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Original Article

An experimental investigation of head loss through a triangular “V- shaped” screen

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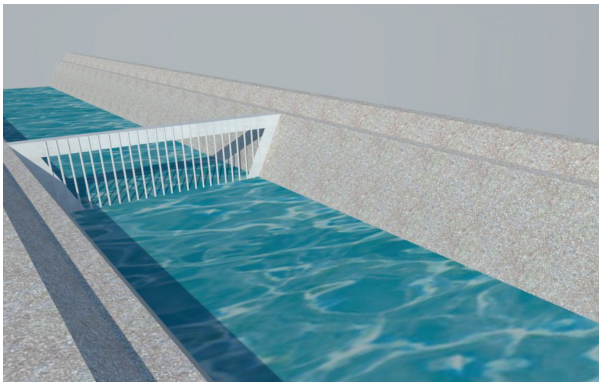
GRAPHICAL ABSTRACT



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ABSTRACT

Common traditional screens (screens perpendicular and vertical to the flow direction) face extensive problems with screen blockage, which can result in adverse hydraulic, environmental, and economic consequences. Experimentally, this paper presents an advanced trash screen concept to reduce traditional screen problems and improve the hydraulic performance of screens. The traditional screen is re-developed using a triangular V shape with circular bars in the flow direction. Triangular V-shaped screen models with different angles, blockage ratios, circular bar designs, and flow discharges were tested in a scaled physical model. The analyses provide promising results. The findings showed that the head loss coefficients were effectively reduced by using the triangular V-shaped screens with circular bars ($\alpha < 90°$) in comparison with the traditional trash screen ($\alpha = 90$). Additionally, the results indicated that the head loss across the screen increased with increasing flow discharge and blockage ratio. The losses considerably increase by large percentages when the screen becomes blocked by 40%. Low head losses were recorded at low screen angles for the circular bars. A new head loss equation is recommended for triangular screens with circular bars.

Introduction

Trash screens are commonly used to trap debris in streams. Debris can accumulate around structures and cause structural failure [1,2], impede the waterway openings (culverts, bridges, etc.),

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adversely affect power generation intakes and flood control projects [3], increase the navigation problems [4], and increase the upstream flood risk potential [5]. Trash screens are used to prevent such hazards associated with debris accumulation. As reported by Blanc [6], controlling debris using trash screens has been studied by numerous investigators [7–11].

The challenges related to trash screens are that they can be blocked by debris accumulations and can cause head losses. Trash screen blockage and losses can have serious hydraulic, environmental and economic consequences. The accumulation process can quickly occur, especially during flood periods; at the same time, the prediction of potential screen blockage is incredibly difficult [12].

In particular, debris enlargements produce improper screen functioning, resulting in a possible increase in the upstream water level, obstructions to flow across screens, and extensive flooding [6,12]. Moreover, debris accumulation at the screen can be a significant problem that increases the downstream velocity and creates scouring [13], breaks down turbines and hydroelectric generation plants [14,15] and yields incorrect predictions for irrigation engineers.

Head loss is a vital factor in how a trash screen is designed. The head loss across the screen significantly increases after it becomes blocked [12]. Notably, the screen head loss is the major part of the total head loss [12]. Flow through trash screens has been investigated by various researchers [16–26], and previous studies treated the screen as a traditional screen without a shape, i.e., only a perpendicular–vertical screen inclined from the bed or angled from the wall.

Meusburger [27], as cited by Raynal et al. [25], proposed a head loss formula for an angled screen, as given in Eq. (1). In this equation, the screen angle and blockage ratio are coupled considering the bar shape coefficient presented by Kirschmer [16] and without assessing the relation between the bar shape and the rack angle.

$$\Delta \mathrm{h} = \mathrm{K}\left(\frac{B}{1-B}\right)^{1.5}\left(\frac{\alpha}{90^{\circ}}\right)\mathrm{B}^{-1.4\tan(90^{\circ}-\alpha)}\cdot\left(\frac{v^{2}}{2g}\right) \tag{1}$$

where Δh is the head loss, K is the bar shape coefficient presented by Kirschmer [16], B is the blockage ratio, α is the screen angle from the wall, v is the approach flow velocity, and g is gravitational acceleration.

Clark et al. [28] investigated tests of straight and oblique approach flows. Eq. (2) was developed for the angle of the trash screen. The tests examined the effect of the bar shape, angle of the approach flow and blockage ratio.

$$\Delta \mathrm{h} = 7.43\eta(1+2.44\tan^{2}\theta)\mathrm{B}^{2}\left(\frac{v^{2}}{2g}\right) \tag{2}$$

where Δh is the head loss, η is the bar shape factor, θ is the approach flow angle, B is the blockage ratio, v is the approach flow velocity, and g is gravitational acceleration.

Wahl [23] presented Eq. (3) for calculating the head loss through screens regardless of the screen angle and bar shape.

$$\Delta \mathrm{h} = (1.45 - 0.45\mathrm{D} - \mathrm{D}^{2})\left(\frac{v^{2}}{2g}\right) \tag{3}$$

where Δh is the head loss, D = 1 – B, B is the blockage ratio, v is the approach flow velocity, and g is gravitational acceleration.

Available formulae for calculating screen head loss under different settings have been presented by various researchers [19,25,26,29–31].

A number of other studies have also been performed, some examples of which include an experimental investigation of flow through vertical angled screens in a diversion structure [32], water energy dissipation using vertically placed screens [33] and an investigation of energy loss due to open channel contractions [34].

