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Design of Coanda Intakes for Optimum Sediment Release Efficiencies

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ABSTRACT

When the water has to be diverted from a turbid source having a great amount of suspended materials in it, bottom intake structures such as Coanda and Tyrolean types are preferred. To perform this task, diverted water is captured by a transversal rack, and a gallery located in the control crest is utilized. This study was motivated by a search for the best design where the quality of the diverted water can be increased by screening out most of the sediments in the flow. Current work focuses on the water capture and sediment release efficiencies of both Tyrolean and Coanda type intakes through experimental work. It complements and extends existing experimental studies by considering sediment-laden flow. We used a novel sediment feeding system designed specifically for this study in the experiments. Study results pointed out that when sediment release efficiency is considered, all types of Coanda intakes having different design parameters performed better as compared to Tyrolean intakes. Water capture and sediment release efficiencies are related to parameters used in the experiments including Coanda type, rack angle, void ratio, sediment amount, and flow rate based on the statistical analyses of these parameters. An optimum design is proposed with the maximum sediment release efficiency to prevent clogging during the operation of the intakes.

1. Introduction

Intake structures on channels or in reservoirs are frequently used to divert/withdraw a certain amount of water discharge for various purposes of use such as irrigation, potable water supply, and generation of hydroelectric power. Hydrologic, geotechnical, topographic, and climatic factors directly affect the type of intake structures that will be constructed. Factors such as excessive rain or snowmelt and greater river bed slope which can result in high flow rates make it impossible to use the frontal and lateral intake structures. When the water has to be diverted from a turbid source having a great amount of suspended materials in it, bottom intakes structure such as Coanda and Tyrolean types are preferred. To perform this task, diverted water is captured by a transversal rack, and a gallery located in the control crest is utilized. With a proper design of the intake, the quality of the diverted water can be increased by screening out most of the sediments in the flow. In the design of the structure, it is necessary to consider different aspects. The efficiency of the intake structure depends on various factors such as the shape of the bars, clear spacing between the bars (void ratio), flow approximation conditions and flow discharge, the angle of the rack, rack length, sediment rate, etc. It is assumed that flux over the rack is one-dimensional, flow decreases progressively, hydrostatic pressure distribution acts over the rack in the flow direction, and energy level or energy head can be considered constant along with the rack. Several researchers have studied this problem using analytical models. Of these studies, pioneer research was conducted by Noseda (1955), where he studied the clear water flow through different racks of a Tyrolean intake. Differences between measured and calculated depth profiles are generally found at the beginning of the rack due to the consideration of hydrostatic pressure distribution, and at the edge of the rack when friction effects are neglected (Brunella et al., 2003). Noseda (1955) defined a variable discharge coefficient for horizontal rack case and subcritical approximation flow:

$$C_q = 0{,}66\ \mathrm{m}^{-0{,}16}\left(\frac{h}{a}\right)^{-0{,}13}, \tag{1}$$

where a is referred to the distance between the centerline of two consecutive bars, m is the void ratio and h is the height of water measured in the vertical direction. Once all the parameters are

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defined, several researchers (Kuntzmann and Bouvard, 1954; Noseda, 1955; Frank, 1956) have proposed the wetted rack length necessary to derive a defined flow rate. The value of the wetted rack length proposed by Noseda (1955) is obtained with the following equation:

$$L = 1{,}1848\frac{h}{C_q m}, \tag{2}$$

where L is the wetted rack length. To estimate the required wetted length for all slopes (up to 33%) the following equation is proposed (Castillo et al., 2017):

$$L = \frac{h}{C_q m}(1+0{,}3 * tan\,\theta)\ . \tag{3}$$

Most of the previous research considered the assumption of gradually varied flow over the rack and on the application of the 1-D energy or momentum conservation equation (i.e., Kuntzmann and Bouvard, 1954; Frank, 1956; Noseda, 1956). More recently, researchers conducted laboratory measurements and presented empirical expressions to compute the wetted rack length (Brunella et al., 2003; Castillo et al., 2016).

In various experimental studies, researchers used different shaped bars in their experiments and defined rack shape coefficient in their studies. All these equations vary from very simple wetted rack length related to flow depth at the end of the rack (Henderson, 1966) to very complex equations (Castillo et al., 2016) where it is related to discharge coefficient, void ratio, rack angle, and other parameters.

Frank (1956) considered the water level over the rack as an elliptic arch which proceeded from a constant energy level over the rack. The major half-axis of the ellipse corresponded to the wetted screen length L, the minor half-axis corresponded to the flow-depth which sets in at the assumed beginning of the rack, at the level of the weir crest, with the angle of inclination a when the energy level gets to its minimum. The wetted rack length then was presented using a reduction factor depending on the inclination of the rack. Table 1 summarizes the equations developed by several researchers within the years.

In more recent studies conducted by Yılmaz (2010) and Şahiner (2012); comprehensive sets of experiments related to Tyrolean intakes were done. As a result of these studies, it was stated that; the water capture efficiency first decreases with increasing rack angle, θ up to a value of about 15 and then increases with increasing value of θ up to the value of about 27° and finally decreases again with increasing θ. For a constant discharge, the water capture efficiency (*WCE*) attains almost the same maximum values at two different rack angles of $\theta = 5°$ and $\theta = 27°$. They stated that, $\theta = 27°$ should be selected to reduce the risk of clogging of the bar openings due to the presence of sediment in the flow in practical applications.

In different studies, researchers investigated the behavior of clear water over the rack with different slopes, bar spacing, and shapes (Yılmaz, 2010; Şahiner, 2012; Castillo et al., 2017) but not many studies could be found where sediment was fed into the system and the sediment characteristics were provided as parameter. So this study aims to fulfill this gap in the literature via a series of experiments.

