ROUGHENED AND CORRUGATED APRONS AS SCOUR COUNTERMERRGED HYDRAULIC JUMPS

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ABSTRACT

Non-erodible horizontal aprons are employed downstream of hydraulic structures to dissipate the kinematic energy and to control the downstream scouring. This paper experimentally explored the effect of the height of roughness elements and height of corrugation aprons on the scour geometry downstream of submerged hydraulic jumps. In the present study, 180 experimental tests were performed on four different aprons with roughness heights of 22, 29, 41 and 51 mm. Two different types of roughness were considered, (roughness due to natural particle with uniform grain sizes and due to U-shaped corrugated aprons), under different flow conditions. A case of smooth apron was included to estimate the influence of both roughness types on the scour hole dimensions. Obtained results were analyzed and graphically presented and simple formulae were developed to estimate the maximum scour length, depth and the scour hole dimensions. The results indicated that as the roughness height increases, a significant reduction in the scour dimensions occurred. Nature rough basins produce minimum scour hole in comparison with the corrugated basins.

Keywords: Roughness aprons, corrugated aprons, submerged hydraulic jump; scour holes.

1 INTRODUCTION

Many studies have been conducted with non-cohesive apron materials in this area. But, most of these studies are related to formation of submerged jump upon flat aprons and few studies are carried out in the case of submerged jets on rough apron and the effect of roughness on local scour process. A jump formed in a horizontal, wide rectangular channel with a flat apron is often referred to as the classical hydraulic jump and has been studied extensively by Peterka (1958), Rajaratnam (1967), McCorquodale (1986) and Hager (1992). The first study on hydraulic jump over rough apron were carried out by Rajaratnam (1968), and this study was mentioned that, the length of jump upon rough apron is smaller than the length of classical jump. Many different corrugated shapes and rough aprons have been proposed studied by Ead and Rajaratnam (2002), Farhad Izadjoo and Shafai (2005), Ead S. Ali (2007), Carollo et al. (2007) and Zedan et al. (2010).

Local scour is considered one of the important and complicated problems facing many of irrigation works, such as weirs, regulators, and dams, which are built crossing the flow of alluvial channels and rivers. It is important to study the characteristics of scour, such as the maximum depth and length of scour that occurs downstream of irrigation structures to protect them from failure. Scour downstream a hydraulic jump has been studied by many researchers such as Novak (1961), Catakli (1973), Pillai (1989), Rice and Kadavy (1993), Baghdadi (1997), Hoffmans (1998) and El-Abd (2002).

El-Abd (2002) found that the scour hole depth increased with the increasing value of Froude number. For bigger values of stilling basin lengths, the values of (d_s/y_2) had small effect on the value of d_s/y_2 for all values of Froude number.

Previously published materials proposed that the scour holes develop rapidly in the early stages and progresses toward an asymptotic stage beyond which the scour profile does not change significantly with time and reaches an equilibrium state, Alihosseini et al. (2008), Oliveto et al.

(2008), Sarathi et al. (2008), Omid et al. (2009) and Hamidifar et al. (2010, 2011). Chen and Siow (2012) confirmed that the equilibrium scour state was never reached when jet-flipping occurred during the scouring processes as it consists of two intermittent and cyclical phases: a digging phase with an attached apron-jet scouring the apron to form a deep scour hole and a filling phase where the attached jet flips to become a surface-jet causing sediments to refill into the scour hole.

Balachandar and Kells (1998), Balachandaret et al. (2000), Kells et al. (2001), Lim and Yu (2002), Sarkar and Dey (2005), Goel and Verma (2005) and Dey and Sarkar (2006) have studied the development of scour holes downstream of an apron for a submerged jet. A comprehensive state of the art review on the investigations done on scour due to jets was introduced by Sarkar and Dey (2004).

The complete protection against scour is too expensive. So, the maximum scour depth and the upstream slope of the scour hole have to be predicted to minimize the risk of failure. There are many formulas for scour following hydraulic jump in a stilling basin such as developed by Schoklitsch (1932), Eggenberger (1944), Shalash (1959), Uymaz (1988), Hoffmans (1998), Dargahi (2003), Aytac and Gunal (2008), Oliveto and Victor (2009), Zidan et al. (2010), El-Gamal (2011) and Ali et al. (2014).