This paper presents a screen development concept that maximizes the hydraulic performance and reduces the hydraulic problems caused by traditional screens (perpendicular–vertical screen, defined as α = 90° and β = 90° based on the direction of flow). In this method, the screen was designed with a triangular V shape based on the flow direction. Additionally, success criteria that govern the screen conditions and a new head loss equation are introduced.

A series of experiments were performed on a hydraulic physical scale model at Channel Maintenance Research Institute Hydraulics Laboratory at the National Water Research Center (NWRC), Egypt. Based on different screen wall angle configurations shapes, and blockage ratios, the various results were analyzed.

Methodology

Experimental setup

All experimental runs were conducted with a trash screen model in a recirculating, 16.22 m long, 0.6 m wide, 0.42 m deep and 1:1 side slope horizontal trapezoidal open channel made of concrete. The flume was attached with a head tank. A constant underground reservoir was provided to supply the flume with water through a 5-inch pipe. Then, the water entering the flume was drained to the underground reservoir. The flow was circulated through the system by two 5-in. centrifugal pumps driven by a motor. A tailgate was attached at the downstream end of the channel to adjust the water levels. The flow discharges, which were adjusted via a discharge valve, were measured with a current flow meter, and a mobile point gage was used to measure the water depths to the nearest ±1 mm.

The model was scaled to simulate the most appropriate method. In the model, four angles were tested: 90° to replicate the traditional popular screen and angles of 75°, 65°, and 55° to verify the influence of the screen angle compared to that of the traditional screen. Flow discharges ranging between 20 L/s and 40 L/s were applied. Ideally, the selected ranges of the discharges represented relatively low, moderate, and high flows that could be created with the experimental test rig under steady flow conditions. The screens were tested under wide ranges of blockage ratios between 0.10 and 0.66 to cover different conditions of blockage simulation.

The screen models, which were vertically installed to the channel bed (β = 90°), were angled from the wall and shaped to form triangular or V-shaped screens (see Fig. 1). Four screen angles were tested; the smallest angle was α = 55°, and the other angles were α = 65°, 75°, and 90° (perpendicular to the channel) to the flow direction. All screens were 25 cm in height, whereas the lengths were different as a result of the screen angles. The screens were composed of circular mild steel bars 3 mm in diameter and with 2 cm spacing. The circular bars were used to make the screen angle the same in any direction.

Four different blockage ratios (0.10, 0.29, 0.47, and 0.66) were used for each screen model. The blockage consists of two main elements: blockage of all parts of the immersed bars and blockage of the row of wooden sheets located at the top of the wetted screen. The blockage ratio (B) can be described by Eq. (4). All blockage elements were coupled between the lateral screen bars and the row of wooden sheets.

$$\mathrm{B} = \frac{A_{b}}{A_{c}} \tag{4}$$

where B is the blockage ratio, A_b is the total area of the immersed blockage, and A_c is the area of the channel.