The review of the existing literature clearly shows that the

Table 1. Summary of Wetted Rack Lengths to Derive an Approaching Flow as Proposed by the Authors

Reference	Discharge coefficient, C_q	Wetted rack length, L (m)
Noseda (1955)	$C_q = 0{,}66m^{-0{,}16}\left(\frac{h}{l}\right)^{-0{,}13}$	$L = \frac{1{,}848h}{C_q \times m}$
Frank (1956)	(No suggested values for C_q)	$L = \frac{1{,}811h}{C_q \times m \times \sqrt{\chi} \times (\cos\theta)^{1{,}5}}$
Drobir et al. (1999)	(No suggested values for C_q)	$L = \frac{0{,}846h}{C_q \times m}$
Brunella et al. (2003)	$C_q = 0{,}87$	$L = \frac{0{,}83h}{C_q \times m}$
Righetti and Lanzoni (2008)	C_q discharge coefficient under static conditions	$\Delta q = \left(C_q \times m \times B \times L \times \sqrt{2gh}\right)\left(\frac{a \times L}{2h} Fr + 1\right)\left(\tanh\left(b_0\left(\sqrt{2} - Fr\right)\right)\right)^{b1}$ $a = -0{,}1056;\ b_o = 1{,}5;\ b_1 = 0{,}478$
Vargas (1998)		$L = 1{,}1 \times \sqrt{\frac{2 \times q^2 \times \cos\theta}{m \times g \times h}}$
Henderson (1966)		$L = 1{,}43 \times h$
Castillo et al. (2017)	$C_q = a \times \exp(-0{,}77m)$ a = 1,43; 1,15; 0,9 for circular, prismatic and T-shaped bars	$L = 1{,}3 \times \left(\frac{h}{m} \times C_q\right)(1 + 0{,}3 \times \tan\theta)$

Note: For details of the experimental setups one should refer to the papers. In the equations, C_q refers to discharge coefficient, m is the void ratio, L is the wetted rack length, h is the head over the weir, θ is the rack angle, χ is the reducing factor for inclination of the rack, q is the unit discharge.

behavior of clear water over the rack is well studied and water trap efficiency of Tyrolean type inlets with respect to rack slopes, bar spacing, and bar shapes are well defined in the previous studies. These studies pointed out certain rack angles and bar spacing for optimum design. The present contribution aims at investigating experimentally the optimum design by both evaluating Coanda and Tyrolean type intakes under sedimentladen flow.

We first evaluate the results of the experiments conducted by the other researchers through statistical analyses, then describe the experiments we conducted by Coanda intakes under sediment-laden flow and finally discuss the results of experiments within this paper.

2. Materials and Methods

2.1 Statistical Analysis of Experimental Data by Multiple Linear Regression

Two basic mechanisms, the shearing effect and orifice effect control how the incoming flow is directed through the screen to the collecting channel. Both mechanisms act simultaneously at different ratios depending on the flow and screen properties. To investigate which dimensionless parameter characterizes diversion of the flow, we conducted dimensional analysis considering the following parameters:

$$A = f\{\alpha, \theta, R, h_0, p, Q_t, L, a, e, V, g, \rho, \rho_s, \upsilon, \sigma, d_{50}, \sigma_D\}, \quad (4)$$

where α = wire tilt angle, θ = screen slope, R = screen curvature radius, h_0 = flow depth at the beginning of the screen, p = accelerator plate height, Q_t = total incoming flow, L = screen length, a = distance between centerline of the two consecutive bars, e = gap distance between two consecutive bars, V = velocity of incoming flow at the beginning of the screen, g = gravitational acceleration, ρ = density of water, ρ_s = density of sediment, υ = kinematic viscosity, σ = surface tension, d_{50} = median of the sediment diameter, σ_D = uniformity coefficient.

In the analysis, viscosity is neglected due to the turbulent character of the flow. The sediment type to be used in the experiments does not change and thus, $\rho s/\rho$ is taken as a constant. Both dependent parameters; water capturing performance (WCP) and sediment release efficiency (*SRE*) are estimated through the following nondimensional independent parameters obtained from the application of Vaschy-Buckingham theorem:

$$\pi = f\left\{\alpha, \theta, \frac{p}{R}, \frac{L}{R}, \frac{e}{a}, \frac{e}{R}, \frac{V}{\sqrt{g.h_0}}, \frac{V}{\sqrt{g.R}}, \sqrt{\frac{Q_t/L}{e^3 g}}, \frac{\rho V^2 R}{\sigma}, \frac{d_{50}}{e}\right\}. \quad (5)$$

Table 2 summarizes the effective nondimensional parameters defined as a result of the analysis.

Using the data from the current experiments, the water capture efficiency for the Coanda type intake is related to independent variables such as rack slope, void ratio, the ratio of the bar opening to curvature radius, the ratio of screen length to the screen curvature, Froude number based on screen curvature and Weber number. As for the prediction of the second dependent parameter; sediment release efficiency, the same independent variables mentioned above together with one additional parameter, the ratio of the mean sediment diameter to the bar opening were utilized.

Table 2. Dimensionless Parameters Affecting Flow on Coanda Screen

Dimensionless parameters	Description
α	Wire tilt angle
θ	Screen slope
p/R	The ratio of accelerator plate to the curvature radius
L/R	The ratio of screen length to the curvature radius
$m = e/a$	Void ratio
e / R	The ratio of the bar opening to the curvature radius
$Fr = \frac{V}{\sqrt{g.ho}}$	Froude number
$Fr_R = \frac{V}{\sqrt{g.R}}$	Froude number based on the screen curvature
$Fre = \sqrt{\frac{Q_t/L}{e^3 g}}$	Froude number based on the bar opening
$We = \frac{\rho V^2 R}{\sigma}$	Weber number
d_{50} / e	The ratio of the mean sediment diameter to the bar opening

For this purpose; we utilized multiple linear regression analysis. Several assumptions with the analysis include: the relationship between the independent and dependent variables to be linear and the errors between observed and predicted should be normally distributed. In the analysis, independent variables were determined by applying Vaschy-Buckingham theorem. Regression coefficients are calculated and the prediction model for the diverted flow rate is established as in the following equation by the multiple linear regression analysis.

$$Y = A + BX_1 + CX_2 + DX_3 + EX_4 + FX_5 + GX_6 \quad (6)$$

Using the data from the current experiments presented in this paper, multiple linear regression analysis is utilized to predict water capture efficiency and the sediment release efficiency for Coanda type intakes. Regression coefficients are calculated and the prediction models for the water capture efficiency and sediment release efficiency are established by the multiple linear regression analysis.