Radial gates are preferred over vertical sluice gates for several advantages. They require smaller hoisting force, have easier operation, produce lower flow disturbance, and provide better discharge, Sehgal (1996). The flow through radial gates is classified as either free flowing or submerged depending upon the tail water depth and the size of the gate opening. Many studies can be found in the literature on free and submerged radial gates e.g. [Buyalski (1983), Clemmens et al. (2003), Bijankhan et al. (2011), Clemmens and Wahl (2012), Bijankhan et al. (2013), Ali et al. (2015), Abdelhaleem (2017)].

In conclusion, the review of the previous published materials showed that the rough aprons can effectively decrease the required conjugate depth and length of the jump. It thus can reduce the cost of energy dissipating aprons.

The present study is an attempt to extend the previous studies by investigating the effect of U-shaped corrugated and rough aprons at downstream of submerged radial gate on the local scour. The submerged flow condition is the most common in Egypt, so, laboratory experiments were carried out using different heights of natural roughness elements and U-shaped corrugated aprons on the stilling basin under submerged flow condition produced by radial gates.

2 DIMENSIONAL ANALYSIS

The maximum scour depth downstream of the submerged radial gate can be expressed as a function of the following independent variables:

$$d_s = f(\mu, \rho, g, \theta, d_{50}, k_s, y_1, y_2, y_3, y_t, v_1, L_j, S) \quad (1)$$

Where: d_s is the maximum depth of scour, μ is the dynamic viscosity of water, ρ is the density of water, g is the acceleration gravity, θ is gate leaf angle, d_{50} is the mean size of bed material, k_s is the roughness height, y_1 is the water depth at vena contracta (minimum jet thickness), y_2 is the sequent depth of submerged hydraulic jump, y_3 is the backup water depth downstream of the gate, y_t is the tailwater depth, y_1 is the mean velocity under gate, L_j is the length of submerged hydraulic jump, and S is the submergence factor.

Applying the Buckingham theorem with ρ, y_1, and g, as repeating variables, Eq. (1) can be written in dimensionless form as following;

$$d_s / y_1 = (Fr_1, R_e, \theta, \frac{d_{50}}{y_1}, \frac{k_s}{y_1}, S, \frac{y_2}{y_1}, \frac{y_3}{y_1}, \frac{y_t}{y_1}, \frac{L_j}{y_1}) \quad (2)$$

In which R_e is the Reynolds number, Fr_1 is the Froude number under gate. Because of d_{50}, μ, ρ, and θ are constants so, can be ignored. Hence, Eq. (2) is reduced to

$$d_s / y_1 = (Fr_1, \frac{k_s}{y_1}, S) \quad (3)$$

By the same method, the maximum scour length L_S is dependent on the following independent variables:

$$L_s / y_1 = (Fr_1, \frac{k_s}{y_1}, S) \quad (4)$$

3 EXPERIMENTAL WORK

The experiments were performed at the hydraulics and irrigation laboratory of the Benha Faculty of Engineering, Benha University, Egypt. Measurements were conducted in a zero slope flume with smooth concrete apron and Plexiglas walls. The flume has a width of 0.4 m, height of 0.6 m, and length of 15.0 m. It has an adjustable tailgate at the downstream end to control the submerged flow condition. At 7.0 m downstream of the entrance, a radial gate was installed. The radial gate was made of steel with sharp edge seal of 4.0 mm thickness. For all experiments, the radial gate radius was 470 mm, the trunnion-pin height was 230 mm, and the gate width was 400 mm. The discharge was measured with a magnetic flowmeter and a digital point gauge with an accuracy of ±0.1 mm was used to measure water and scour depths. The backup water depth was measured with the static side of a 5 mm diameter Prandtl tube that was placed in the center of the flume.

A definition sketch of side view of scour due to submerged jump on different aprons downstream radial gate is shown in Fig. 1. In this figure, *a* is the gate trunnion-pin height (height of gate pivot point above invert), *r* is the radius of the radial gate, *w* is the gate opening, y_o the upstream water depth, y_1 is the water depth at vena contracta (minimum jet thickness), y_3 is the backup water depth downstream of the gate, y_t is the tailwater depth, k_s is the roughness height, and θ is gate leaf angel, [$\theta = cos^{-1}((a - w)/r)$].