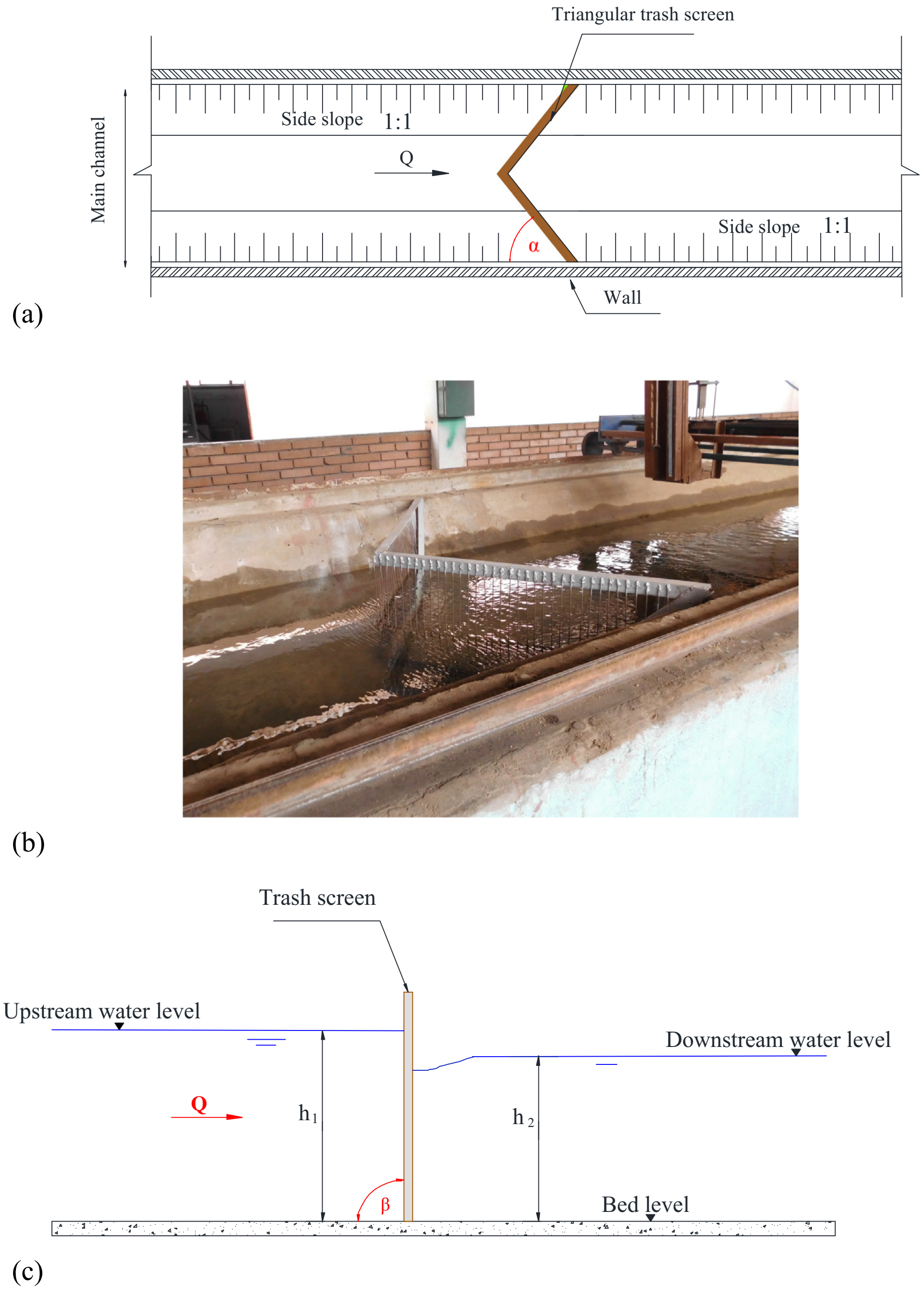


Fig. 1. Diagram of the triangular screen in the channel: (a) plan details for a triangular screen from the wall (not to scale), (b) picture of a triangular screen, (c) side view of the details of the triangular screen from the channel bed (β = 90°) (neither to scale nor to geometric projection).

Five discharges, Q = 20 L/s, 25 L/s, 30 L/s, 35 L/s, and 40 L/s, were used for each screen arrangement. A 3-D Vectrino device was used to measure the approach flow velocity. To minimize the potential errors of fluctuations in the flow rate, an appropriate length of time surpassed to establish steady conditions. The conditions were allowed to stabilize for 15 min before testing.

Experimental procedure

The considered parameters, screen angles of the triangular screens from the wall, unit discharge, and blockage ratio were carefully assessed. Throughout the experiments, each screen angle was examined for each discharge and blockage ratio. After fixing the screen model at the middle of the flume downstream of the head tank, the tailgate was adjusted to predefine the gate opening. Then, flow passed through the system. In both the center of the flume and near the wall of the flume, the upstream and downstream water depths (h_1 and h_2, respectively) were measured every 15 cm near the screen and then every 50 cm. Then, the average of h_1 and h_2 was calculated to avoid errors for each configuration. The test was repeated again with another blockage ratio. Then, the experiment was repeated with another screen angle. Finally, the head loss was calculated, and the head loss coefficient was extrapolated using Eq. (5).

$$\Delta h = \Delta h_c \left(\frac{v^2}{2g}\right), \quad \Delta h_c = \left(\frac{\Delta h}{v^2/2g}\right) \tag{5}$$

where Δh is the head loss, Δh_c is the head loss coefficient, v is the approach flow velocity, and g is gravitational acceleration.

To minimize any errors associated with the experimental conditions, the measurements were evaluated at different points during each session. Furthermore, the test sets did not always begin at the same time of the day or week to reduce any possible environmental effects, such as changes in fluctuations and water temperature. In terms of accuracy, the tested measurements were repeated to estimate the uncertainty. The mean absolute error associated with measurements did not exceed 1.23%.

Non-dimensional analysis

The effects of the triangular screen angles, unit discharge, and blockage ratio on the head losses were studied for various settings. To generalize the experimental observations, the head loss and the main evolution factors were reported with non-dimensional variables. The factors that affected the head loss can be defined as shown in Eq. (6):

$$\Delta h = f(q, v, \alpha, B, g) \tag{6}$$

where Δh is the head loss, $q = Q/b$ is the unit discharge, Q is the flow discharge, b is the channel width, v is the approach flow velocity, α is the screen angle from the wall, B is the blockage ratio, and g is gravitational acceleration.

The head loss coefficient (Δh_c) was expressed above in Eq. (5). By applying non-dimensional terms using the Buckingham π theorem [35], Eq. (7) can be derived.

$$\left(\frac{\Delta h}{v^2/2g}\right) = f\left(\frac{qg}{v^3}, \sin\alpha, B\right) \tag{7}$$

where $\Delta h/(v^2/2g) = \Delta h_c$ is the head loss coefficient, Δh is the head loss, qg/v^3 is a dimensionless discharge that is expressed as a discharge coefficient, q is the unit discharge, g is gravitational acceleration, v is the approach flow velocity, α is the screen angle from the wall, and B is the blockage ratio.

To identify the state of the flow during the experiments, the Froude number (Eq. (8)) was applied; based on the method of Chow [36]. The results indicate that F_r ranges between 0.044 and 0.12, suggesting that the state of the flow was subcritical.

$$F_r = \frac{v}{\sqrt{gh_1}} \tag{8}$$

where v, g, and h_1 are the approach flow velocity, gravitational acceleration, and upstream water depth, respectively.

Results and discussion

A sensitivity analysis was conducted to assess how the triangular screen angles, unit discharge, and blockage ratio affect the screen head losses.

Effect of the triangular screen angle

Experiments were performed for screen angles (α = 55°, 65°, 75° and 90°) to assess the associated impact on the screen head losses. The results of the screen angle variations are reported in Fig. 2 for different test arrangements. The effect is particularly evident in Fig. 2, which shows that the triangular screen angles strongly affect the head loss coefficients. For each blockage ratio, Δh_c decreases with decreasing triangular screen angle (α). In other words, the large gaps in the triangular screen with circular bars have a higher tendency to reduce the head loss coefficients than do small gaps. These results were potentially because that at high screen lengths, the distribution area of the flow increases and the head loss decreases. Clearly, the results are similar for all the discharge coefficients.