2.2 Experimental Setup

Experiments are conducted in the hydraulics laboratory of Izmir Institute of Technology in Turkey, utilizing a setup specifically designed for this study (Fig. 1). Two types of intake structures – Tyrolean and Coanda types are built so that the effects of intake type, incoming flow rate, sediment concentration and composition, rack angle, and the void ratio on the water capture efficiency, and the sediment release efficiency can be studied via experiments.

Fig. 1. Experimental Setup

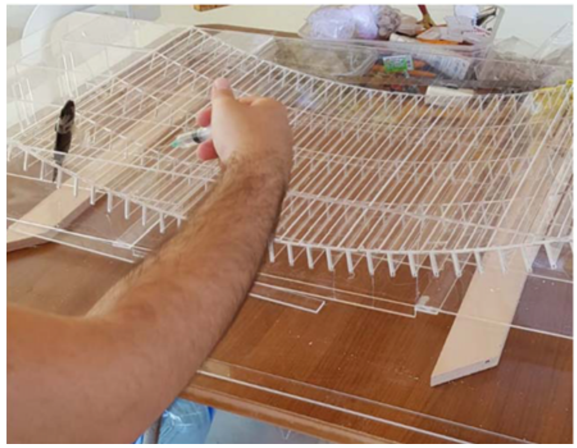

Fig. 3. Manufacturing of the Coanda Intake

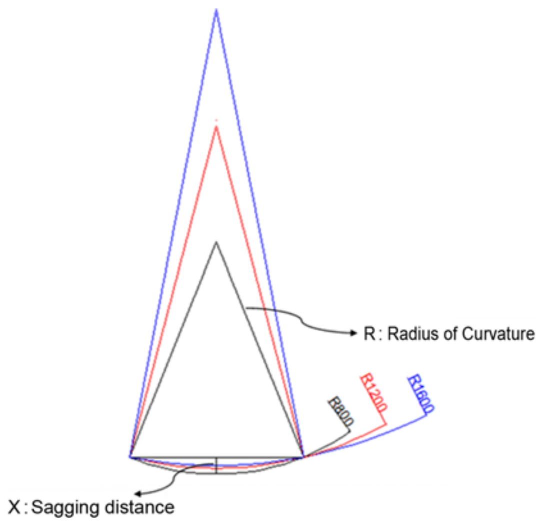

Fig. 2. Derivation of Coanda Shapes Based on Curvature Slices for Various Radius Values (R = 800, 1200, 1600 mm)

While designing Coanda intakes, no specifications could be found in the literature. So the design utilized in this study is based on curvature slices obtained from various Radius values (R = 800, 1200, 1600 mm). The intakes are designed so that the slice would fit a constant channel width (B = 40 cm). The selected curbs have a constant ratio of the sagging distance over curvature radius (X/R). During the experiments, various Coanda intake designs (having ratios of 0,079; 0,032; 0,0156 for curvature radius values of R = 800, 1200, 1600 mm) are implemented. The characteristics of the final curbs as shown in Fig. 2 are used in the final design of the Coanda intakes.

Figure 3 shows the manufacturing stages of the Coanda type intake having a curvature radius of 1200 mm. The details of the rack are provided in Fig. 4. T shaped bars are used to create the uniform spacing in each rack. A total of 30 T shaped bars are used to manufacture each rack.

Figure 5 shows the Tyrolean and Coanda type intakes used during the experiments. Wood sockets mounted on the two sides of the intake walls served the purpose of eliminating the human error when varying the rack angle from 0 to 30 degrees at 5 degrees increments. Initially 300 g of sediments having d = 0,8 mm is fed into the system by a novel sediment feeder system designed specifically for this study. Then sediment amount and composition are varied to investigate different parameters. The sediment feeding system is designed using Arduino which is an open-source electronics platform used for building interactive prototypes. The sediment feeding system allowed the user to control the frequency and amount of the feeding of sediments to the intake structure. Fig. 6 shows the sediment feeding system used in the experiments.

Sediments passing through the intake structure are collected using a drawer-like sediment trap designed for the setup. At the end of each experiment, trapped sediments are dried and weighed.

During the experiments, water pumped from the storage tank is directed into 1 tone of tank attached to the setup to dissipate

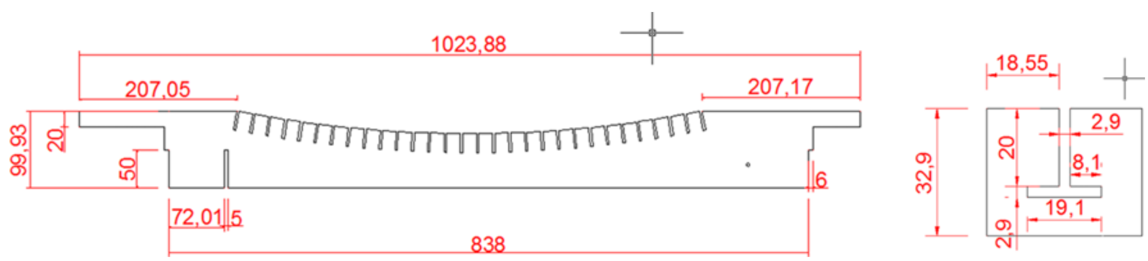

Fig. 4. Details of the Coanda Intake Having a Curvature Radius of 1200 mm and Void Ratio of 1 mm (The dimensions shown are in mm.)

(a) (b)

Fig. 5. Tyrolean and Coanda Type Intakes Used during the Experiments: (a) Tyrolean, (b) Coanda

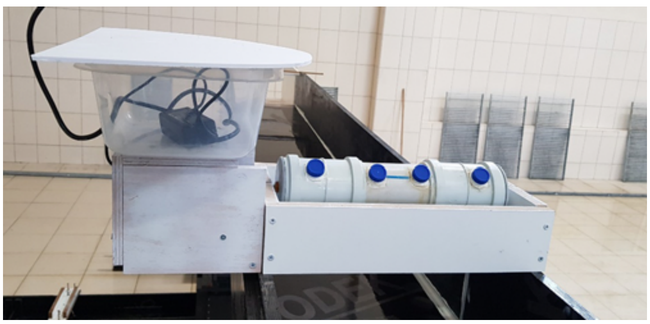

Fig. 6. Sediment Feeding System Used in the Experiments

excess energy, and water is let into the channel through a weir. Two different pumps; submersible pump having a discharge capacity of 4 l/s (constant head) for low discharge experiments and the main pump in the laboratory having a discharge capacity of 120 l/s (having adjustable efficiency and time-variable discharge) are used in the experiments.

