

## Impact of box section coverage on the hydraulic parameters of open channels

Emam A. Osman \* and Zahraa Taha

Channel Maintenance Research Institute (CMRI), National Water Research Center (NWRC), Cairo, Egypt

\*Corresponding author. E-mail: emam15032000@yahoo.com

 EAO, 0000-0003-2103-0113

### ABSTRACT

The effects of box coverage blockage on the hydraulic characteristics of open channels within the case of sub-critical flow in the open channel were explored experimentally in research. Fifty-two test runs were utilized to attain the research's objectives, with four water discharges of 2, 5, 8, and 11 L/sec, three-box coverage side dimensions of 8.8, 10.4, and 12.90 cm, and four coverage blockage ratios of 0, 10, 20, and 30%. The water depth and velocity were measured in each run. The results revealed that increasing the blockage ratios, water discharge, and a diminishing within the area passing water through the coverage led to an increment of the heading up, head losses, and water surface level. The worst-case situation was a little coverage dimension (8.80 cm side) with 30% blockage and discharge of 11 L/s. Within blockage ratios, of 0, 10, 20, and 30% and discharge 11 L/s, the relative heading up ratio ( $h_{Ru}$ %) values were 85, 97, 111, and 125 percent respectively, and for the relative head losses ratio values downstream the coverages ( $h_{Rloss}$ %) were 88, 99, 113, and 131 percent respectively related to the depth of a non-coverage case. The flow velocities and the relative area passing water through the coverage were the most effective variables on heading up and head losses. The relative heading up and the relative head loss increased with the increment of the Froude number ( $Fr_d$ ). Within a constant relative wetted area of coverage ( $A_r$ ), and increasing the Froude number ( $Fr_d$ ) by 0.01 percent, the relative heading up and relative head loss approximately increased by 5.5% and 6.2% respectively. It is recommended to implement the periodic maintenance of the coverage to improve the discharge capacity of the open channel.

**Key words:** blockage, coverage, heading up, head losses, hydraulic parameters

### HIGHLIGHT

- The research discusses the problems that may be happening in the open channels due to the presence of coverage and bad behavior of the citizens who throw out solid wastes into the canals, also the presence of aquatic weeds that block the water flow through the coverage. All these problems cause bad water distribution and conveyance

### NOMENCLATURE

$\mu$	dynamic water viscosity (Kg/m.s)
$g$ (m/s <sup>2</sup> )	gravitational acceleration (m/s <sup>2</sup> )
$\rho$	water density (Kg/m <sup>3</sup> )
$Y_u$	upstream water depth in presence of coverage (m)
$Y_d$	downstream water depth in presence of coverage (m)
$Y_s$	water depth in case of no coverage (m)
$Q$	total discharge (L/s)
$B$	blocking ratio
$A_r$	the relative wetted area of coverage
$A_{we}$	the wetted area of canal upstream coverage (m <sup>2</sup> )
$A_p$	the area passing water through coverage of box section (m <sup>2</sup> )
$V_u$	water velocity upstream coverage (m/s)
$Fr_u$	the Froude number of the flow upstream the coverage
$Fr_d$	the Froude number of the flow downstream from the coverage
$h_{Ru}$ %	relative heading up ratio
$h_{Rloss}$ %	relative head loss ratio downstream from the coverage

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## 1. INTRODUCTION

The efficiency of watercourses is harmed by improper coverage design, upstream coverage blockage, human activity, and a lack of maintenance. As a result, it was suggested that the impact of box coverage with various dimensions and upstream blockage ratios on watercourse hydraulic parameters be investigated. The researchers looked at several studies on the influence of culverts on watercourses. Sorourian *et al.* (2014) studied scouring with downstream box culverts and discovered that the maximum scour hole is larger in the presence of blocked culverts than in the absence of blocked culverts, and scour parameters (length, area, and depth) all increase significantly with partially blocking coverage. In an experiment with scouring and sedimentation minimizing downstream of a pipe culvert with limited floor protection, Negm *et al.* (2014) proposed a vertical flow deflector (VFD) with various heights and positions downstream of the culvert. The results of the experiments showed that VFDs minimise the scour dimensions, a 68 percent reduction of the scour parameters was observed, and the geometry of the culvert was changed. Aly (2017) investigated the impact of inclined headwalls in culverts upstream and downstream on canal efficiency, comparing the results to culverts without headwalls. The study concluded that the 15° inclination angle of the headwall in the opposite direction of the flow under the same upstream water depth in the case of using the U.S. headwall only gives the best results in terms of efficiency. In Wollongong, Australia, Rigby *et al.* (2002) researched the clogging of culverts. The study found that the size of the culvert's clear openings is the most important element influencing the degree of blockage, and that culvert blockage is related to other downstream culverts, culvert material, catchment area, and watercourse characteristics. To minimize scour downstream culverts, Mustaffa *et al.* (2013) researched ways to convert supercritical to subcritical flow. To limit water velocity downstream culverts and reduce energy, three baffle models were proposed. The baffle model with the highest surface area coverage offered the best performance, according to the report, and energy reduction was advised.