Likewise, the experimental data from analyses of traditional horizontal screen (α = 90°) head losses were compared with those collected for various triangular screen angles. The analysis showed the following results for screen angles of 75°, 65° and 55°: (1) for a blockage ratio of 0.10, the head loss Δh decreased by 75%, 79.5%, and 85%, respectively; (2) for a blockage ratio of 0.29, Δh decreased by 41%, 51%, and 70.6%, respectively; (3) for a blockage ratio of 0.47, Δh decreased by 34.5%, 47.7%, and 65.5%, respectively; and (4) for a blockage ratio of 0.66, Δh decreased by 20%, 32.6%, and 49%, respectively. Therefore, it is evident that by increasing the blockage ratio, the effect of the screen angle decreases.

In summary, the head losses are decreased by using a triangular screen ($\alpha < 90°$) with circular bars compared with the traditional horizontal screen (α = 90°).

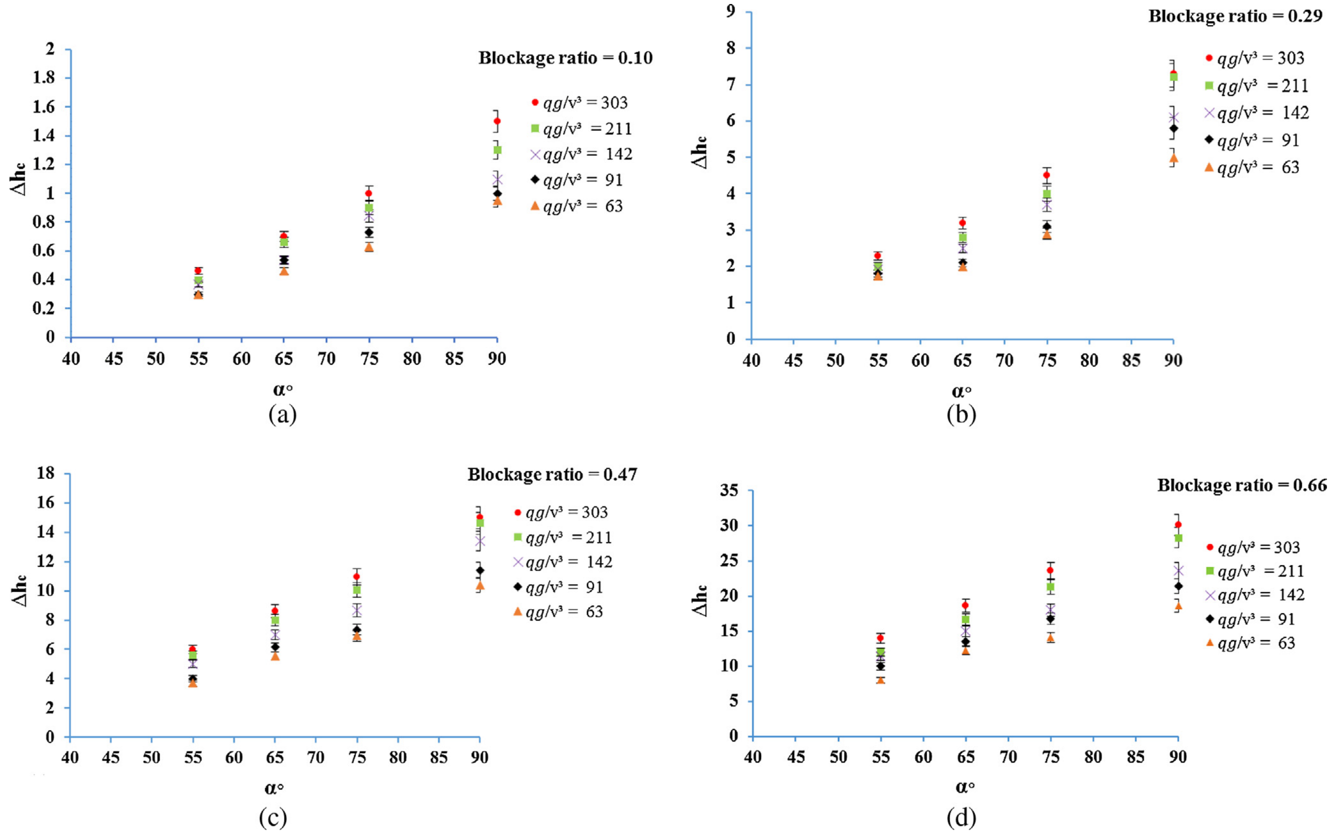
Based on the experimental results of the head losses, a paired *t*-test statistical analysis was used to define whether there was a statistically significant difference in the head losses found for the tested screen angles under various conditions. The paired *t*-test results are presented in Table 1. As shown in Table 1, significant differences between the screen angles according to the head loss values were found for all scenarios. Consequently, the results confirm that the screen angle is a valuable element in practical applications, and it clearly influences the head loss.

Effect of discharge

For different screen angles and blockage ratios, a wide range of discharge values (20 L/s, 25 L/s, 30 L/s, 35 L/s, 40 L/s) was established during the experiments to consider the associated effect on head losses. The non-dimensional discharge is defined as the discharge coefficient equal to qg/v^3. Fig. 3 shows the relationships between the dimensionless Buckingham π term head loss coefficient Δh_c and the non-dimensional discharge coefficient qg/v^3 (303, 211, 142, 91, and 63) for triangular screen angles of 55°, 65°, 75° and 90° and blockage ratios of 0.10, 0.29, 0.47 and 0.66. The results of these tests indicate that as the non-dimensional discharge coefficient increases, the head loss coefficient Δh_c also increases. Furthermore, low Δh_c values result in consistently low screen angles for different blockage ratios. As a result, it is evident that head loss increases with discharge (and thus the approach flow velocity). Therefore, the flow discharge is considered an important parameter, and the head loss is a function of discharge.