The incoming flow rate and the diverted discharge are measured using two different methods. A vertical point gauge is used to measure head over sharp-crested weir installed at the outlet for diverted discharge measurement. The measured head is then converted to flow rate via weir Eq. (7):

$$Q = \frac{2}{3} C_w W \sqrt{2g} h^{3/2} , \quad (7)$$

where h is the measured head, W is the channel width, and C_w is the weir coefficient ($C_w = 0{,}635$) calibrated in the experiments. A Sontek Flowtracker (10 MHz) Acoustic Doppler Velocimeter (ADV) is also used to validate the measured flow velocities. The rated accuracy of the system is 1% of the current speed. A 20-s averaging interval is applied to data with a sample interval of 1 s.

3. Experiments

The water capture efficiency and the sediment release efficiency of the two types of intakes are evaluated through experiments. The angle of rack inclination, θ is selected as 5, 10, 15, 20, 25, and 30 in the experiments. Each experiment is repeated 3 times and the average values of these experiments are presented in the

Table 3. Parameters Utilized in the Experiments

Intake type	θ (°)	m	Qdiverted (l/s)	*Si* (g)	*WCE* (%)	*SRE* (%)
Coanda (R80)	5	0,046	3,68	240	66	48
Coanda (R80)	10	0,046	3,23	182	58	55
Coanda (R80)	15	0,046	3,16	122	57	69
Coanda (R80)	20	0,046	3,11	111	56	71
Coanda (R80)	25	0,046	3,08	102	55	73
Coanda (R80)	30	0,046	2,80	72	50	79
Coanda (R120)	5	0,046	4,66	403	84	31
Coanda (R120)	10	0,046	4,16	305	75	41
Coanda (R120)	15	0,046	4,00	243	72	51
Coanda (R120)	20	0,046	3,84	238	69	50
Coanda (R120)	25	0,046	3,92	244	71	50
Coanda (R120)	30	0,046	3,95	210	71	57
Coanda (R160)	5	0,046	4,00	286	72	43
Coanda (R160)	10	0,046	3,61	200	65	56
Coanda (R160)	15	0,046	3,53	165	63	63
Coanda (R160)	20	0,046	3,38	150	61	65
Coanda (R160)	25	0,046	3,08	120	55	69
Coanda (R160)	30	0,046	3,01	84	54	78
Coanda (R80)	5	0,092	4,32	444	78	18
Coanda (R80)	10	0,092	4,08	370	73	27
Coanda (R80)	15	0,092	3,98	340	72	32
Coanda (R80)	20	0,092	3,68	295	66	36
Coanda (R80)	25	0,092	3,61	270	65	40
Coanda (R80)	30	0,092	3,45	274	62	36
Coanda (R80)	5	0,138	4,83	468	87	22
Coanda (R80)	10	0,138	4,49	330	81	41
Coanda (R80)	15	0,138	4,16	275	75	47
Coanda (R80)	20	0,138	4,08	278	73	45
Coanda (R80)	25	0,138	4,00	273	72	46
Coanda (R80)	30	0,138	3,97	264	71	47
Coanda (R160)	5	0,092	4,08	329	73	36
Coanda (R160)	10	0,092	3,68	236	66	49
Coanda (R160)	15	0,092	3,53	193	63	56
Coanda (R160)	20	0,092	3,45	182	62	58
Coanda (R160)	25	0,092	3,42	175	62	59
Coanda (R160)	30	0,092	3,38	163	61	61

Note: Here θ is the angle of rack inclination, m is the void ratio defined by the ratio of the spacing between the bars to the total distance, $Q_{diverted}$ is the water entering into the intake, *WCE* is the water capture efficiency of the intake, *Si* is the amount of sediments captured by the intakes and *SRE* is the ratio of nondimensionalized concentration of the sediments passing over the intake system.

study. The spacings between the bars of the rack are selected as 1, 2, and 3 mm, which resulted in void ratios of 0,046, 0,092, 0,138 respectively. The experiments continued for three minutes after the feeding of the sediment started and a constant discharge was maintained. Water height above the weir (h) is measured via a point gauge for the given discharge. Considering that 300 g of sediment is fed into the system for three minutes, the concentration of the sediments is calculated as 0,7 g/l during the experiments. This value is comparable to a turbid river in nature. Table 3 presents the parameters and the observed values utilized in experiments of Coanda intakes where 695-gram sediments were fed to the flow rate of 5,56 l/s.

4. Results

4.1 Results of the Statistical Analysis

A total of 271 experiment data from three studies (Yılmaz, 2010; Castillo et al., 2017; and our results) are used in the analysis to predict the diverted discharge in Tyrolean type intakes. The statistical analysis leads to the following equation relating water capture efficiency to rack angle, θ; the ratio of bar opening to screen length, e/L; void ratio, m; and Froude number based on bar opening, Fre:

$$WCE = 119{,}1 - 0.59(\theta) - 13{,}5\left(\frac{e}{L}\right) - 205{,}9(m) - 0.00048(Fre)\,. \quad (8)$$

The adjusted variance value is 0,74 for the analysis indicating that the diverted discharge is predicted well based on the independent parameters. An analysis on the relative importance of independent parameters to predict WCE in Tyrolean type intakes showed that void ratio, m had the highest relative importance by 50% whereas Froude number based on bar opening, Fre had the second relative importance by 27%, and the ratio of bar opening to screen length, e/L followed these two parameters by 18%. The results showed that the rack angle, θ did not have a significant effect on the prediction of WCE as compared to the other parameters.

Multiple linear regression is also utilized to derive a formulation for water capture performance and sediment release performance of the Coanda type intakes. A total of 108 experiment data monitored during this study are utilized in the analysis. The statistical analysis leads to the following equation relating water capture efficiency to the rack angle, θ; void ratio, m; the ratio of the bar opening to the curvature radius, e/R; the ratio of the screen length to the curvature radius, L/R; Froude number based on the screen curvature, Fr_R; and Weber number, We:

$$WCE = 128 - 0.555(\theta) - 121.8(m) + 11255\left(\frac{e}{R}\right) - 36\left(\frac{L}{R}\right) - 114.3\left(\frac{V}{\sqrt{g.R}}\right) - 0.00187\left(\frac{\rho V^2 R}{\sigma}\right). \quad (9)$$

The adjusted variance value is 0.93 for the analysis indicating that the diverted discharge is predicted well based on the independent parameters. Results of the multiple linear regression analysis used to predict the WCE in Coanda intakes are presented in Table 4. The comparison of the predicted WCE values with the monitored values is plotted in Fig. 7.