In the lab, El-Azab Helal (2014) conducted 117 tests to see how varied jet discharges, positions, and tailwater levels affected scour downstream of the control structure. The proposed technique lowered scour depth by 50 to 90 percent and hole scour length by 42 to 85 percent when compared to the situation without water jets. Barthelmess & Rigby (2011) predicted coverage and bridge blockage based on debris availability, mobility, and transportability parameters, explored coverage blockage mechanisms and their impact on flood behavior, and observed flow diversion caused by coverage blockage. In comparison to unblocked coverage, even a little obstruction at the coverage entrance produces flow constriction and significantly affects flood behavior. Different flow conditions were utilized to examine how to reduce maximum scour downstream from a box culvert by Abdel Aal *et al.* (2019). Changes in wing wall angle downstream of the culvert are effective in reducing the relative depth of scour at the outlet, with the sudden expansion of the wing wall angle of 90° yielding the lowest value of that depth. In the lab, Kramer *et al.* (2016) studied the effects of large debris blockage on a box culvert and observed that the debris tends to align itself with the flow direction along its long axis. The information presented in this investigation allowed for the determination of worst-case estimations of hydraulic blockage and no 100 percent blockage conditions were recorded. A simple waterway hood enhanced hydraulic performance under unobstructed situations. Helal *et al.* (2013) carried out 144 experimental tests for the scour downstream of hydraulic structures, including no sill (case 1), single line sill (case 2), and fully sill floor (case 3) with varying heights and placements. Cases 1 and 2 lowered scour depth and case 3 reduced scouring parameters more than the others, according to the study. Furthermore, the values (Hd/Lf) 0.04 and 0.013, where Hd and Lf are the height and position of the sill, respectively, yielded smaller and greater scouring parameter values. El-Zaher (2006) tested the parameters that influence culvert behavior and provided a complete hydraulic design consideration of the culvert, as indicated in the Egyptian irrigation code, using a computer simple model. In an experimental setting, Tahaa *et al.* (2018) tested the effect of covering a section of a watercourse with a pipe, concluding that the heading up is directly proportionate. They also showed empirical equations that describe the relationship between scour and flow parameters. The velocity distribution at the pipe culvert inlet was examined using a physical model by Kolerski & Weilgat (2014). The velocity increased fast in the zone within one culvert diameter of the culvert entry, and the flow has normal velocity and turbulence intensity profiles over distances more than two times the culvert diameter, according to the data. Karimpour & Gohari (2020) investigated the effect of flow blockage at rectangular culvert inlets on the scour downstream from a culvert and the water level upstream of a culvert using a hydraulic model set up in the lab. The study's most notable findings are that debris accumulation increases near-wall scouring, providing a direct threat to the structure's stability and

that the upstream water level increased as the culvert entrance blockage rate increased. Taha *et al.* (2020) evaluated the effects of debris accumulations upstream and through hydraulic structures such as culverts in an experimental setting. The results demonstrated that as the submergence ratio increases, the maximum scour depth reduces for the same discharge rate, and the relative energy rate loss in the non-blocked case reduces as well. In the non-blocked case, the discharge rate was the same, and the relative energy rate loss was similarly lower.

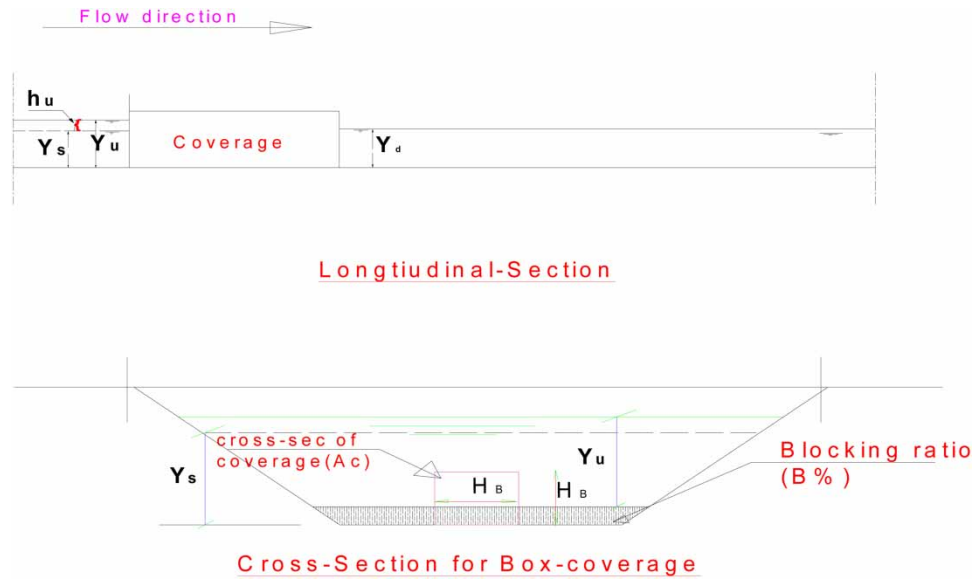
The purpose of this research is to determine how the box coverage blockage influences the hydraulic characteristics of open channels.