Effect of the blockage ratio

The blockage ratios (0.10, 0.29, 0.47, and 0.66) were analyzed carefully for all the tested screen model arrangements. Fig. 4 presents Δh_c as a function of B for tests with a triangular screen angle equal to 55°, 65°, 75° and 90° and different discharge coefficients. For all the screen angles and discharge coefficients evaluated, the results show that Δh_c rapidly increases with B, as expected; however, this increase becomes less notable as the screen angle decreases. In addition, Δh_c is similar for all the tested screen models, and for screen blockage ratios greater than 40%, Δh_c considerably increases. A paired *t*-test statistical analysis was used to determine the statistically significant difference between screen blockage ratios based on the obtained head loss values, and the results are detailed in Table 2. Table 2 shows that significant statistical differences exist between the blockage ratios according to the



(a) (b) (c) (d)

Fig. 2. Relationships between the head loss coefficients and screen angles for different discharge coefficients and blockage ratios of (a) 0.10, (b) 0.29, (c) 0.47, and (d) 0.66.

Table 1
Paired *t*-test of different screen angles based on head loss standards (critical ($P = 0.05$)).

Blockage ratio	Screen angle (Degrees)	Screen angle (Degrees)	*t*-state	*P*-value	Significantly different
0.1	90	75	3.75	0.020	yes
0.29	90	75	7.80	0.001	yes
0.47	90	75	4.81	0.009	yes
0.66	90	75	6.89	0.002	yes
0.1	75	65	3.31	0.030	yes
0.29	75	65	4.23	0.013	yes
0.47	75	65	5.15	0.007	yes
0.66	75	65	4.66	0.010	yes
0.1	65	55	4.58	0.010	yes
0.29	65	55	6.52	0.003	yes
0.47	65	55	8.63	0.001	yes
0.66	65	55	12.57	0.000	yes

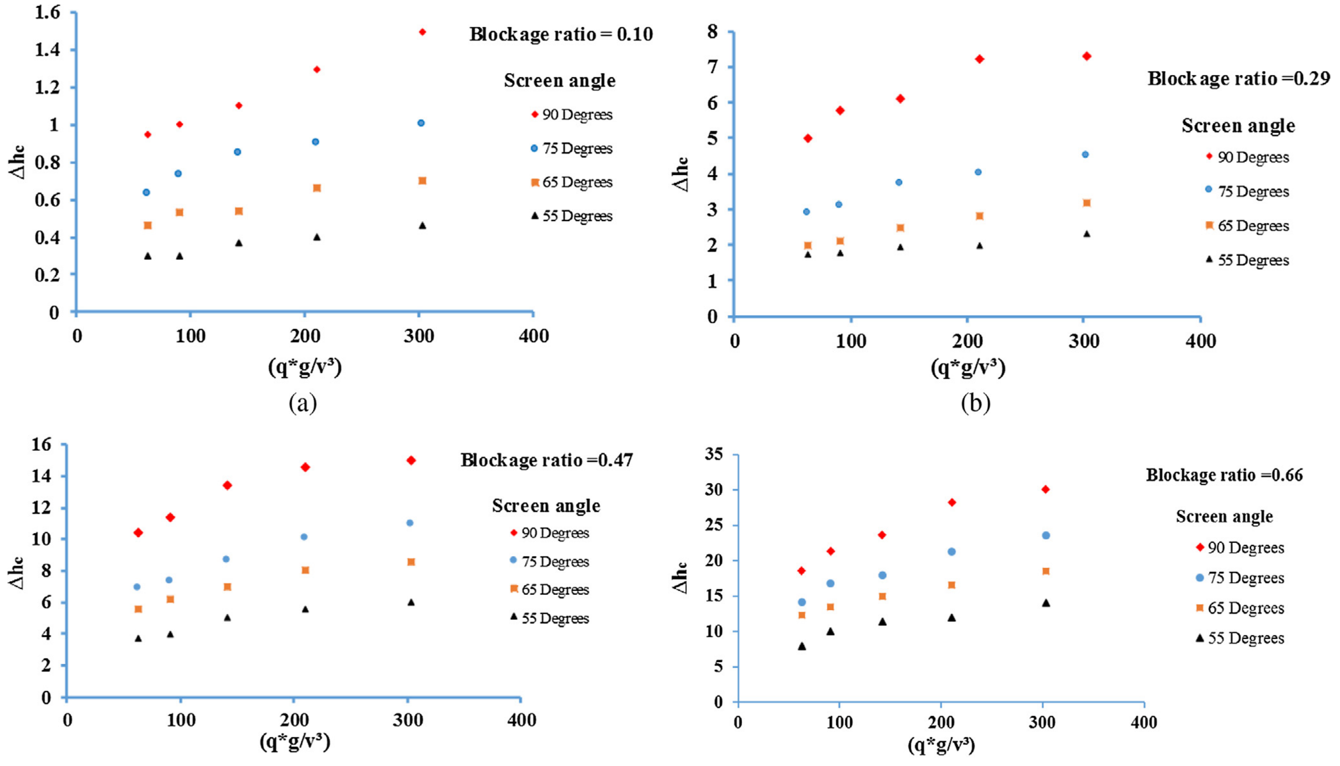
head loss values for all screens. In fact, for all the tested models, the head loss is a function of the blockage ratio.