An analysis on the relative importance of independent parameters to predict WCE in Coanda type intakes showed that

Table 4. Summary Output Table for the Multiple Linear Regression Analysis for Prediction the *WCE* for Coanda Intakes

Summary Output

Regression Statistics	
Multiple R	0,9633396
R Square	0,9280232
Adjusted R Sq	0,9138464
Standart Error	4,6297846
Observations	108

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	7	27913,18441	3987,598	217,0384	1,69572E-57
Residual	101	2164,925423	21,43491		
Total	108	30078,10984			

	Coefficients	*Standart Error*	*t Stat*	*P-value*	*Lower %95*
Intercept	127,96522	5,293969174	24,17189	8,7E-44117,4634119	
X Variable 1	-0,554968	0,052171762	-10,6373	3,55E-18	-0,658463219
X Variable 2	-121,7578	62,84746464	-1,93735	0,055495	-246,430313
X Variable 3	11255,001	2672,245599	4,211814	5,51E-05	5953,984756
X Variable 4	-36,04914	9,340592657	-3,85941	0,000201	-54,57835964
X Variable 5	-114,2906	15,20485961	-7,51672	2,34E-11	-144,4530014
X Variable 6	-0,001874	0,000239776	-7,81598	5,36E-12	-0,002349734

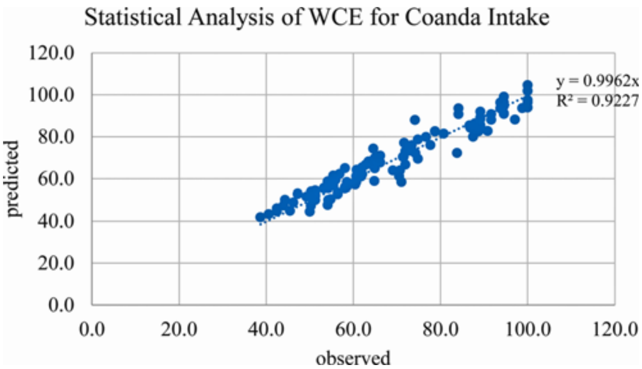

Fig. 7. Comparison of Observed Water Capture Efficiency (*WCE*) Values with the Predicted Values

Froude number based on the screen curvature, Fr_R; and Weber number, *We* had the highest relative importance by 40% and 37%, respectively, whereas rack angle, θ; the ratio of the bar opening to the curvature radius, *e/R; and* void ratio, *m*; were almost equally important to predict *WCE* having 9%, 7% and 6% relative importance percentages. The results showed that the ratio of the screen length to the curvature radius, *L/R* did not have a significant effect on the prediction of *WCE* in Coanda type intakes.

The prediction model for the sediment release efficiency is established by the multiple linear regression analysis. The statistical analysis leads to the following equation relating sediment release efficiency, *SRE* to the rack angle, θ; void ratio, *m*; the ratio of the bar opening to the curvature radius, *e/R*; the ratio of the screen length to the curvature radius, *L/R*; Froude number based on the screen curvature, Fr_R; Weber number, *We*; and the ratio of the mean sediment diameter to the bar opening, d_{50}/e:

$$SRE = -143.3 + 0.95(\theta) + 1102.9(m) - 30945\left(\frac{e}{R}\right) + 56.1\left(\frac{L}{R}\right) + 207.1\left(\frac{V}{\sqrt{g.R}}\right) + 0.0018\left(\frac{\rho V^2 R}{\sigma}\right) + 91.5\left(\frac{d_{50}}{e}\right). \qquad (10)$$

The adjusted variance value is 0.82 for the analysis indicating that the *SRE* is also predicted well based on the independent parameters. An analysis on the relative importance of independent parameters to predict sediment release efficiency, *SRE* in Coanda type intakes showed that Froude number based on the screen curvature, $Fr_{R,}$ and Weber number, *We* had the highest relative importance by 35% and 33%, respectively. Rack angle, θ was also effective with a relative importance of 12%, whereas void ratio, *m*; the ratio of the bar opening to the curvature radius, *e/R;* and the ratio of the mean sediment diameter to the bar opening, d_{50}/e were almost equally important to predict *SRE* having 7%, 6% and 6% relative importance percentages. The results showed that the ratio of the screen length to the curvature radius, *L/R* did not have a significant effect on the prediction of *SRE* in Coanda type intakes.

Multiple linear regression analysis showed that diverted discharges highly depended on the Froude number based on the screen curvature, Fr_R; and Weber number, *We* for the Coanda type intakes whereas void ratio, *m* was the most effective parameter for the Tyrolean type intakes. As a result of multiple linear regression analysis, water capture efficiency and sediment release efficiency relations are established as a function of nondimensional parameters for the first time in the literature for Coanda type intakes based on experimental data.

4.2 Effects of Intake Type and Rack Angle

As described earlier, three different Coanda intake designs and one Tyrolean intake all having the same dimensions and void ratios (m = 0,046) are used and their results are compared in the experiments. The angle of rack inclination, θ is selected as 5, 10, 15, 20, 25, and 30 degrees in the experiments. Water capture efficiencies, (*WCE*) are calculated for each case and presented in Fig. 8.

Water capture efficiencies of Tyrolean type and Coanda type having a curvature radius of 120 cm performed similarly and had slightly higher water capture efficiency as compared to other Coanda type intakes (Fig. 8). As the rack angle decreases water capture efficiency also increases, although this change is not linear. For rack angle varying between 20 and 30 degrees, water capture efficiencies remained the same for Tyrolean and Coanda types having a curvature radius of 120 cm.