The experimental work was carried out using three materials downstream the radial gate to simulate the roughness elements, the first one is spaced corrugated apron (U-shaped) with different heights of (22, 29, and 41 mm), the second materials is gravel with d_{50} of 8 mm with roughness heights of (22, 29, and 41 mm), and the third material is a big gravel with average roughness heights of 51 mm as shown in Fig. 2. the testes also included a smooth floor without roughness to represent the reference case. In all cases, the constant length of apron 120 cm and the rear reach of the channel downstream the apron is filled with a 30-cm layer of sand with d_{50} = 0.37 mm, in order to represent the movable bed.

All tests were carried out with a radial gate under submerged flow condition; this hydraulic condition was quantified by applying the formula of Bijankhan et al. (2011) on smooth basins.

Steady state hydraulic parameters including upstream water depth, supercritical depth, tailwater depth, backup depth, and discharge were measured with different gate openings. The upstream and tailwater depths, y_o and y_t were measured at distances 3.0 m upstream and 5.0 m downstream of the gate, respectively. These distances were always far away from any zone of water surface turbulence. The minimum jet thickness, y_1 was measured at a distance of 1.15 times the gate opening from the gate lip, this is the approximate location of the vena contracta, Chow (1959). In this study, the submergence ratios is defined as $S= (y_t - y_2)/y_2$, where y_2 is the subcritical sequent depth for a submerged jump corresponding to the supercritical depth of y_1, computed by the illustrious Belanger equation, Chow (1959). A total of 180 tests were performed. For each run, after the desired water depth and the discharge were achieved, the running time of the test was started. For comparison purposes, duration of four hours was maintained. At the end of every test the flume was slowly drained and the geometry of the scour hole was measured. A grid of 2.0 cm x 2.0 cm was used to survey the bed topography and the maximum scour depth and length was observed.

4 ANALYSIS AND DISCUSSION

4.1 Scour hole depth

Figs. 3 and 4 describe the relation between Froude number Fr_1, with relative depth of scour d_s/y_1 at different values of submergence factor S.

From this figures, it was found that, the scour hole depth increases as the Froude number increases; The scour hole depth decreases as the submergence factor decreases due to the reduce of the jump length. The scour hole depth increases as the supercritical depth y_1 decreases. The scour hole depth downstream rough and corrugated aprons decreases as the roughness height increases. However the rough apron (big gravel with average roughness heights of 51 mm) could be considered the least for the reduction of the scour hole depth compared to others rough aprons, because the proportion of blanks is high and therefore the flow downstream the radial gate is being highly turbulent. The scour depth at corrugated, rough aprons, and big gravel aprons decreases by average percentage of 44%, 60%, and 51% respectively in comparison with the scour depth of smooth apron. The rough apron could be considered give the maximum reduction of the scour hole depth, and the rough apron at k_s=41 mm could be considered the best rough apron for the reduction of the scour hole depth, decreases by average percentage of 65% in comparison with the scour depth of smooth apron .

Based on the experimental data and using the statistical method, for different Froude number, submergence factor S and roughness heights, several models were proposed and their regression coefficients were estimated. The best empirical equations predicting the relative scour depth can be put in the following form:

$$d_s / y_1 = 0.4\, F_{r1}^{\;1.07}\, S^{0.1} \tag{5}$$

$$d_s / y_1 = 0.222\, F_{r1}^{\;1.163}\, S^{0.168} \left(\frac{k_s}{y_1} \right)^{-0.145} \tag{6}$$

$$d_s / y_1 = 0.081\, F_{r1}^{\;1.606}\, S^{0.199} \left(\frac{k_s}{y_1} \right)^{-0.297} \tag{7}$$

$$d_s / y_1 = 0.217\, F_{r1}^{\;1.073}\, S^{0.162} \tag{8}$$

Eq. (5) is valid for submerged radial gates with smooth apron and Eqs. (6-8) are proposed for submerged radial gates with artificial spaced corrugated aprons (U-shaped), natural rough aprons, and big gravel aprons respectively. The predictive capability of Eqs. (5, 6, 7, and 8) was remarkably high (R^2 = 97.27%, 96.94%, 95.82%, and 97.6% respectively).