Derivation of a new empirical equation

The noted influential factors have been identified, considering the non-dimensionality of terms, to develop a new equation for estimating the head loss for triangular screens with circular bars. Multivariable regression analysis was applied, and the parameters were correlated to establish the new head loss Eq. (9) at a 95% probability significance level.

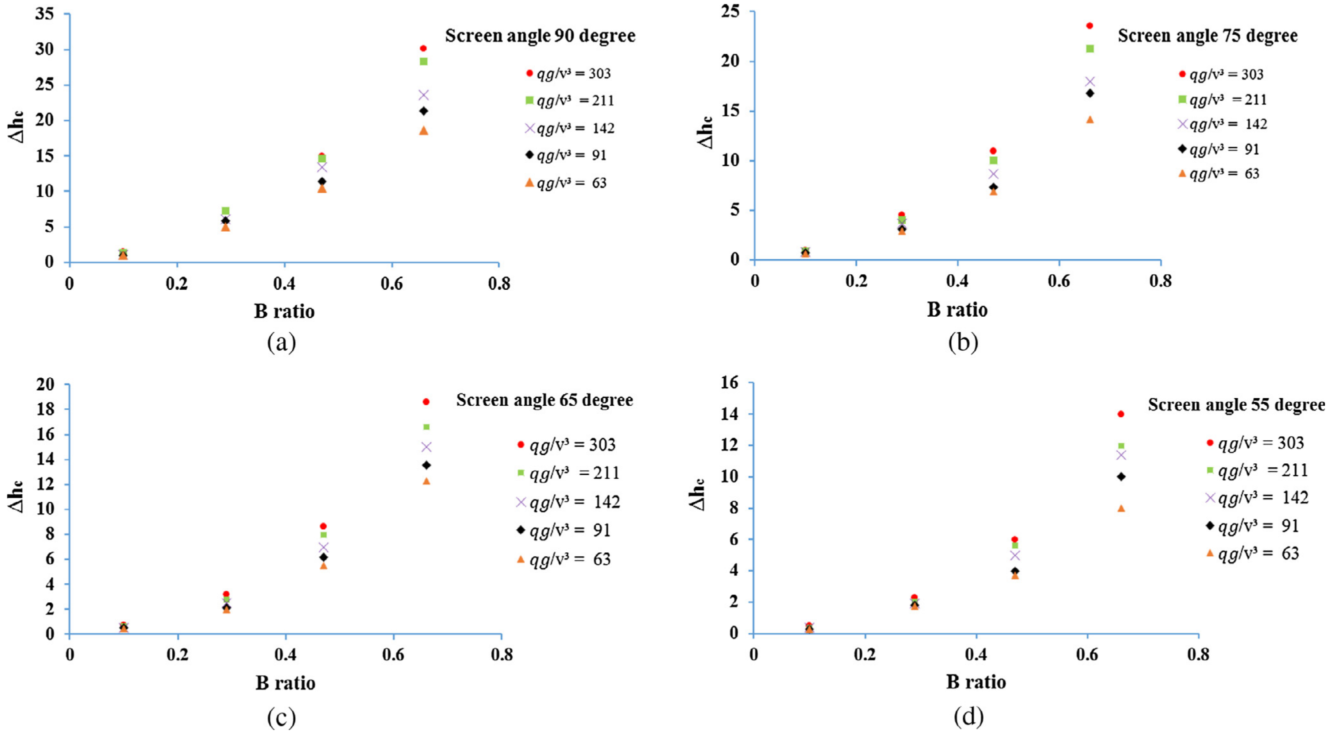
$$\left(\frac{\Delta h}{v^2/2g}\right) = 11.45\left(\frac{qg}{v^3}\right)^{0.25}(B)^{1.58}(\sin\alpha)^{4.7} \tag{9}$$

From a statistical perspective, the model had a high adjusted determination coefficient (R^2) value of 0.95, indicating that it exhibited a good fit with the experimental test data. All contributing factors were found to be significant predictive factors, whereas all non-dimensional factors had *P*-values < 0.0001. The form of Eq. (9) indicates that the screen head loss involves three terms: the non-dimensional discharge, the screen angle, and the blockage ratio. Therefore, the screen head loss can easily be obtained by applying the proposed equation in the tested range of parameters. Fig. 5 shows a comparison of the measured head loss coefficients and those predicted by Eq. (9). The comparison yielded a high determination coefficient (R^2) of 0.96. Thus, the derived Eq. (9) is an effective equation of head loss prediction. The developed equation is applicable to triangular screens or V-shaped screens inserted in a straight channel based on the flow direction, with an angle from wall α between 90° and 55°, blockage ratio between 0.10 and 0.66, and circular bars. It could be notable to verify the current study by numerical verification in future works.



(a) (b) (c) (d)

Fig. 3. Relationships between the head loss coefficients and discharge coefficients (qg/v^3) for different screen angles and blockage ratios of (a) 0.10, (b) 0.29, (c) 0.47 and (d) 0.66.



(a) (b) (c) (d)

Fig. 4. Relationships between the head loss coefficients and blockage ratios for different discharge coefficients and screen angles of (a) 90°, (b) 75°, (c) 65° and (d) 55°.

Table 2
Paired *t*-test of different blockage ratios based on head loss standards (critical ($P = 0.05$)).

