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Critical Submergence for Horizontal Intake Structures under Symmetrical Approach Flow Conditions

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Outline

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- Modeling Air- Entraining Vortices
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- Conclusions

Introduction

Definition of;

Vortex: Simply, swirling motion with an air ingestion into a pipe

Critical Submergence: A vertical distance between the free- surface and the intake where air-entraining vortices start to occur

Reasons of vortices;

- Eccentric place of intake
- Velocity gradients
- Obstructions in flow fields

Problems due to the occurrence of Vortices;

- Increasing loss of hydraulic load
- Loss of discharge at the water intake structure
- Loss of efficiency in hydraulic machines such as turbines due to low discharge
- Operational problems in hydraulic machines
- Suction, cavitation and vibration problems in hydraulic machines

Introduction

Motivation of the Study;

- There is no study presented in the literature that investigates the effect of the approach Froude number on the formation of air-entraining vortices at horizontal intake structures.
- A geometry parameter based on the sidewall clearances and intake size as a function of dimensionless critical submergence was only revealed by Baykara (2013), Haspolat (2015) and Gokmener (2016). However, these studies did not consider the approach Froude number and have some limitations in terms of flow conditions and geometrical properties.
- For instance, Gökmener (2016) carried out experiments on a large-scale intake structure when compared to Baykara (2013) and Haspolat (2015), but tested a constant pipe diameter having narrow ranges of Froude, Reynold and Weber numbers. On the other hand, Baykara (2013) and Haspolat (2015) conducted experiments on small-scale intake structures but tested varying intake pipe diameters with a wide range of Froude, Reynold and Weber numbers.
- Consequently, as the main aim of this study, the data of Baykara (2013), Haspolat (2015) and Gokmener (2016) are combined and reanalyzed to eliminate the limitations of these studies and to propose new and more general dimensionless equations to predict critical submergence under symmetrical approach flow conditions as a function of flow and geometrical parameters.

Modeling of Air- Entraining Vortices

$$S_c = f_1(\rho, \mu, \sigma, g, V_i, V_{app}\, \Gamma, D_i, a, b_1, b_2\ )$$

$$S_c = f_2(\frac{b_1+b_2}{D_i}, \frac{a}{D_i}, (Fr)_{app}, (Fr)_i, Re, We, K_o)$$

$$S_c = f_3({}^{2b}/_{D_i}, (Fr)_{app}, (Fr)_i, Re, We)$$

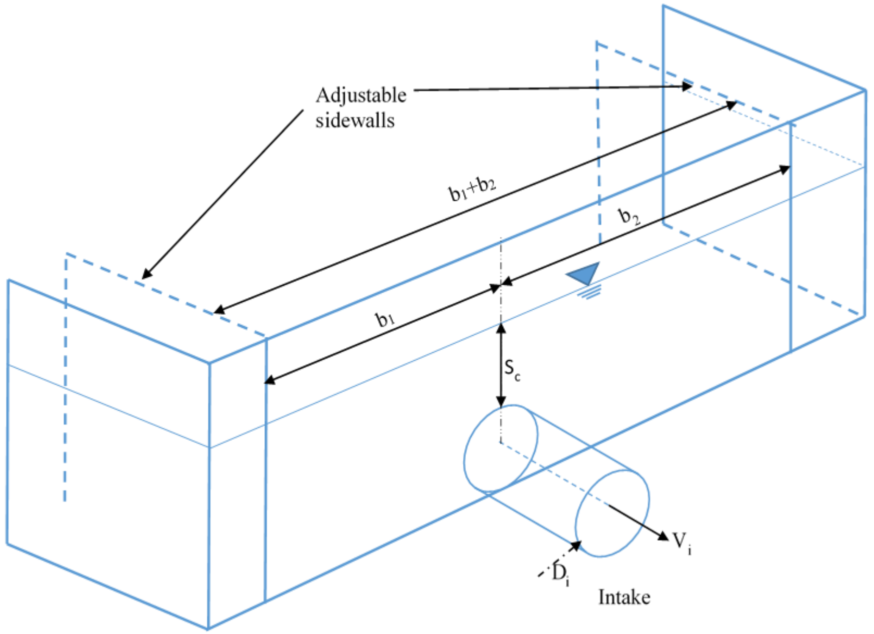

Fig. 1. A sketch of the horizontal intake structure

Modeling of Air- Entraining Vortices

- 409 experimental data from Baykara (2013), Haspolat (2015) and Gokmener (2016) are considered and analyzed to investigate the effect of flow and geometry properties on critical submergence at single horizontal intakes under symmetrical approach flow conditions.