## 2. EXPERIMENTAL FACILITIES

Four experimental cases of 52 runs were applied according to upstream blockage reach in an artificial canal with a trapezoidal concrete section of 16.22 m length, 0.6 m horizontal bed width, 0.44 m maximum depth, and 1:1 side slope. A square box section of acrylic material with a length of 1.00 m and three side dimensions of 8.8, 10.4, and 12.90 cm was installed in the middle of the flume length, as shown in Figure 1. Four box blockage ratios of 0, 10, 20, and 30% were simulated to reflect upstream vegetation and sedimentation, as illustrated in Figure 2. A Current flow meter/uniflow universal portable flow meter, as shown in Figure 3(a), was used to measure four water discharges of 2, 5, 8, and 11 L/sec that passed through the canal. Water surface levels were measured every 0.50 m along the artificial canal's centerline using a measuring carriage (point gauge) as shown in Figure 3(b) and were intensified for a distance of 1.00 m upstream and downstream for the coverage to be every 0.10 m as shown in Figure 4; two water velocity profiles were determined at the flume using a Vectrino 3D water velocity sensor, as shown in Figure 3(c). One was upstream of the coverage at a distance 2.5 times the height of the box sections, while the other was downstream of the coverage at a distance 3.5 times the height of the box sections. The velocity in the flow direction was measured three times (10 seconds each), and the average value was determined. Four cases of experimental work were applied due to the presence of coverage blockage ratio upstream coverage, with an extra case of no coverage generating fifty-two runs, as indicated in Table 1. The applied data is included in the study's output data for determining the hydraulic efficiency of coverages.



**Figure 1** | The artificial canal, coverage of box section.



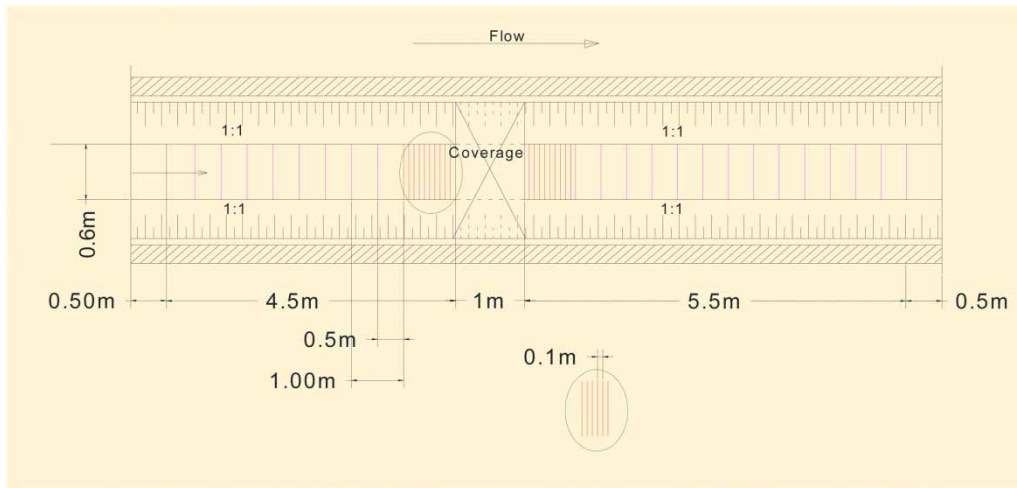
**Figure 2** | The flume structure and coverage.



**Figure 3** | The experimental tools. (a) Current flow meter/ uniflow universal; portable flow meter. (b) Measuring levels: point gauge. (c) Vectrino 3D water velocity sensor.

### 3. DIMENSIONAL ANALYSIS

The dependent and independent variables were related using dimensional analysis. These are the major variables that determine the features of hydraulic efficiency, which cover the examined models of coverage phenomena; ( $\mu$ ) is the dynamic water viscosity ( $\text{Kg/m.s}$ ), ( $g$ ) is the gravitational acceleration. ( $\text{m/s}^2$ ), ( $\rho$ ) is the water density ( $\text{Kg/m}^3$ ), ( $Y_u$ ) is the upstream water depth in presence of coverage (m), ( $Y_d$ ) is the downstream water depth in the presence of coverage (m), ( $Y_s$ ) is the water depth in the case of no coverage (m), ( $Q$ ) is the total discharge ( $\text{L/s}$ ), ( $B$ ) is the blocking ratio, ( $A_r$ ) is the relative wetted area of coverage, and equal ( $A_p$ )/( $A_{we}$ ) (where ( $A_{we}$ )



**Figure 4** | The locations of measured water surface profiles.

**Table 1** | Experimental cases

Cases	Dimension	Number of discharge	Number of blockages	Number of runs
Case 1 (No coverage) (Trapezoidal C.S.)	(60 cm bed width & 1:1 side slope)	4 2,5,8, and 11 L/s	No coverage	4
Case 2 (Box section)	(8.80 cm * 8.8 cm)	4 2,5,8, and 11 L/s	4 0,10,20, and 30%	16
Case 3 (Box section)	(10.40 cm * 10.40 cm)	4 2,5,8, and 11 L/s	4 0,10,20, and 30%	16
Case 4 (Box section)	(12.90 cm * 12.90 cm)	4 2,5,8, and 11 L/s	4 0,10,20, and 30%	16
Total number of runs				52

is a wetted area of canal upstream coverage (m<sup>2</sup>), and (A<sub>p</sub>) is the area passing water through coverage of the box section (m<sup>2</sup>), (V<sub>u</sub>) is water velocity upstream coverage (m/s), (F<sub>ru</sub>) is the Froude number of the flow upstream of the coverage, (F<sub>rd</sub>) is the Froude number of the flow downstream from the coverage, and the heading up (h<sub>Ru</sub>) is the difference between the water depth upstream coverage and the case of no coverage (m). The general functional relationship between the above variables could be represented as follows:

$$f(Y_u, Y_d, V_u, V_d, Q, A_{we}, A_p, h_{up}, \rho, g, \mu, \rho_s, B, Y_s) = 0 \tag{1}$$

Buckingham's theorem was utilized for dimensional analysis in this study to determine the relationship between the various parameters that influence the characteristics that affect the flow through the models studied.