Screen angle (Degrees)	Blockage ratio	Blockage ratio	*t*-state	*P*-value	Significantly different
90	0.1	0.29	−5.239	0.006	yes
75	0.1	0.29	−3.698	0.006	yes
65	0.1	0.29	−3.447	0.026	yes
55	0.1	0.29	−2.830	0.047	yes
90	0.29	0.47	−5.295	0.006	yes
75	0.29	0.47	−7.425	0.002	yes
65	0.29	0.47	−7.039	0.002	yes
55	0.29	0.47	−4.603	0.010	yes
90	0.47	0.66	−13.153	0.000	yes
75	0.47	0.66	−6.058	0.004	yes
65	0.47	0.66	−5.131	0.007	yes
55	0.47	0.66	−4.143	0.014	yes

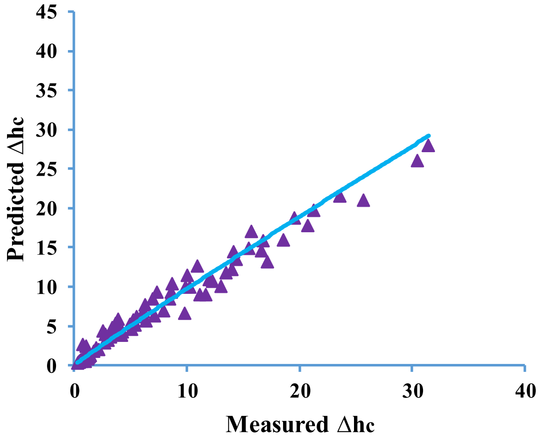


Fig. 5. Comparison of measured Δh_c values and those predicted by Eq. (9).

Conclusions

This research analyzed the experimental and statistical results of using triangular screens to investigate how the hydraulic problems produced by screen blockage can be reduced. Different screen angles with circular bars, blockage ratios, and discharges have been identified. The results and conclusions of the analysis are as follows:

- This paper produced a detailed methodology that can be useful in assessing the performances of different trash screen arrangements.
- The contributing parameters, screen angles, blockage ratios, and discharges were analyzed based on their influence of the screen head loss.
- The results indicated that a low screen angle leads to a low screen head loss coefficient, whereas high blockage ratios will decrease the effect of the screen angle. In other words, increasing the triangular screen lengths by decreasing the screen gaps will reduce the screen head loss coefficient; thus, the triangular screen angle ($\alpha < 90°$) can decrease the head loss coefficient in comparison with the common traditional horizontal screen ($\alpha = 90°$).
- A low head loss coefficient will yield a low non-dimensional discharge; at the same time, a low screen angle will lead to a low head loss coefficient.
- The head loss is a function of the blockage ratio. For all the non-dimensional discharges, the screen head loss coefficient rapidly increased with the blockage ratio; however, at low screen angles, low Δh_c values were generally obtained.
- When the screen was blocked by 40% or more, Δh_c was generally high.
- Statistically, the results indicate that significant differences between the screen angles and blockage ratios are found for all screen considerations based on the head loss values.
- Because multiple contributing parameters (screen angle, blockage ratio, and discharge) directly influence the practical head loss of a screen, head loss can be considered a vital factor in assessing the hydraulic performance of a screen.
- A new equation (Eq. (9)) was derived for the proposed method. This equation can be used to estimate the head loss of triangular screens with circular bars.
- Triangular V-shaped screens may be more likely to deflect floating matter to the channel sides without human interference (self-cleaning screens). This result may be due to the water excitation forces that affect the debris orientation toward the sides and facilitate the flow of the waterway through the screen.
- The results provide a better understanding of triangular screen blockage and can help in designing triangular V-shaped screens with circular bars.

Notation

Ab	area of immersed blockage
A_c	area of the channel
B	blockage ratio = A_b/A_c
b	channel width
F_r	Froude number of upstream flow
g	gravitational acceleration
h_1	upstream water depth
h_2	downstream water depth
K	bar shape coefficient presented by Kirschmer [16]
Q	flow discharge
q	unit discharge
v	approach flow velocity
η	bar shape factor
α	trash screen angle from the wall
β	trash screen angle from the channel bed
θ	approach flow angle
Δh	head loss through the trash screen
Δh_c	trash screen head loss coefficient

Conflict of interest

The authors have declared no conflict of interest.

Compliance with Ethics Requirements

This article does not contain any studies with human or animal subjects.

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References

[1] Diehl TH. Potential drift accumulation at bridges. FHWA-RD-97-28, Washington DC: US Department of Transportation, Federal Highway Administration; 1997.

[2] Chang FFM, Shen HW. Debris problems in the river environment. FHWA-RD-79-62, Washington DC: US Department of Transportation, Federal Highway Administration; 1979.

[3] Perham RE. Floating debris control: a literature review. Hanover: US Army Cold Regions Res Lab; 1987.

[4] Wallerstein N, Thorne CR. Debris control at hydraulic structures – management of woody debris in natural channels and at hydraulic structures. Waterways Experiment Station: US Corps of Engineers; 1996.

[5] Bradley JB, Richards DL, Bahner CD. Debris control structures evaluation and countermeasures. 3rd ed. US Department of Transportation, Federal Highway Administration; 2005.

[6] Blanc J. An analysis of the impact of trash screen design on debris related blockage at culvert inlets [Ph.D. thesis]. School of the Built Environment, Heriot-Watt University; 2013.

[7] Abt SR, Brisbane TE, Frick DM, Mcknight CA. Trash rack blockage in supercritical flow. J Hydraul Eng 1992;118(12):1692–6. In: Blanc J. An analysis of the impact of trash screen design on debris related blockage at culvert inlets, PhD thesis. School of the Built Environment, Heriot-Watt University; 2013..

[8] Wahl TL, Einhellig RF. Laboratory testing and numerical modelling of Coanda-effect screens. In: Joint conference on water resources engineering and water resources planning & management, Minneapolis, Minnesota; 2000. In: Blanc J. An analysis of the impact of trash screen design on debris related blockage at culvert inlets, PhD thesis. School of the Built Environment, Heriot-Watt University; 2013.