D_i (cm)	Q_i (lt/s)	S_c/Di	$(Fr)_{app}$	$(Fr)_i$	Re	We	$2b/D_i$	No. Of Observations
30	64.34 ~ 29.19	1.91 ~ 0.28	0.112 ~ 0.029	0.53 ~ 0.24	273053 ~ 123883	3408 ~ 701	4.67 ~ 1.33	63
26.5	126.83 ~ 77.53	2.08 ~ 1.37	0.067 ~ 0.018	1.43 ~ 0.87	609393 ~ 372496	19215 ~ 7179	10.57 ~ 3.02	21
25	62.55 ~ 24.35	2.43 ~ 0.44	0.111 ~ 0.031	0.81 ~ 0.32	317168 ~ 123419	5561 ~ 842	5.60 ~ 1.60	90
19.4	62.55 ~ 21.69	3.33 ~ 0.64	0.114 ~ 0.034	1.53 ~ 0.53	408721 ~ 141729	11902 ~ 1431	7.22 ~ 2.01	73
14.4	62.55 ~ 21.69	5.24 ~ 1.07	0.133 ~ 0.038	3.23 ~ 1.12	550638 ~ 190941	29102 ~ 3499	9.72 ~ 2.78	67
10	51.65 ~ 17.84	6.65 ~ 1.88	0.123 ~ 0.038	6.64 ~ 2.29	654745 ~ 227213	59251 ~ 7079	12.00 ~ 4.00	67
5	14.69 ~ 5.20	4.42 ~ 1.04	0.115 ~ 0.038	10.68 ~ 3.78	372438 ~ 132522	38343 ~ 4816	20.00 ~ 8.00	28

Table 1 Ranges of significant hydraulic and geometric parameters analyzed in this study under symmetrical approach flow conditions