Figure 9 shows that a significantly higher amount of sediments

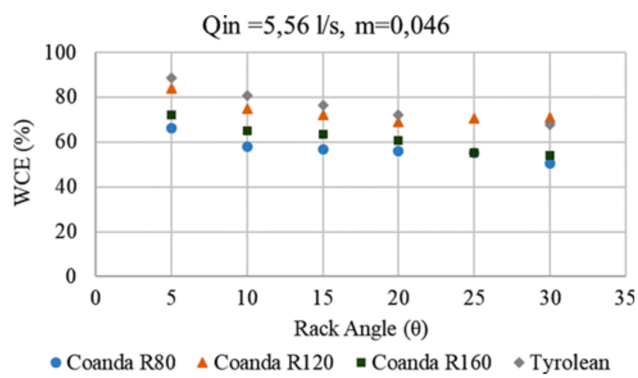

Fig. 8. Comparison of Water Capture Efficiencies by All Types of Intakes at Different Rack Angles

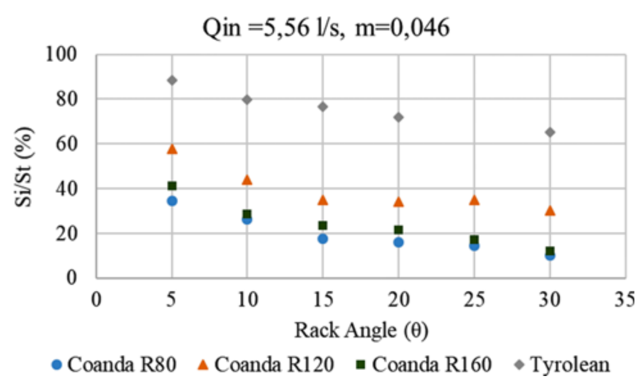

Fig. 9. Comparison of Sediments Trapped by All Types of Intakes at Different Rack Angles

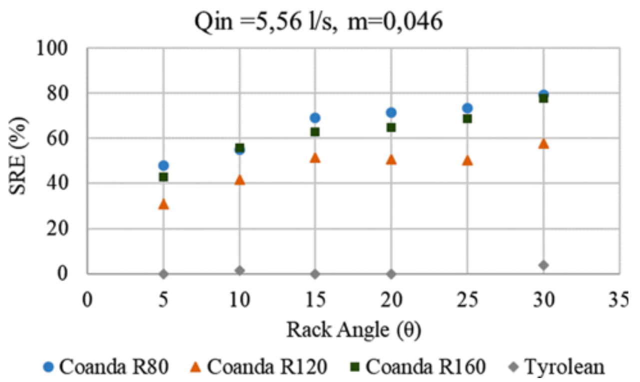

Fig. 10. Comparison of Sediment Release Efficiencies for All Types of Intakes at Different Rack Angles

were trapped by Tyrolean type intakes as compared with Coanda types. Coanda type having a curvature radius of 80 and 160 cm behaved alike and had the least amount of sediments captured by the intakes. Similar to diverted water behavior, as the angle increased sediments entering the intake structure decreased for all types.

Figure 10 shows that Tyrolean type intake is very ineffective when sediment release efficiency is considered. This type lets all the sediments in the approaching flow into the intake structure together with the diverted flow. Coanda types, on the other hand, showed a much better performance reaching up to 80% of the sediment release ratio for 30 degrees of rack angle for both Coanda types having 80 cm and 160 cm curvature radius.

4.3 Effects of Flow Rate

The effects of three different flow rates are discussed for Coanda type intake having a curvature radius of $R = 80$ cm and void ratio $m = 0{,}046$. In all three cases, supercritical flow conditions ($Fr = 2{,}55$) is maintained. In general, results of the experiments conducted via the lowest flow rate, $Q = 2{,}4$ l/s are distinctly different than the other two experiments conducted via flow rates of 5,56 l/s and 7,96 l/s (Fig. 11). For the lowest flow rate, diverted flow and trapped sediments are higher whereas sediment release efficiency is lower as compared to the other two flow rates (Figs. 12 and 13). These results for 5,56 l/s and 7,96 l/s are observed to be very close as expected. This result suggests that for low flow rates, the experiments may not correctly describe the flow and sediment behavior over the intake.

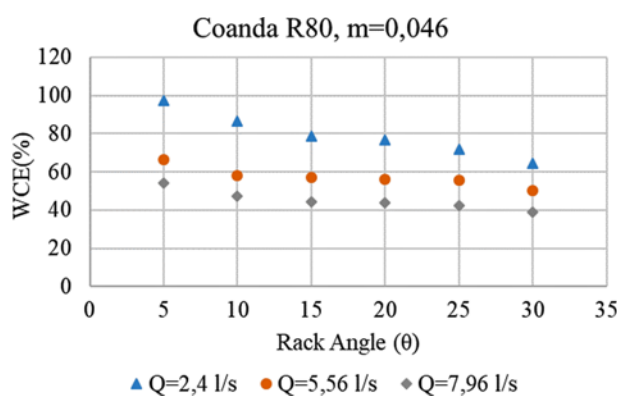

Fig. 11. Comparison of Water Capture Efficiencies for Three Different Flow Rates at Different Rack Angles

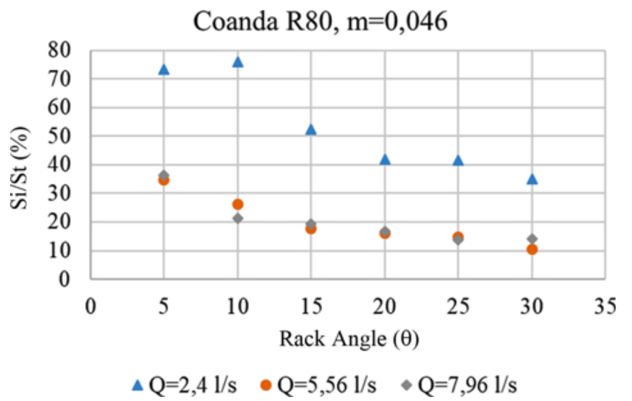

Fig. 12. Comparison of Sediments Trapped for Three Different Flow Rates at Different Rack Angles

