short intervals and duration. It is very hard to follow the formation and entrainment of the air vortex. Air enters the intake very quickly in the form of small or large bubbles. This event makes the vortex very unsteady and unstable.

The effect of the clearance of the intake to the canal bottom is demonstrated in Fig. 9(b) (for all cases horizontal distances to the dead-end wall are identical, l_d/a=2). As the clearance of the canal bottom to the intake decreases, the critical submergence increases. The reason is as follows. Yıldırım [16] showed that the critical submergence of a rectangular intake is equal to the radius of a critical hemi-spherical sink surface or radius of a critical cylindrical sink surface. At each of these critical surfaces velocities are different constants depending on flow and geometrical conditions. Therefore, due to loss of surface areas from these sink surfaces caused by the canal bottom; the critical submergence should increase to satisfy the continuity. In Fig. 9(c), the cases in which the rectangular intake is on the same plane as the canal bottom, and the dead-end wall are compared. The critical submergence is considerably small when the intake is level with the dead-end wall because of the reasons explained earlier.

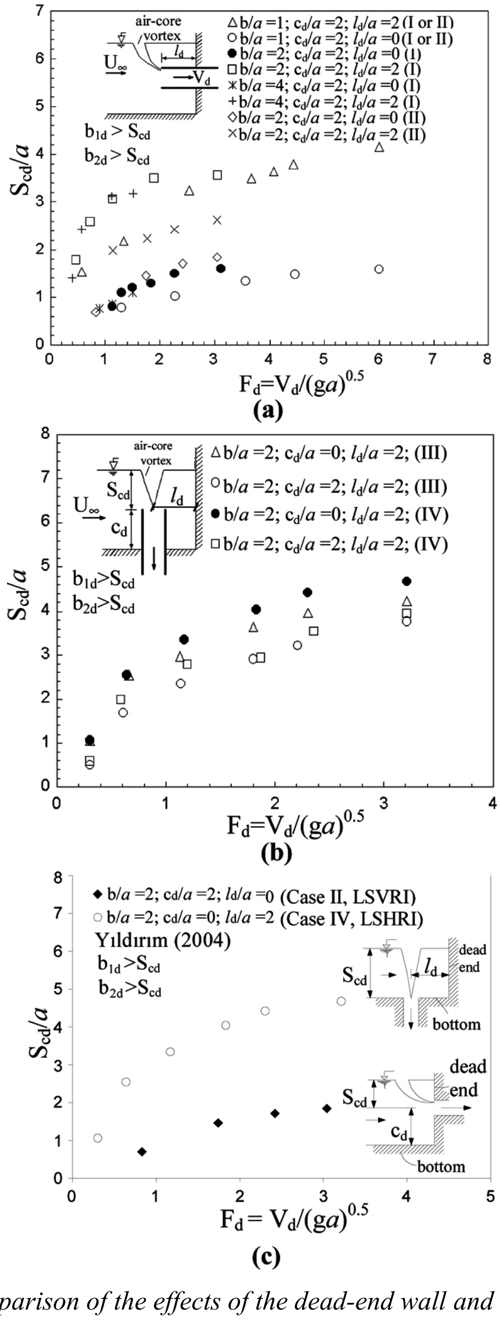

Figure 9. a,b,c) Comparison of the effects of the dead-end wall and the canal bottom for a rectangular intake