Results

Variation of S_c/D_i with Dimensionless Flow and Geometric Parameters

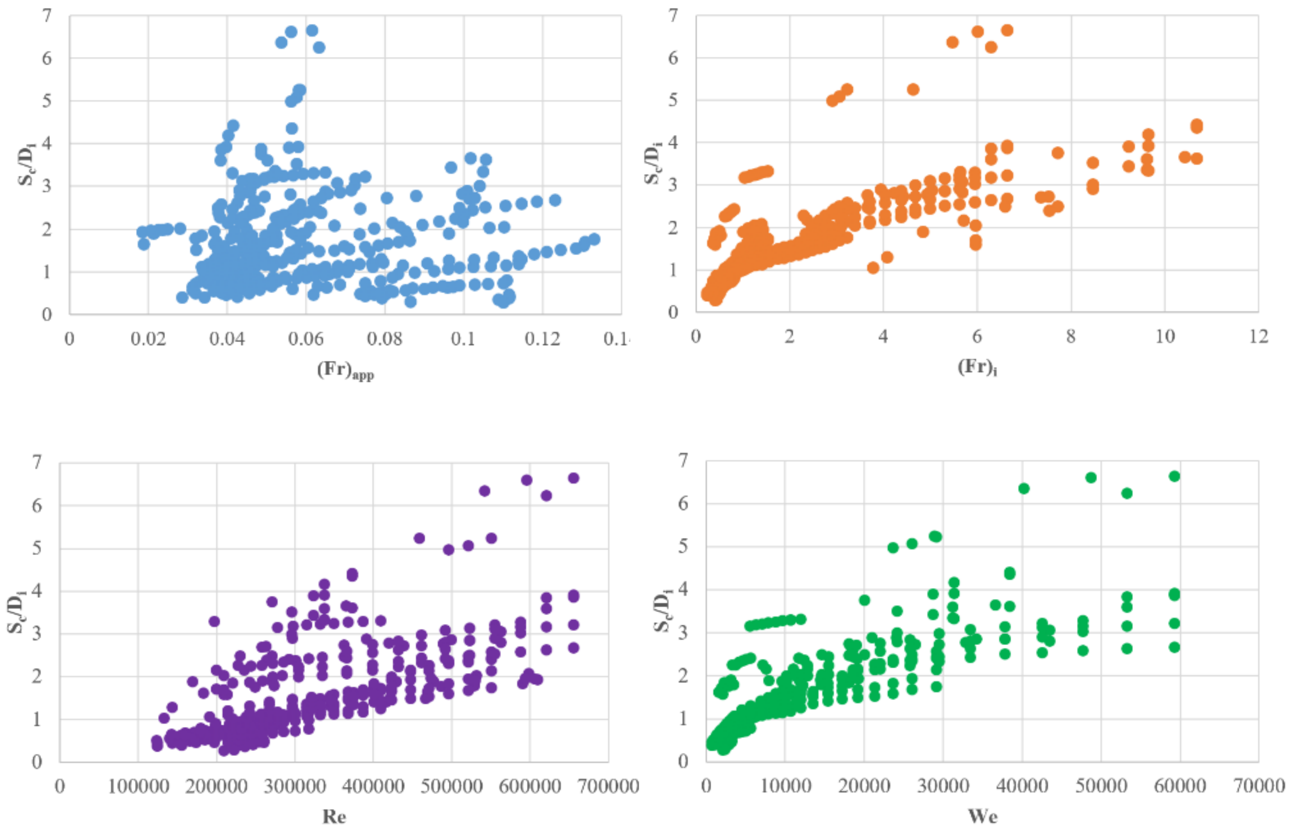

Fig. 2 Variation of dimensionless critical submergence, S_C/D_i with $(Fr)_{app}$, $(Fr)_i$, Re and We under symmetrical approach flow conditions