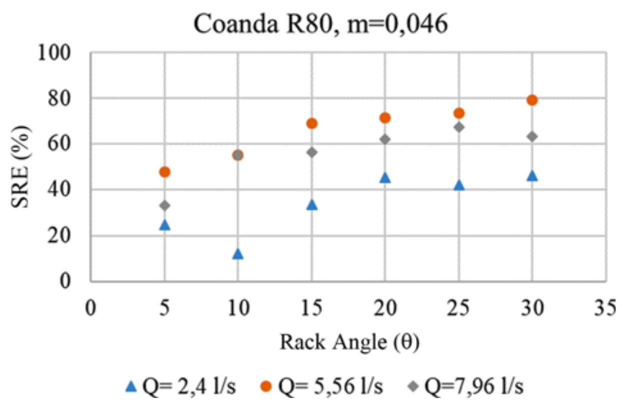

Fig. 13. Comparison of Sediment Release Efficiencies for Three Different Flow Rates at Different Rack Angles

4.4 Effects of Void Ratio

For the investigation of the effect of void ratio on water capture efficiencies, 3 different Coanda type intakes having a curvature radius of $R = 80$ cm with different bar spacings are manufactured and used in the experiments. Various flow rates are passed through three different racks having bar spacings of $e = 1$, 2, and 3 mm corresponding to void ratios of $m = 0{,}046$, 0,092, 0,138 respectively. Uniform sediments having a 0,8 mm median diameter are fed to the system in the experiments using the feeding system explained earlier. Results showed that as void ratios increased, so did the water capture efficiency and the sediment amount entering the intake (Figs. 14 and 15). Sediment release efficiency, however, increased with the rack angle up to 20 degrees and then remained constant at approximately 70%, for bar spacings of $e = 2$ and 3 mm and at approximately 90%, for bar spacing of $e = 1$ mm (Fig. 16).

Following this analysis, the Froude number based on bar

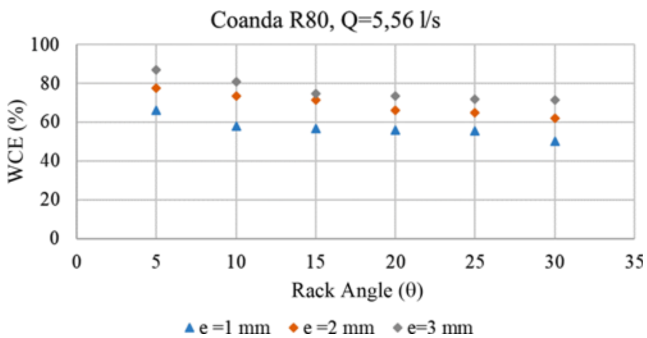

Fig. 14. Variation of Water Capture Efficiencies with Rack Angles for Three Different Bar Spacings

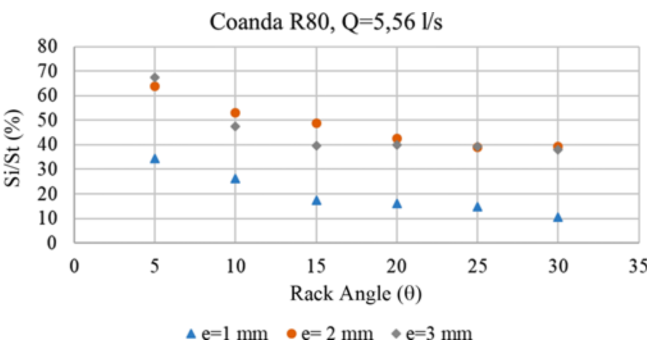

Fig. 15. Variation of Captured Sediments with Rack Angles for Three Different Bar Spacings

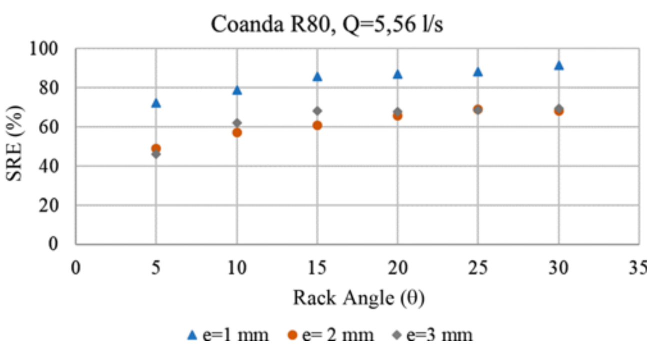

Fig. 16. Variation of Sediment Release Efficiencies with Rack Angles for Three Different Bar Spacings

opening, Fr_e; is used to evaluate the diverted discharge for various rack angles. Values of Froude number based on bar opening are plotted against nondimensionalized diverted discharge for various rack angles. Fig. 17 shows that for lower Fr_e (approximately 50) diverted discharge reaches maximum value and decreases as the Fr_e increases. Also, it can be interpreted from the figure that, for rack angles greater than 15 degrees, the rack angle did not have a significant effect on the results.

4.5 Effects of Sediment Composition

The effect of sediment composition on the results is investigated by changing the sediment composition of 695 grams of sediments varying between 0,71 to 1 mm (D_{50} = 0,8 mm), to a composition of sediments ranging between 0,5 to 2 mm. The sediment sample used in the experiments is composed of 300 g of sediments having a diameter size of 0,5 to 0,71 mm, 130 g of sediments having a diameter size of 0,71 to 1 mm, 200 g of sediments having a diameter size of 1 to 1,7 mm, and 65 g of sediments having a diameter size of 1,7 to 2 mm, adding up to 695 grams in total. The gradation is checked by the coefficient of curvature as formulated below:

$$C_c = \frac{d_{30}^2}{d_{60} d_{10}}, \tag{11}$$

where d_{10}, d_{30}, d_{60} represent the particle diameters, where 10, 30 and 60 percent of the mass of particles are smaller than the corresponding diameters respectively. The coefficient of curvature is found to be 1,3 suggesting a well-graded soil. Fig. 18 presents the comparison of trapped sediment percentages concerning rack angles as captured by the Coanda type having a curvature radius of 160 cm for both uniform and graded compositions as described above. For graded sediments, the capture percentage is lower as compared to the uniform sediments suggesting that coarser sediments provided clogging during the experiments. Clogging of the rack bar spacing also results in a reduction of the water capture efficiencies of the intakes. Also, it can be interpreted from the figure that, results do not vary with the rack angle significantly as it does with the uniform sediment results.