Fig. 5 depicts the comparison between the measured values of the ratio d_s/y_1 downstream of smooth apron throughout the present study and those calculated by Dragahi (2003), Ali et al. (2014), Zidan et al. (2010), Abdelhaleem (2013), and Elnikhely (2017) at these conditions. Dragahi (2003) considered free hydraulic jumps downstream of smooth spillway, Ali et al. (2014) presented submerged hydraulic jumps on smooth apron at Froude numbers ranging from 1.68 to 9.29, Zidan et al. (2010) studied free hydraulic jumps on smooth apron downstream the vertical sluice gate at Froude number ranging from 1.61 to 6.56, Abdelhaleem (2013) presented free hydraulic jumps downstream a Fayoum type weir, Elnikhely (2017) considered free hydraulic jumps downstream of smooth spillway. According to Fig. 5, the results of the present study were in a very good agreement with of Ali et al. (2014). This is due to that the operation conditions are almost the same. Although, the different conditions with Abdelhaleem (2013), the results are in a very close to him.

In Fig. 6, the comparison between the measured values of the ratio d_s/y_1 downstream of rough and U-shape corrugated aprons and those calculated by Dragahi (2003), Ali et al. (2014), Zidan et al. (2010), Abdelhaleem (2013), and Elnikhely (2017). Fig. 6 confirms the equations introduced by Zidan et al. (2010) and Ali et al. (2014).

4.2. Scour hole length

Figs. 7 and 8 give the relation between Froude number Fr_1 with relative length of scour L_s/y_1 at different values of submergence factor S.

It may be concluded from these figures that, the scour hole length increases as the Froude number increases; The scour hole length increases as the supercritical depth y_1 decreases. The scour hole length increases as the submergence factor increases due to increasing of the submerged hydraulic jump length. The scour hole length downstream rough and corrugated aprons decreases as the roughness height increases. However the rough apron (big gravel with average roughness heights of 51 mm) could be considered the least for the reduction of the scour hole length compared to others rough aprons, because the proportion of blanks is high and therefore the flow downstream the radial gate is being highly turbulent. The rough apron could be considered the best for the reduction of the scour length, and the rough apron at k_s=41 mm could be considered the best rough apron for the reduction of the scour length.

The scour length at corrugated, rough aprons, and big gravel aprons decreases by average percentage of 29%, 46%, and 38% respectively in comparing with the scour length of smooth apron.

Based on the experimental data and using the statistical method, for different Froude number, submergence factor S, and roughness height, several models were proposed and their regression coefficients were estimated. Out of all trials, the average best empirical equation predicting the relative scour length can be put in the following form:

$$L_s / y_1 = 18.56\, F_{r1}^{\;0.474}\, S^{0.317} \tag{9}$$

$$L_s / y_1 = 8.4\, F_{r1}^{\;0.672}\, S^{0.223} \left(\frac{k_s}{y_1}\right)^{-0.149} \tag{10}$$

$$L_s / y_1 = 4.277\, F_{r1}^{\;0.9}\, S^{0.218} \left(\frac{k_s}{y_1}\right)^{-0.213} \tag{11}$$

$$L_s / y_1 = 8.17\, F_{r1}^{\;0.588}\, S^{0.224} \tag{12}$$

Eq. (9) is valid for submerged radial gates with smooth apron and Eqs. (10), (11), and (12) are proposed for submerged radial gates with artificial spaced corrugated aprons (U-shaped), natural rough aprons, and natural big gravel apron respectively. The predictive capability of Eqs. (9, 10, 11, and 12) was remarkably very high (R^2 = 98.4%, 93.3%, 93.07%, and 92.35% respectively).

In Fig. 9, the comparison between the measured values of the ratio L_s/y_1 downstream of smooth apron and those calculated by Dragahi (2003), Ali et al. (2014), Zidan et al. (2010), and Abdelhaleem (2013). The results of the present study are close to Ali et al. (2014) whenever Froude number decreases.