The following function was obtained using Buckingham's theorem, using upstream water depth (Y<sub>u</sub>), upstream velocity (V<sub>u</sub>), and fluid density (ρ) as repeated variables:

$$f(Y_d/Y_u, Q/Y_u^2 * V_u, A_{we}/Y_u^2, A_p/Y_u^2, h_{up}/Y_u, V_d/V_u, B/Y_u) = 0 \tag{2}$$

Finally, the function may be written in the following form (3):

$$(h_{Ru}^0, h_{Rloss}^0) = (Fr_U, Fr_d, Q/Y_u^2 * V_u, A_r, B^0) \tag{3}$$

where: relative heading up ratio (h<sub>Ru</sub> %) is the difference between the water depth upstream coverage and a case

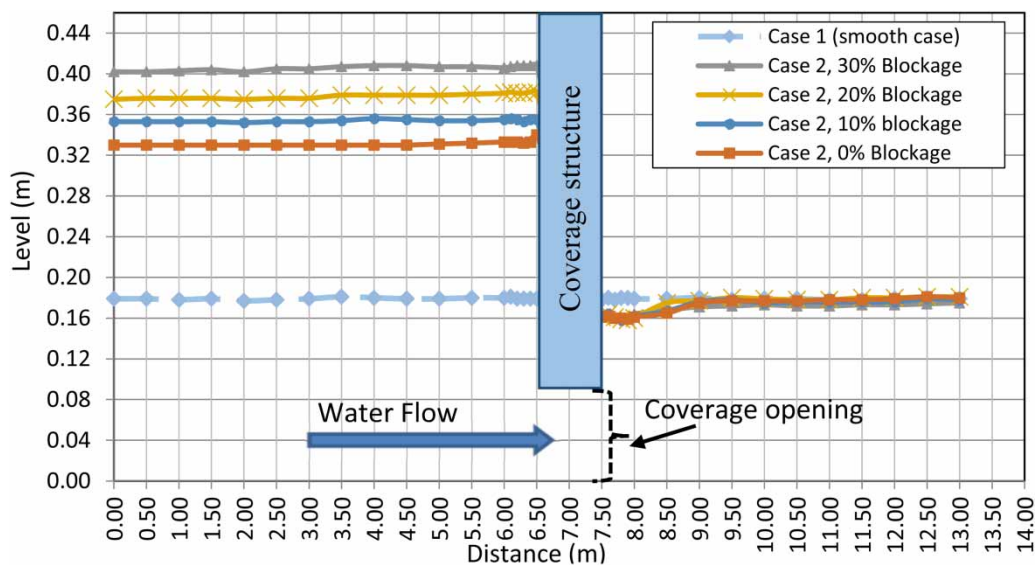
of no coverage divided by the water depth of the no coverage case [ $h_{Ru} = (Y_u - Y_s)/Y_s$ ], and relative head loss ratio downstream from the coverage ( $h_{Rloss}$  %) is the difference between the upstream and downstream water depth for the same case divided by the water depth of no coverage case [ $h_{Rloss} = (Y_u - Y_d)/Y_s$ ].

#### 4. RESULTS AND DISCUSSIONS

The hydraulic characteristics were analyzed in the presence of varied ratios of blockages upstream coverage, based on the experimental data, and a dimensionless analysis is used to develop relationships between hydraulic parameters and blockage.

##### 4.1. The effect of coverage blockage in the water surface

The relationships between the longitudinal distance and the water surface along the flume for a non-coverage case, as well as various coverage dimensions, blockage rates, and discharges, are shown in Figures 5–7. When the blockage ratio, discharge, and coverage inlet area were increased, the relative heading up ratio upstream of coverage ( $h_{Ru}$  %) and relative head loss downstream of coverage ( $h_{Rloss}$  %) increased as well. A smaller coverage dimension (case 2, 8.80 cm side) with 30% blockage and 11 L/s discharge was the worst-case situation. In comparison to the depth of a non-coverage, the ( $h_{Ru}$ %) values of case 2 with 0, 10, 20, and 30% blockage and discharge 11 L/s were 85, 97, 111, and 125%, respectively, while the ( $h_{Rloss}$  %) values were 88, 99, 113, and 131% respectively. Also, with constant discharge (11 L/s) and constant blockage ratio (30%), the inlet dimension of coverage has a significant impact on ( $h_{Ru}$ %) and ( $h_{Rloss}$ %), wherein cases of box sec coverage of dimensions 8.80, 10.40, and 12.90 cm, the ( $h_{Ru}$ %) values were 125, 74, and 24%, respectively, while the ( $h_{Rloss}$  %) values were 131, 77, and 28%.