[9] Ho J, Hanna L, Mefford B, Coonrod J. Numerical modeling study for fish screen at river intake channel. In Randall Graham PE, editor, Proceedings of the 2006 World environmental and water resources congress, Omaha, Nebraska; 2006. In: Blanc J. An analysis of the impact of trash screen design on debris related blockage at culvert inlets, PhD thesis. School of the Built Environment, Heriot-Watt University; 2013.

[10] Padilla R, Clark K. Debris rack: debris capture and fish passage. Bay Delta Office Memorandum, California Department of Water Resources; 2008. In: Blanc J. An analysis of the impact of trash screen design on debris related blockage at culvert inlets, PhD thesis. School of the Built Environment, Heriot-Watt University; 2013.

[11] Xiang F, Kavvas LM, Zhiqiang C, Bandeh H, Ohara N, Kim S, Jang S, Churchwell R. Experimental study of debris capture efficiency of trash racks. J Hydro-environment Res 2009;3(3):138–47. In: Blanc J. An analysis of the impact of trash screen design on debris related blockage at culvert inlets, PhD thesis. School of the Built Environment, Heriot-Watt University; 2013..

[12] EA.Trash and security screen guide. Bristol: Environment Agency; 2009.

[13] Gamal T. Design and operation of floating weed' barriers for controlling scour in open channels [Ph.D. thesis]. Egypt: Faculty of Engineering, Ain Shams University; 2014.

[14] Ibrahim H, Osman EA, El-Samman TA, Zayed M. Aquatic weed management upstream New Naga Hammady Barrages. In: Eighteenth International Water Technology Conference, IWTC18, Sharm El-Sheikh, Egypt; 2015.

[15] ACEP, Alaska Center for Energy and Power. River debris: causes, impacts, and mitigation technique;. 2011. Available from: <http://www.uaf.edu/files/acep/2011_4_13_AHERC-River-Debris-Report.pdf>.

[16] Kirschmer O. Untersuchungen über den gefällsverlust an rechen. Munich, Germany: Mitteilungen des hydraulischen Instituts der TH München; 1926.

[17] Taylor GI, Batchelor GK. The effect of wire gauze on small disturbances in a uniform stream. Q J Mech Appl Math 1949;2(1):1–29.

[18] Elder JW. Steady flow through non-uniform gauzes of arbitrary shape. J Fluid Mech 1959;5:355–68.

[19] Osborn JF. Rectangular-bar trash rack and baffle head losses. J Power Div, ASCE 1968;94(PO2):111–23.

[20] Stefan H, Fu A. Head loss characteristics of six profile-wire screen panels. Report No. 175. Minneapolis, Minnesota: St. Anthony Falls Hydraul Lab, University of Minnesota; 1978.

[21] Idel'cik IE. Mémento des pertes de charge – Coefficients de pertes de charge singulières et pertes de charge par frottement. Collection de la direction des études et recherches d'Electricité De France, Paris; 1979.

[22] Yeh HH. Free-surface flow through screen. J. Hydraul Eng 1989;115(10):1371–85.

[23] Wahl TL. Trash control, structures and equipment: a literature review and survey of Bureau of Reclamation Experience. US Bureau of Reclamation, Report No. R-92-05. USBR, Denver CO; 1992. p. 1–35.

[24] Tsikata JM, Katopodis C, Tachie MF. Experimental study of flow near model trash racks. J Hydraul Res 2009;47(2):275–80.

[25] Raynal S, Courret D, Chatellier L, Larinier M, David L. An experimental study on fish friendly trash racks- part 2. Angled trash racks. J Hydraul Res 2013;51(1):57–67.

[26] Josiah NR, Tissera HPS, Pathirana KPP. An experimental investigation of head loss through trash racks in conveyance systems. Engineer 2016;XLIX(01):1–8.

[27] Meusburger H. Energieverluste an Einlaufrechen von Flusskraftwerken [Ph.D. thesis]. Bau-Ing, ETH-Zürich; 2002. In: Raynal S, Courret D, Chatellier L, Larinier M, David L. An experimental study on fish friendly trash racks- part 2. Angled trash racks. J Hydraul Res 2013; 51(1): 57–67.

[28] Clark SP, Tsikata JM, Haresign M. Experimental study of energy loss through submerged trash racks. J Hydraul Res 2010;48(1):113–8.

[29] Zimmermann J. Widerstand schräg angeströmter rechengitter. Universität Fridericana Karlsruhe, Theodor-Rhebock-Fluβbaulaboratorium, Mitteilungen Heft 157; 1969.

[30] Meusburger H, Volkart P, Minor HE. A new improved formula for calculating trash rack losses. In: Proceedings of the XXIX IAHR Congress, Beijing; 2001.

[31] Raynal S, Courret D, Chatellier L, Larinier M, David L. An experimental study on fish-friendly trash racks – Part 1. Inclined trash racks. J Hydraul Res 2013;51(1):56–66.

[32] Katopodis C, Ead SA, Standen G, Rajaratnum N. Structure of flow upstream of vertical angled screens in open channels. J Hydraul Eng 2005;131(4):294–305.

[33] Bozkus Z, Cakir P, Ger AM. Energy dissipation by vertically placed screens. Can J Civil Eng 2007;34.

[34] Wu B, Molinas A. Energy losses and threshold conditions for choking in channel contractions. J Hydraul Res 2005;43(2):139–48.

[35] Buckingham E. Model experiments and the forms of empirical equations; 1915.

[36] Chow V. Open channel hydraulics. New York: McGraw-Hill; 1959.