In Fig. 10, the comparison between the measured values of the ratio L_s/y_1 downstream of rough and corrugated aprons and those calculated by Ali et al. (2014), Zidan et al. (2010), and Abdelhaleem (2013). According to Fig. 10, the present study at corrugated apron is a very close to Zidan et al. (2010) despite different conditions, and Ali et al. (2014) trend is located between the present study at corrugated and rough aprons.

5 CONCLUSIONS

The results of the experimental and statistical study for the submerged hydraulic jump over smooth, rough, and U-shaped corrugated aprons and downstream local scour have been presented. The discussion and analysis of the results highlighted the following conclusions:

- Four different aprons (smooth, U-shaped corrugated, natural rough, and natural big gravel) have been used to study the effect of different aprons on the characteristics of scour downstream submerged hydraulic jumps using sample of sand.
- Many parameters affect the scour properties for the same sample of sand but, only some of these parameters such as initial Froude number, submergence ratio and the relative roughness are used to express these properties.
- Corrugation aprons (u-shaped) reduce the maximum scour hole depth and length by average percentage of 44%, and 29% respectively in comparing with the scour depth of smooth apron.
- Rough aprons reduce the maximum scour hole depth and length by average percentage of 60%, and 46% respectively in comparing with the scour depth of smooth apron.
- Natural big gravel apron reduce the maximum scour hole depth and length by average percentage of 51%, and 38% respectively in comparing with the scour depth of smooth apron.
- Using rough and corrugated stilling basins downstream of hydraulic structures is an effective engineering approach to minimize Scour holes dimensions.
- The rough apron could be considered better than the corrugated apron for the reduction of scour hole depth and length.
- At optimal roughness height k_s = 41 mm the minimum dimensions scour occurred and large energy has been dissipated**.**
- Increasing the blanks in the rough bed leads to the flow downstream the radial gate is being highly turbulent and thus scour hole more of the rough bed with less blanks.
- Some experimental equations were presented by using regression analysis to express the relationships between both the scour depth and length and the main effective parameters for a range of Froude number from 4.03 to 8.23.

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NOTATION

The following symbols were used in this paper:
a: gate trunnion-pin height;
d_s: maximum scour depth;
d_{50}: mean size of apron material;
Fr_1: initial Froude number;
k_s: roughness height;
L: length of stilling basin;
L_j: length of submerged hydraulic jump;
L_r: roller length;
L_s: maximum scour length;
Q: flow discharge;
r: radius of the radial gate;
S: submergence factor;
w: gate opening;
y_o: upstream water depth;
y_1: water depth at vena contracta (minimum jet thickness);
y_2: sequent depth of submerged hydraulic jump;
y_3: backup water depth downstream of the gate;
y_t: tailwater depth;
θ: gate leaf angel; and
δ: contraction coefficient.