**Figure 5** | Water surface profile comparison for a non-coverage case, and case 2 (8.80 cm side) for different blockages and constant discharge 11 L/s.

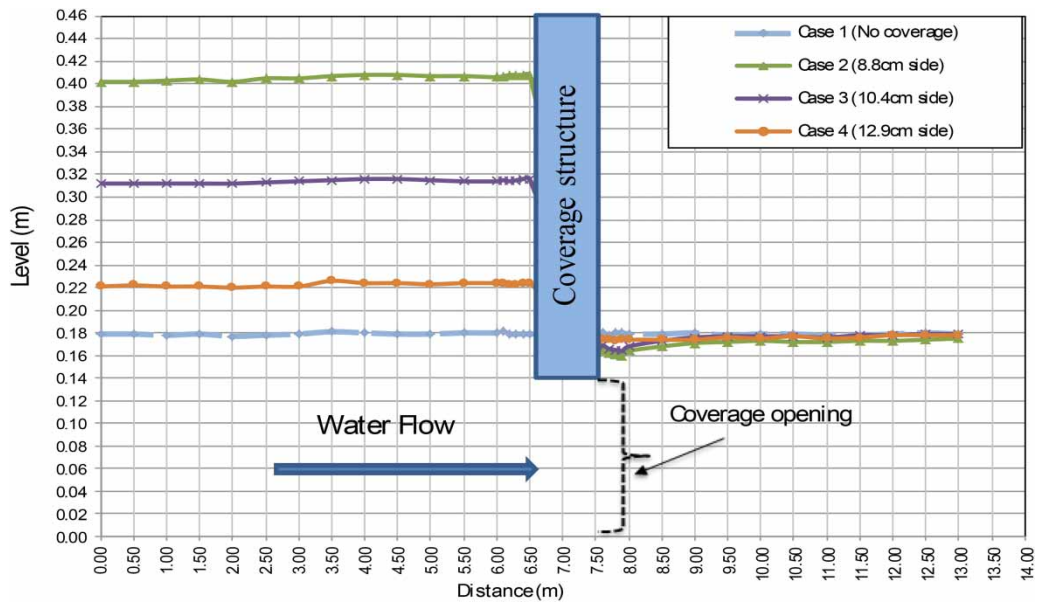
##### 4.2. The effect of coverage blockage in Froude number

The Froude number ( $Fr$ ) is a dimensionless number defined as the ratio of the flow inertia to the external field (the latter in many applications simply due to gravity). The Froude number is based on the speed-length ratio and was defined as (Shih 2009) and (White 1999):

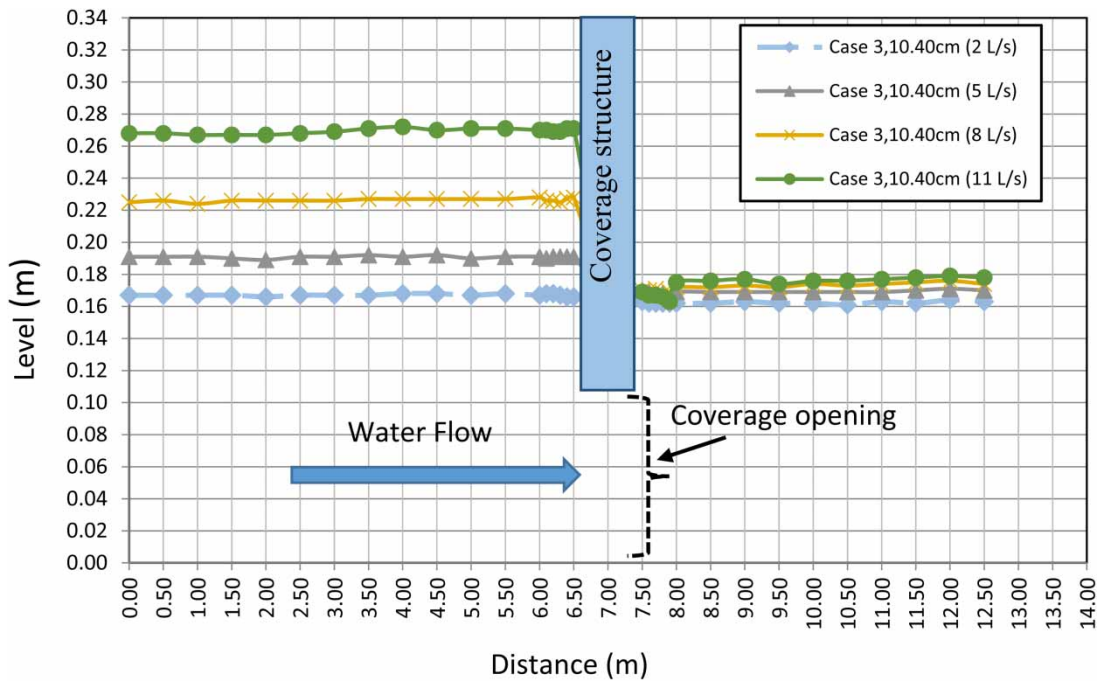
$$Fr = \frac{V}{\sqrt{gD}}$$

where:

$V$  = Water velocity



**Figure 6** | Water surface profile comparison for no coverage case, and the other cases with constant blockage 30% and discharge 11 L/s.