Results

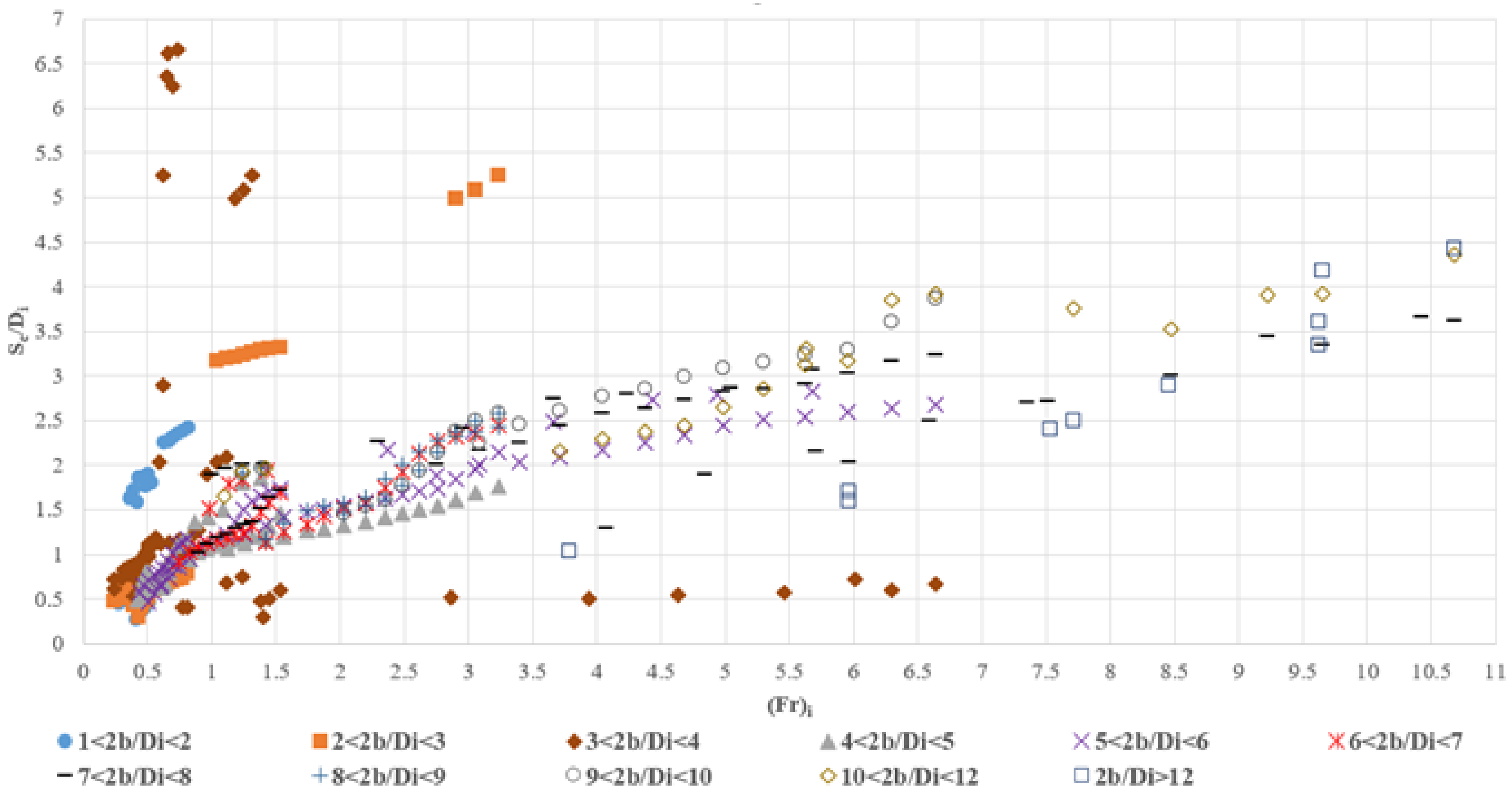

Fig. 3 Variation of S_c/D_i with $(Fr)_i$ for varying $2b/D_i$ under symmetrical approach flow conditions

Results

Scheme of the derived empirical equations;

4. $\frac{S_C}{D_i} = (Fr_{app})^a (Fr)^b (Re)^c (We)^d \left(\frac{2b}{D_i}\right)^e$

5. $\frac{S_C}{D_i} = (Fr_{app})^a (Fr)^b (Re)^c \left(\frac{2b}{D_i}\right)^d$

6. $\frac{S_C}{D_i} = (Fr_{app})^a (Fr)^b \left(\frac{2b}{D_i}\right)^c$

7. $\frac{S_C}{D_i} = (Fr_{app})^a (Fr)^b$

8. $\frac{S_C}{D_i} = (Fr_{app})^a$

9. $\frac{S_C}{D_i} = (Fr_{app})^a \quad \frac{S_C}{D_i} = (Fr)^a (Re)^b (We)^c \left(\frac{2b}{D_i}\right)^d$

10. $\frac{S_C}{D_i} = (Fr)^a (Re)^b \left(\frac{2b}{D_i}\right)^c$

11. $\frac{S_C}{D_i} = (Fr)^a \left(\frac{2b}{D_i}\right)^b$

12. $\frac{S_C}{D_i} = (Fr)^a$

Table 2. Derived empirical equations with their performance indicators

Equation Number	Regression Coefficients					R^2	SER	MAPE (%)	AAD	RMSE
	a	b	c	d	e					
Eqn. (4)	-0.910	0.808	-0.226	0.198	-0.895	0.988	0.118	9.61	0.089	0.117
Eqn. (5)	-0.931	0.982	-0.089	-0.937	-	0.984	0.137	11.79	0.116	0.136
Eqn. (6)	-0.522	0.877	-0.862	-	-	0.937	0.272	19.50	0.219	0.272
Eqn. (7)	-0.088	0.502	-	-	-	0.675	0.618	26.97	0.367	0.617
Eqn. (8)	-0.162	-	-	-	-	-0.025	1.096	73.66	0.841	1.095
Eqn. (9)	0.333	-0.218	0.412	-0.417	-	0.780	0.510	23.02	0.343	0.507
Eqn. (10)	0.687	0.076	-0.502	-	-	0.762	0.530	27.07	0.385	0.528
Eqn. (11)	0.560	0.056	-	-	-	0.621	0.668	19.23	0.348	0.666
Eqn. (12)	0.629	-	-	-	-	0.616	0.671	19.44	0.361	0.671

Discussion

- The intake Froude number $(Fr)_i$ is the most influential parameter affecting dimensionless critical submergence (S_c/D_i) with a nonlinear increasing trend that plateaus at high values due to inertia dominance.
- Narrow sidewall configurations $(1<2b/D_i<4)$result in significantly higher S_c/D_i values, as confined flow areas intensify vortex strength and demand greater submergence to prevent air entrainment.
- Wider intake geometries $(2b/D_i>12)$ reduce the critical submergence requirement by promoting uniform flow distribution, lowering velocity gradients, and minimizing vortex formation.
- Intermediate geometries $(4<2b/D_i<12)$ exhibit a stabilizing effect on vortex dynamics, with reduced sensitivity of S_c/D_i to changes in $(Fr)_i$, indicating more balanced and less turbulent flow conditions.
- Empirical models incorporating both $(Fr)_i$ and $2b/D_i$ demonstrate the highest predictive accuracy, while models excluding geometric effects or using only $(Fr)_i$ show moderate reliability.
- Although $(Fr)_{app}$ has weak direct correlation with S_c/D_i , its inclusion in dimensionless formulations enhances prediction due to its implicit role in dimensional analysis. Additionally, the inclusion of Reynolds and Weber numbers slightly improves prediction accuracy despite their relatively limited physical influence.