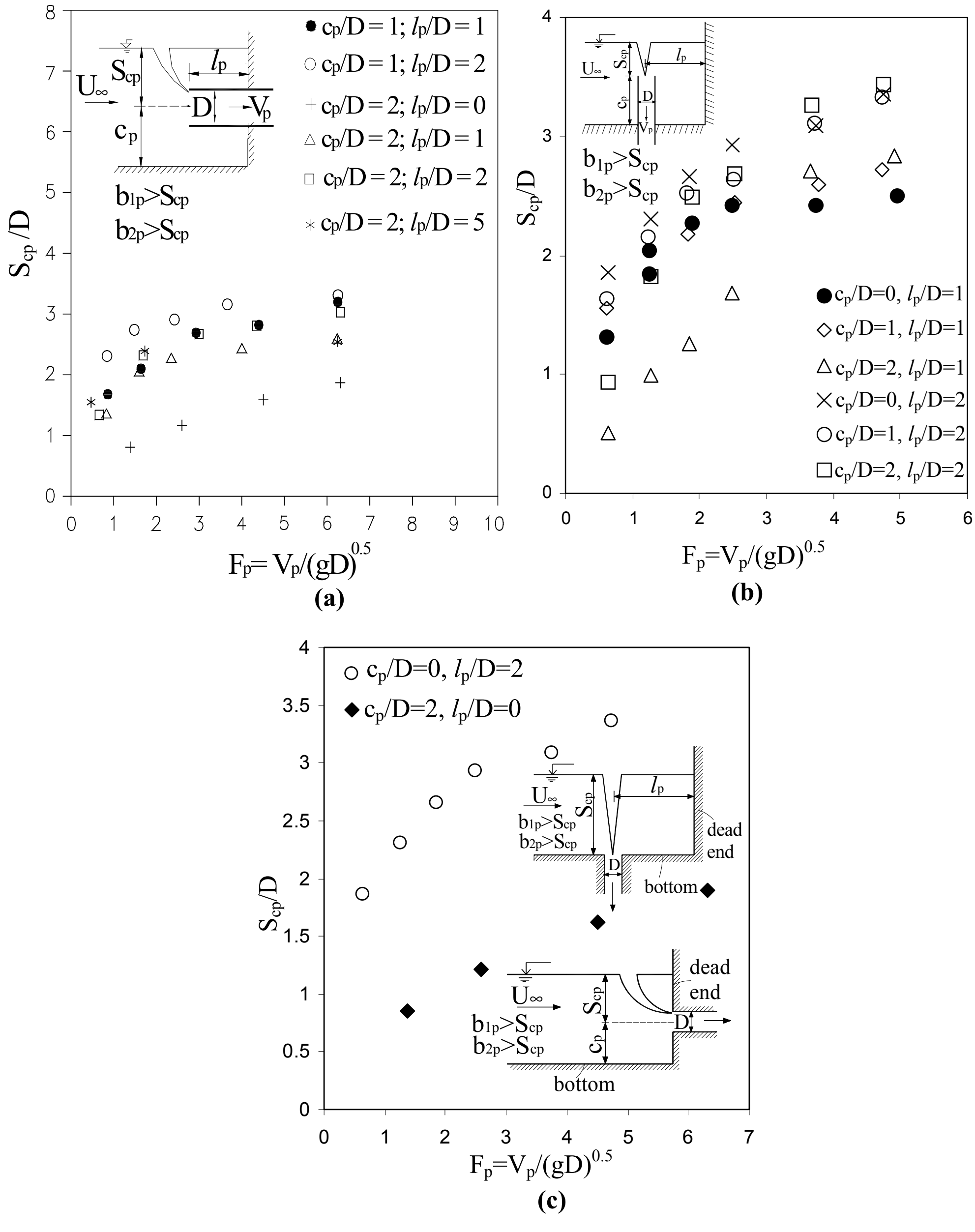

Figure 10. a,b,c) Comparison of the effects of the dead-end wall and the canal bottom for a pipe intake

In reality the dead-end wall and the canal bottom represent the effects of a boundary cutting the free surface and a sub-surface boundary, respectively. As it is seen from Figs. 9 and 10 the effect of the dead-end wall (boundary cutting the free surface) is much greater than that of the canal bottom (sub-surface boundary). Since the air-core vortex starts from the free surface, the occurrence of it is very sensitive to surface disturbances (or perturbations). While the boundary cutting the free surface above the intake causes large friction, a sub-surface boundary causes negligible friction on the air-entraining vortex. Therefore, the boundary cutting the free surface reduces the strength of the circulation and dampens the surface disturbances. A sub-surface boundary does not have such effects (or its effects can be ignored). This is the reason why the effect of a boundary cutting the free surface is greater than that of the sub-surface boundary.

In practice, since the intake dimensions and the velocity are known, intake Froude number can be calculated, and with the known intake Froude number the critical submergence can be found (read) from Figs. 9 and 10.

In Fig. 10 the variation of the critical submergence of a pipe intake with F_p is demonstrated. Because of the similar reasons explained for the rectangular intake, as the clearance of the intake to the dead-end wall decreases the critical submergence decreases, and as the clearance of the intake to the canal bottom decreases the critical submergence increases.

6. CONCLUSIONS

From this study, the following conclusions may be drawn:

1. The clearances of the intake to the dead-end wall and canal bottom influence critical submergence.
2. As the clearance of the intake to a boundary cutting the free surface decreases, the critical submergence considerably decreases due to boundary friction.
3. As the clearance of the intake to the canal bottom decreases critical submergence increases.
4. The effect of the Froude number increases as the intake gets closer to the dead-end wall (boundary cutting the free surface).

Symbols

a : Length of the short edge of the rectangular intake

b : Length of the long edge of the rectangular intake

b_{1d} : Distance between the point M_1 and the canal right side wall for rectangular intake

b_{2d} : Distance between the point M_2 and the canal left side wall for rectangular intake

b_{1p} : Distance between the intake center and the canal right side wall for a pipe intake

b_{2p} : Distance between the intake center and the canal left side wall for a pipe intake

c_d : Vertical clearance of the point C to the canal bottom for cases I, III and IV (Vertical clearance of the point M_l to the canal bottom for case II)

c_p : Vertical clearance of the intake center to the canal bottom for a pipe intake

D : Internal diameter of the pipe intake

e_d : Wall thickness of the rectangular intake

F_d : Froude number for the rectangular intake

F_p : Froude number for the pipe intake

g : Gravitational acceleration

K : Circulation number

l_d : Horizontal distance of the rectangular intake to the dead-end wall

l_p : Horizontal distance of the pipe intake to the dead-end wall

R : Reynolds number

S : Submergence, in general

S_c : Critical submergence, in general

S_{cd} : Critical submergence for rectangular intake

S_{cp} : Critical submergence for pipe intake

U_∞ : Average approach flow velocity

V_d : Average rectangular intake velocity

V_p : Average pipe intake velocity

W : Weber number

μ : Dynamic viscosity

ρ : Density

Γ : Circulation

σ : Surface tension

ν : Kinematic viscosity

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