**Figure 7** | Water surface profile comparison for a non-coverage case, and case 3 (10.40 cm side) for different discharges and constant blockage (20%).

$D$  = hydraulic depth (cross sectional area of flow/top width)

$g$  = gravity

When:

$Fr = 1$ , critical flow,

$Fr > 1$ , supercritical flow (fast rapid flow),

$Fr < 1$ , subcritical flow (slow/tranquil flow)

The following was obtained after evaluating the measurements:

- The Froude number upstream and downstream coverage in all of the study cases was between (0.01 and 0.05), and the flow in the open channel was sub-critical ( $Fr < 1$ ).
- The values of downstream Froude numbers were higher than those of upstream Froude numbers.
- Table 2 indicates the values of the upstream and downstream Froude numbers in the case of a 30% blockage and 11 L/s water discharge.

**Table 2** | The values of Froude number for blockage 30% and discharge 11 l/s

Case	8.8 cm side	10.4 cm side	12.9 cm side
$fr_u$	0.0098	0.016	0.029
$fr_d$	0.047	0.045	0.045

#### 4.3. The effect of coverage blockage and the hydraulic parameters on the water heading up

Statistical software packages [Datafit 9 software (DataFit Curve Fitting and Data Plotting Software by Oakdale Engineering), ANOVA test, and linear stepwise regression analysis] were used to derive equations relating water surface heading upstream of coverage and head losses with hydraulic parameters and coverage blockage parameters. The most effective variables are used in linear stepwise regression, whereas the less effective variables are excluded. The relative wetted area of coverage ( $A_r = (A_p)/(A_{we})$ ) is the ratio of the area passing water of a box section ( $A_p$ ) per the upstream wetted area of the canal ( $A_{we}$ ), and flow velocity are the most effective variables on heading up. The results of the ANOVA test are shown in Table 3; this is a statistical analysis tool that divides observed aggregate variability within a data set into two parts: systematic factors and random factors. Random factors have no statistical impact on the given data set, whereas systematic factors do. In a regression study, analysts use the ANOVA test to determine the impact of independent variables on the dependent variable. The relevance of the varying coefficients of the different variables in Equation (4) is shown in Table 4.

$$(h_{Ru}^0) = 5.536 F_{rd} - 0.426 \text{LN} A_r - 1.1613 \quad R^2 = 0.87 \quad (4)$$

**Table 3** | Results of ANOVA test

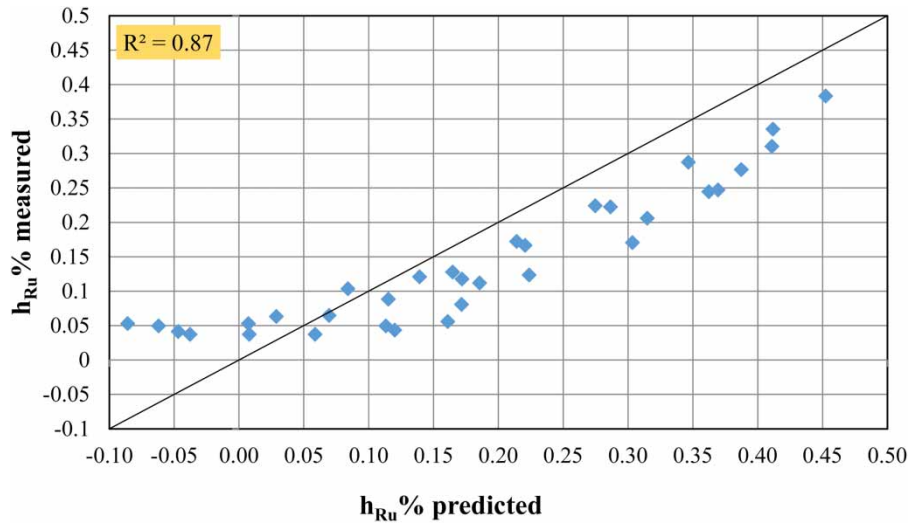
Variance analysis					
Source	DF	Sum of squares	Mean square	F Ratio	Prob(F)
Regression	2	3.859	1.929	152.531	0
Error	45	0.569	0.013		
Total	47	4.428			