FIGURE CAPTIONS

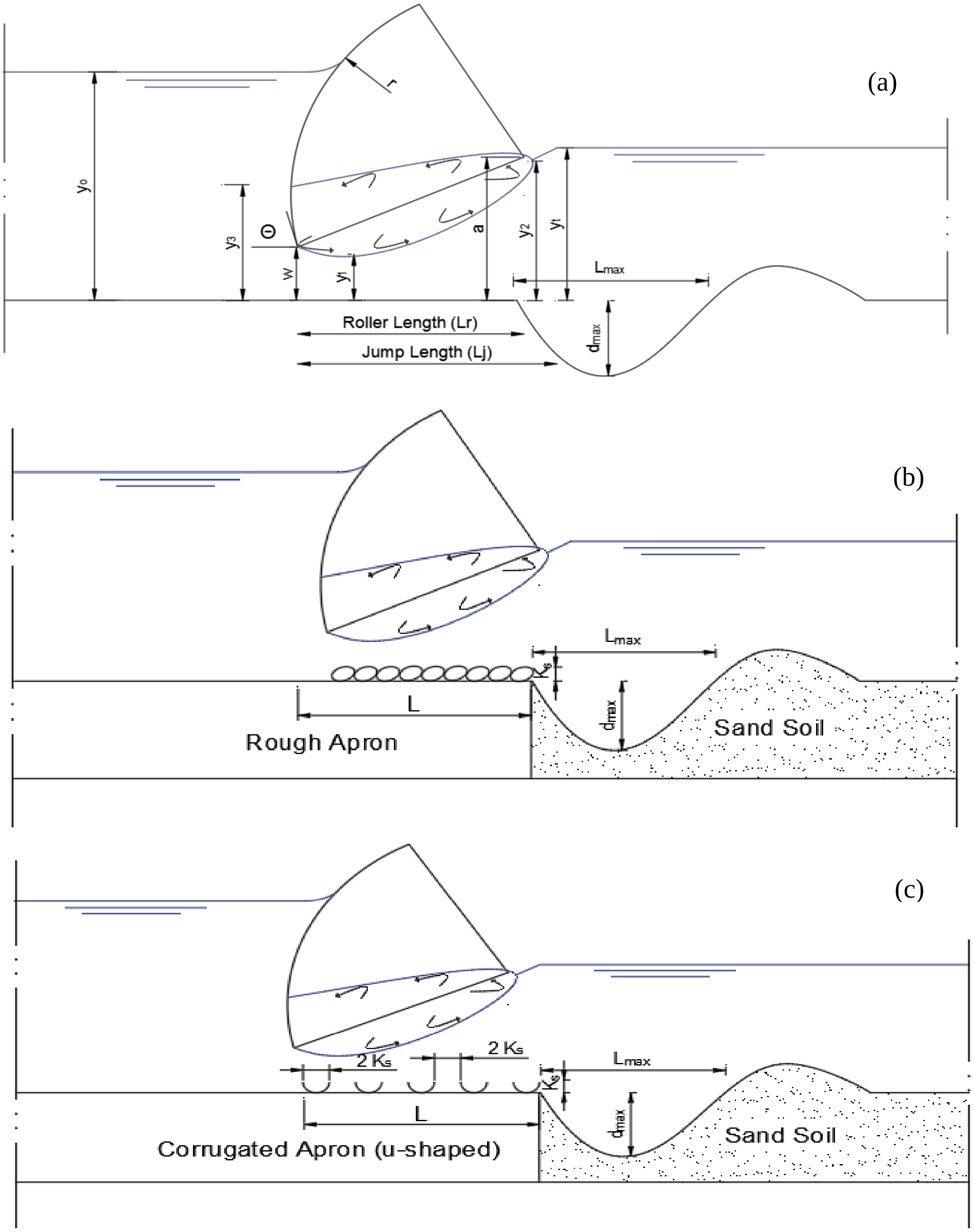

Figure 1. Layout of scour due to submerged jump on different aprons a) Smooth apron b) Rough Apron c) Corrugated Apron downstream radial gate.

Figure 2. The different materials used downstream the radial gate.