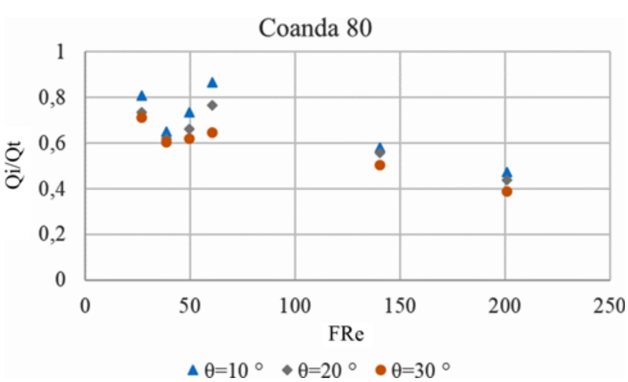

Fig. 17. Variation of Diverted Discharge Ratios with Froude Numbers Based on Bar Opening for Three Different Rack Angles

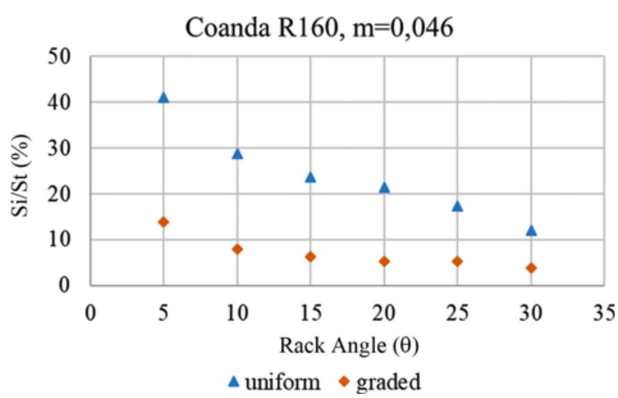

Fig. 18. Variation of Captured Sediments with Rack Angles for Uniform and Graded Sediments

5. Conclusions

In this study, the effect of rack angle, void ratio, sediment amount fed to the system, flow rate, and type of intake used on water capture efficiencies and sediment release efficiencies are investigated. Expressions for water capture efficiencies for both Tyrolean and Coanda type intakes are derived based on the statistical analysis of experimental results and presented. For Coanda type intakes, an expression for sediment release efficiency is derived where efficiency is related to Coanda type, rack angle, void ratio, sediment amount, and flow rate for the first time in the literature. An optimum design is proposed with the maximum sediment release efficiency to prevent clogging during the operation of the intakes. According to the experimental results, Coanda type intakes having 80 cm and 160 cm curvature radius showed a much better performance reaching up to 80% of the sediment release ratio when set to 30 degrees of rack angle.

The authors believe this study will lay the groundwork for future investigations on Coanda type intakes. From the analysis of the experimental results, the following conclusions are stated:

1. Using the data from both previously published studies and the experimental data presented in this study, the water capture efficiency for the Tyrolean type intakes is related to void ratio, rack slope, the ratio of bar opening to screen length, and Froude number based on bar opening, which depends mainly on approaching flow discharge. The relation between the water capture efficiency and the independent parameters is presented in Eq. (8). Void ratio is found to have the highest relative importance among these parameters.
2. Statistical analysis is also utilized to derive a formulation for water capture efficiency and sediment release efficiency of the Coanda intakes. A total of 108 experiment data monitored during this study are used in the analysis and water capture efficiency is related to rack angle, void ratio, the ratio of the bar opening to the curvature radius, the ratio of the screen length to the curvature radius, Froude number based on the screen curvature, and Weber number. As for the sediment release efficiency one additional dimensionless parameter is considered: the ratio of the mean sediment diameter to the bar opening. The relation between the water capture efficiency and the independent parameters is presented in Eq. (9) for Coanda type intakes. Similarly, the relationship between the sediment release efficiency and the independent parameters is provided in Eq. (10). In both cases, diverted discharges highly depended on the Froude number based on the screen curvature, and Weber number suggesting that both flow velocity and curvature radius are significant influencers in Coanda type intakes.
3. In general, it is observed that, as the rack angle decreases, water capture efficiency increases, although this change is not linear. Variation of rack angle between 20 and 30 degrees, did not have a significant effect on water capture efficiencies for both Tyrolean and Coanda types.
4. Tyrolean type intake is found to be very ineffective, as compared to Coanda type intakes when sediment release efficiency is considered. Coanda types showed a much better performance reaching up to 80% of the sediment release ratio for 30 degrees of rack angle.
5. For unit flow rates less than 14 l/s/m, diverted flow and trapped sediments are found to be at higher rates as compared to higher flow rates showing comparable results.
6. Results show that when Froude numbers calculated based on bar openings are plotted against nondimensionalized diverted discharges; for lower Fr_e (approximately 50) diverted discharge reaches maximum values and decreases as the Fr_e increases.
7. When a well-graded sediment composition is considered instead of uniform sediments, sediment capture percentage is observed to be lower for graded sediments as compared to the uniform sediments suggesting that coarser sediments provided clogging during the experiments. Clogging of the rack bar spacing also results in a reduction of the water capture efficiencies of the intakes.

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Nomenclature

a = Distance between centerline of the two consecutive bars
A, B ,C, D, E, F, G = Coefficients of regression analysis
C_c = Coefficient of curvature
C_q = Discharge coefficient
C_w = The weir coefficient (= 0,635)
d_{10}, d_{30}, d_{50}, d_{60} = Percent of the particles
e = Gap distance between two consecutive bars
Fr = Froude number
Fr_e = Froude number based on bar opening
Fr_R = Froude number based on curvature radius
g = Gravity
h_0 = Height of water measured in vertical direction
L = Screen length
m = Void ratio
$Q_{diverted}$ = Diverted discharge
Q_{in} = Approaching flow discharge
R = Curvature radius
Si = Sediment amount in diverted flow
SRE = Sediment release efficiency
St = Sediment amount fed into the system
V = Velocity of incoming flow at the beginning of the screen
W = Channel width
WCE = Water capture efficiency
X = Sagging distance

$X_1, X_2, X_3, X_4, X_5, X_6$ = Representative independent variables
Y = Any dependent parameter
α = Wire tilt angle
θ = Screen slope
ρ = Density of water
ρ_s = Density of sediment
υ = Kinematic viscosity
σ = Surface tension
σ_D = Uniformity coefficient

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