**Table 4** | Coefficient and significance of different variables in Equation (2)

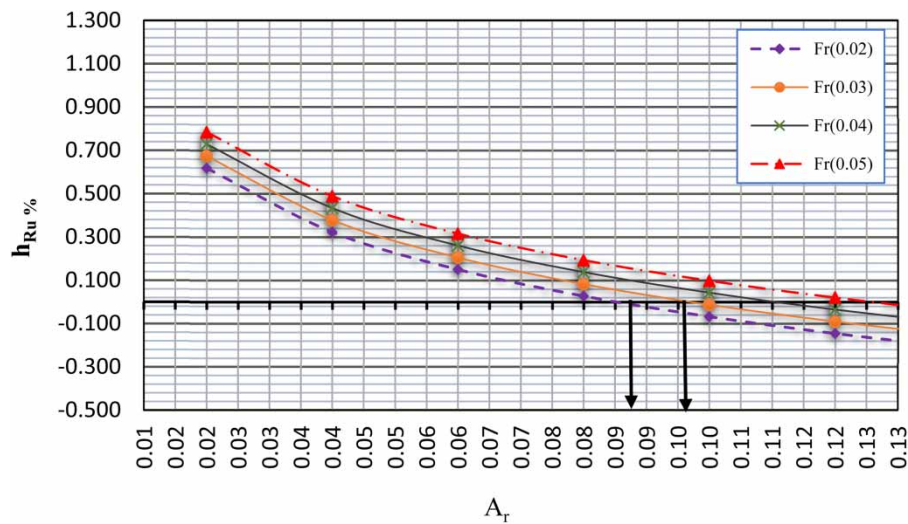
95% Confidence Intervals							
Variable	Value	95% (+/-)	Lower limit	Upper limit	Standard error	t-ratio	Prob(t)
a	-1.161	0.185	-1.346	-0.977	0.092	-12.679	0
b	5.536	2.006	3.530	7.543	0.996	5.557	0
c	-0.426	0.070	-0.497	-0.356	0.035	-12.265	0

The comparison of measured relative heading up values, predicted values, and relative wetted area of coverage is shown in Figures 8 and 9.





**Figure 8** | Comparison between measured and predict  $h_{Ru}\%$ .



**Figure 9** | The relation between relative heading up ( $h_{Ru}$ ) and relative wetted area of coverage ( $A_r$ ).

The following findings were obtained using Equation (4) and Figures 8 and 9: -

- There was an inverse relationship between relative heading up ( $h_{Ru}$ ) and relative wetted area of coverage ( $A_r$ ).
- As the Froude number ( $Fr_d$ ) increased, the relative heading up ( $h_{Ru}$ ) increased as well in this study (the flow is sub-critical).
- The relative heading up increased by around 5.5% by raising  $Fr_d$  by 0.01 while  $A_r$  was constant.
- The slope of the curves reduced once  $A_r$  exceeded 6%.
- $Fr_d$  was increased by 0.01 to keep relative heading up ( $h_{Ru}$ ) without changing. It will be necessary to increase the relative wetted area of coverage ( $A_r$ ) by about 1.25% compared to the canal's upstream wetted area.

**4.4. Effect of coverage blockage and the hydraulic parameters on the water head loss**

Linear stepwise regression analysis was used to establish an equation relating water head loss with open channel hydraulic parameters and coverage blockage parameters the most effective variables on relative head loss ( $h_{Rloss}$ ) are the flow velocity and the relative wetted area of coverage ( $A_r$ ). The results of the ANOVA test of Equation (5) are shown in Table 5. The coefficients of the various variables in the equation, as well as their significance, are

**Table 5** | Results of ANOVA test

Variance analysis					
Source	DF	Sum of squares	Mean square	F Ratio	Prob(F)
Regression	2	4.078	2.039	158.999	0
Error	45	0.577	0.013		
Total	47	4.655			

shown in Table 6.

$$(h_{Rloss} \%) = (6.243 F_{rd} - 0.424 LN A_r - 1.169) \quad R^2 = 0.88 \quad (5)$$

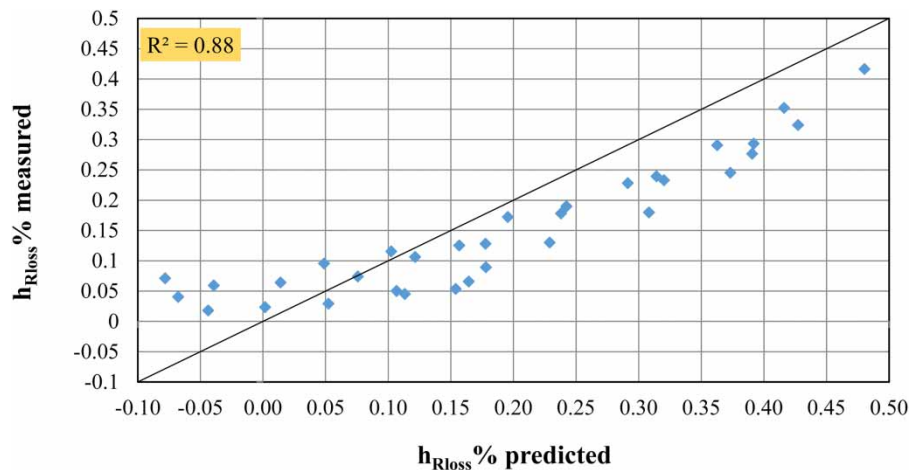
**Table 6** | Coefficient and significance of different variables in Equation (5)

95% Confidence Intervals							
Variable	Value	95% (+/-)	Lower limit	Upper limit	Standard error	t-ratio	Prob(t)
a	-1.169	0.186	-1.355	-0.984	0.092	-12.677	0
b	6.243	2.020	4.222	8.263	1.003	6.224	0
c	-0.424	0.071	-0.494	-0.353	0.035	-12.100	0