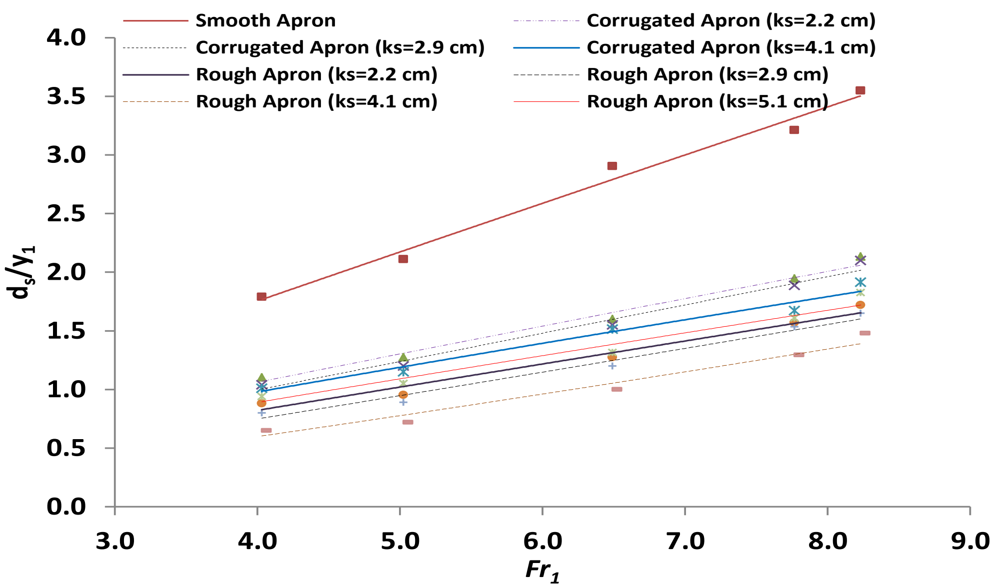

Figure 3. Relationship between observed relative scour depth (d_s/y_1) with Fr_1 over smooth, corrugated and rough aprons at submergence factor S = 0.4

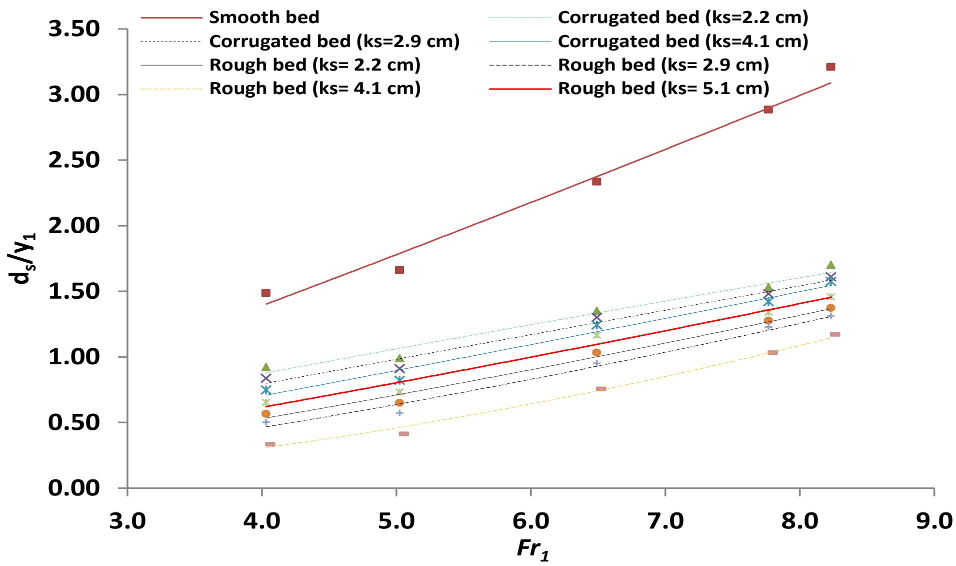

Figure 4. Relationship between observed relative scour depth (d_s/y_1) with Fr_1 over smooth, corrugated and rough aprons at submergence factor S = 0.1