Discussion

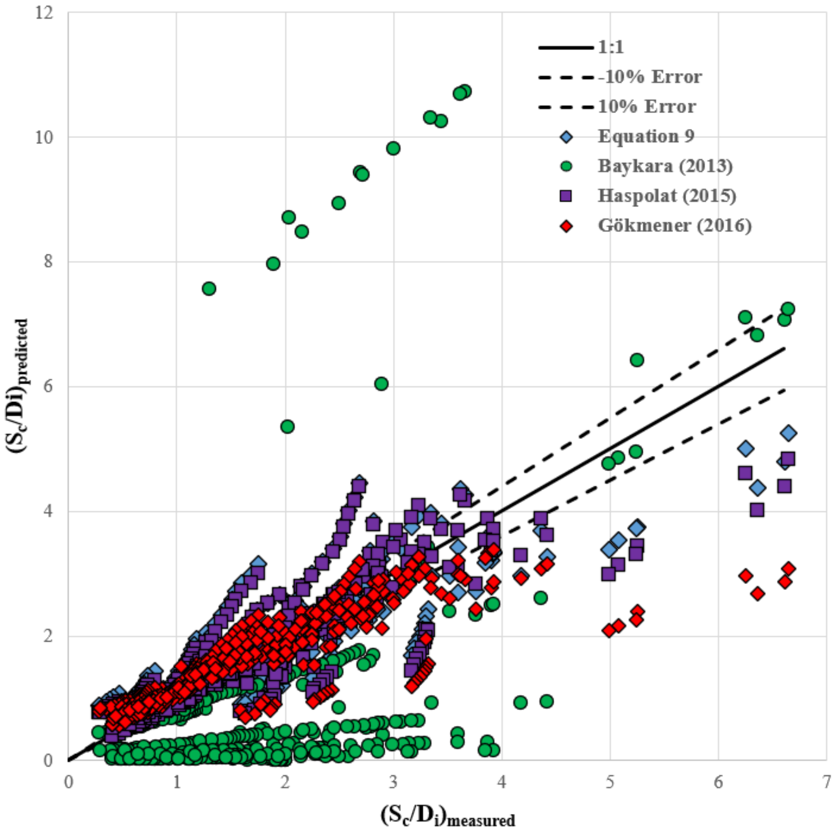

Fig. 7 Comparison of $(S_c/D_i)_{measured}$ and $(S_c/D_i)_{predicted}$ from Eqn. (9), Baykara (2013), Haspolat (2015) and Gökmener (2016)

- Most data points cluster around the 1:1 line, indicating good agreement, particularly for Eqn. (9), which demonstrates the most consistent predictive performance across the combined dataset.
- In contrast, the predictions of Baykara's equation show a wider scatter, particularly at higher S_c/D_i values, suggesting limitations in generalizability when applied to the broader dataset.
- Conversely, the equations of Haspolat (2015) and Gökmener (2016) exhibit closer alignment with the 1:1 line, indicating relatively better predictive performance.
- These results suggest that Eqn. (9), by leveraging the combined data, provides a more generalized and robust predictive capability compared to the individual empirical equations, particularly under a variety of flow and geometric conditions.

Conclusions

- The intake Froude number $(Fr)_i$ and geometric ratio $2b/D_i$ are the most critical parameters influencing dimensionless critical submergence (S_c/D_i), with narrow geometries requiring higher submergence due to stronger vortex effects.
- Equation (4), incorporating all key flow and geometric variables, achieved the highest predictive accuracy with R^2=0.988, making it a reliable model for engineering design applications.
- The study provides a valuable theoretical basis for optimizing intake design under symmetrical flow conditions.

For further research:

- Similar studies should be carried out considering the asymmetrical approach flow conditions.
- Scale effect between the model and prototype should also be investigated.

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