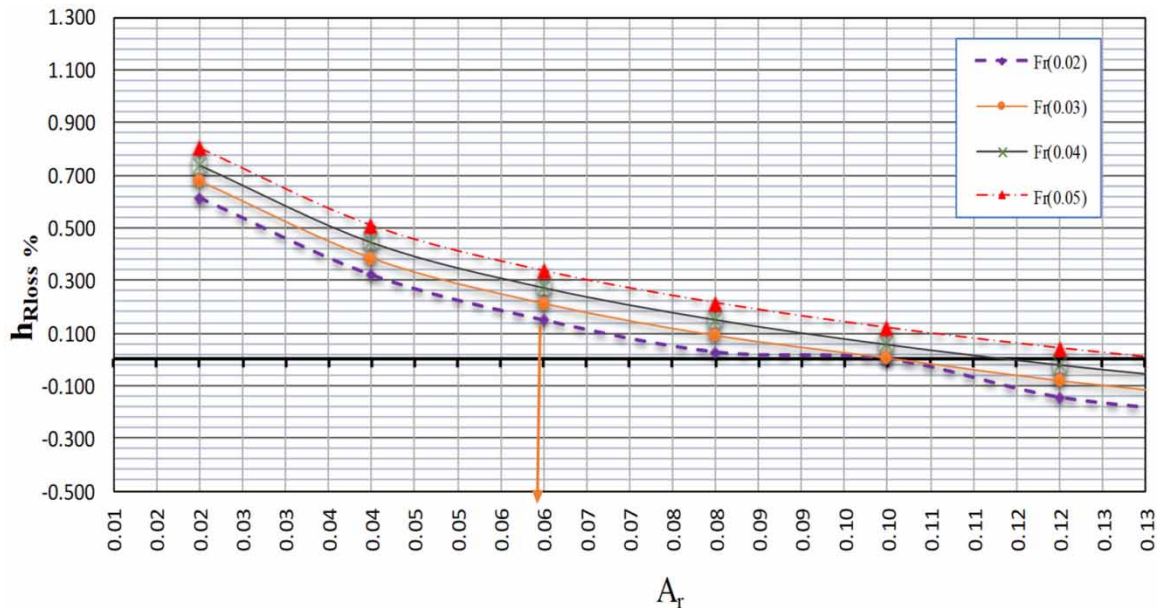
Figures 10 and 11 present a comparison of values for measured relative head loss, predicted values, and relative wetted area of coverage.

The following findings were obtained using Equation (5) and Figures 10 and 11:

1. The relative head loss ( $h_{Rloss}$ ) and the relative wetted area coverage had an inverse relationship ( $A_r$ ).
2. As the Froude number ( $F_{rd}$ ) increased, the relative heading up ( $h_{Ru}$ ) increased as well in this study (the flow is sub-critical).
3. The relative head loss increased by around 6.2% by raising  $F_{rd}$  by 0.01 while maintaining  $A_r$  unchanged.
4. The slope of the curves reduced once  $A_r$  exceeded 6%.
5. Maintaining the same level of head loss ( $h_{Rloss}$ ) while increasing  $F_{rd}$  by 0.01. It will be necessary to increase the relative wetted area of coverage ( $A_r$ ) by about 1.3% compared to the canal's upstream wetted area.



**Figure 10** | Comparison between measured and predict  $h_{Rloss}\%$ .



**Figure 11** | The relation between head loss ( $h_{Rloss}$ ) and relative wetted area of coverage ( $A_r$ ).

## 5. CONCLUSIONS AND RECOMMENDATIONS

The goal of this research was to see how the presence of box coverage and blockage influenced the open channel's hydraulic properties in the case of sub-critical flow. Various situations were evaluated in the hydraulic laboratory to meet the research goal, with the following results:

1. The increment of the coverage blockage ratio and discharge lead to an increase in the water surface profile, relative heading up value, and relative head loss value.
2. The presence of coverage in the open channel caused an increase in the water surface profile.
3. As the inlet area of the coverage was reduced, the water surface profile, heading up value, and head loss value are increased.
4. The worst-case situation was a little coverage dimension (8.80 cm side) with 30% blockage and discharge 11 L/s. Within blockage ratios, 0,10,20, and 30% and discharge 11 L/s, the relative heading up ratios ( $h_{Ru} \%$ ) values were 85, 97, 111, and 125% respectively, and the relative head loss ratio values downstream from the coverage ( $h_{Rloss} \%$ ) were 88, 99, 113, and 131% respectively related to the depth of a non-coverage case.
5. Flow velocities and the relative wetted area of coverage ( $A_r$ ) are the most effective variables for relative heading up and relative head loss. The relative head losses and relative heading up of the water displayed an inverse relationship with  $A_r$ .
6. As the Froude number ( $F_{rd}$ ) was increased in this investigation, the relative heading up and relative head loss increased (the flow is sub-critical).
7. With a 0.01 increase in  $F_{rd}$  and a fixed relative wetted area of coverage ( $A_r$ ), the relative heading up increased by about 5.5 percent.
8. Increasing  $F_{rd}$  by 0.01 while keeping  $A_r$  unchanged, increased relative head loss by 6.2 percent.

To minimize the impact of coverage and blockage on the hydraulic characteristics of the open channel, it is recommended that coverage be maintained regularly and that a trash rack be constructed upstream of the coverage to avoid the accumulation of solid waste and aquatic weeds.

## DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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