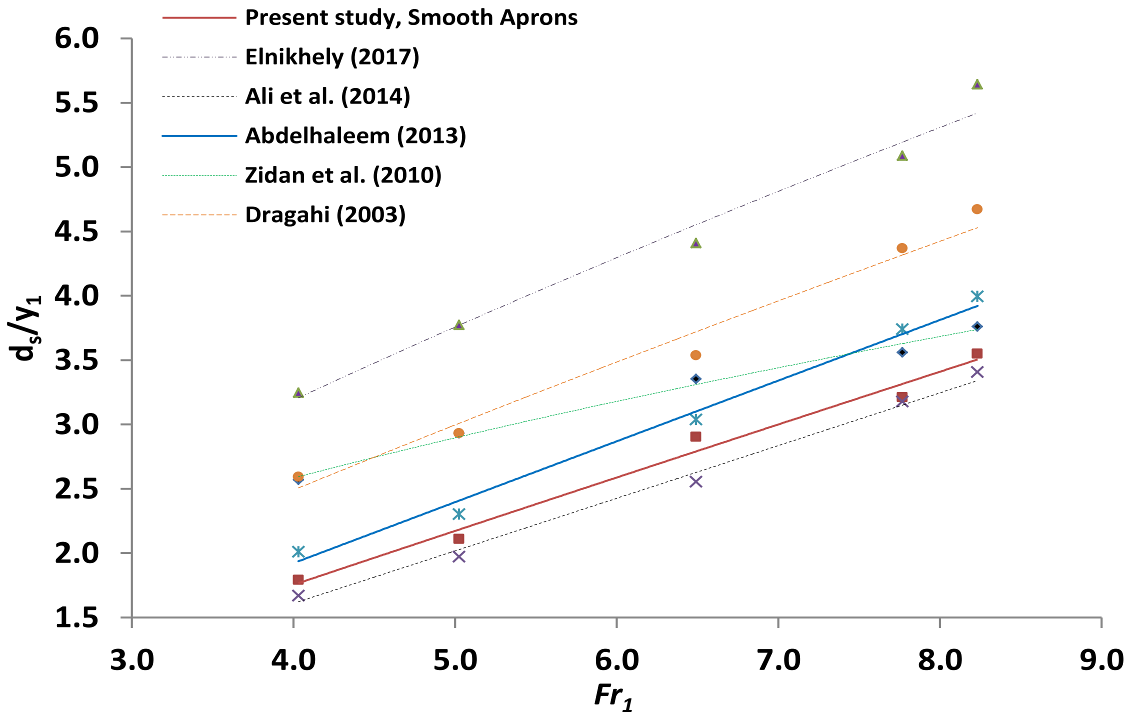

Figure 5. Relationship between (d_s/y_1) and Fr_1 over smooth apron for the present study and previous research works.

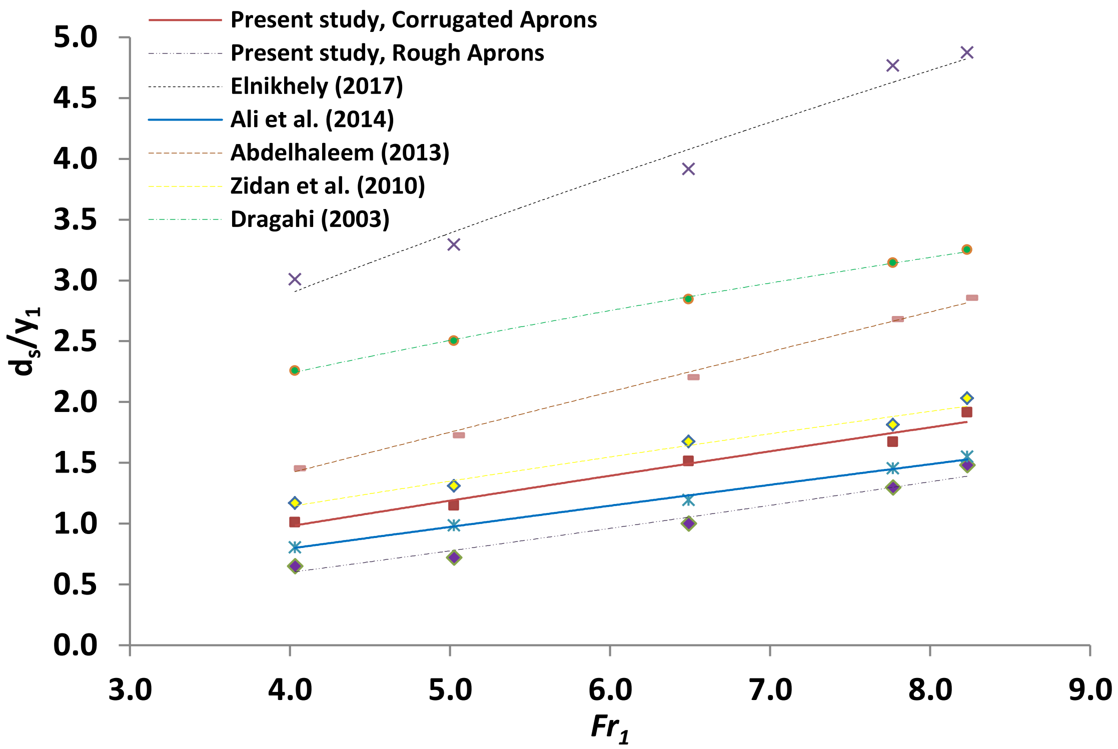

Figure 6. Relationship between (d_s/y_1) and Fr_1 over corrugated and rough aprons for the present study and previous research works.

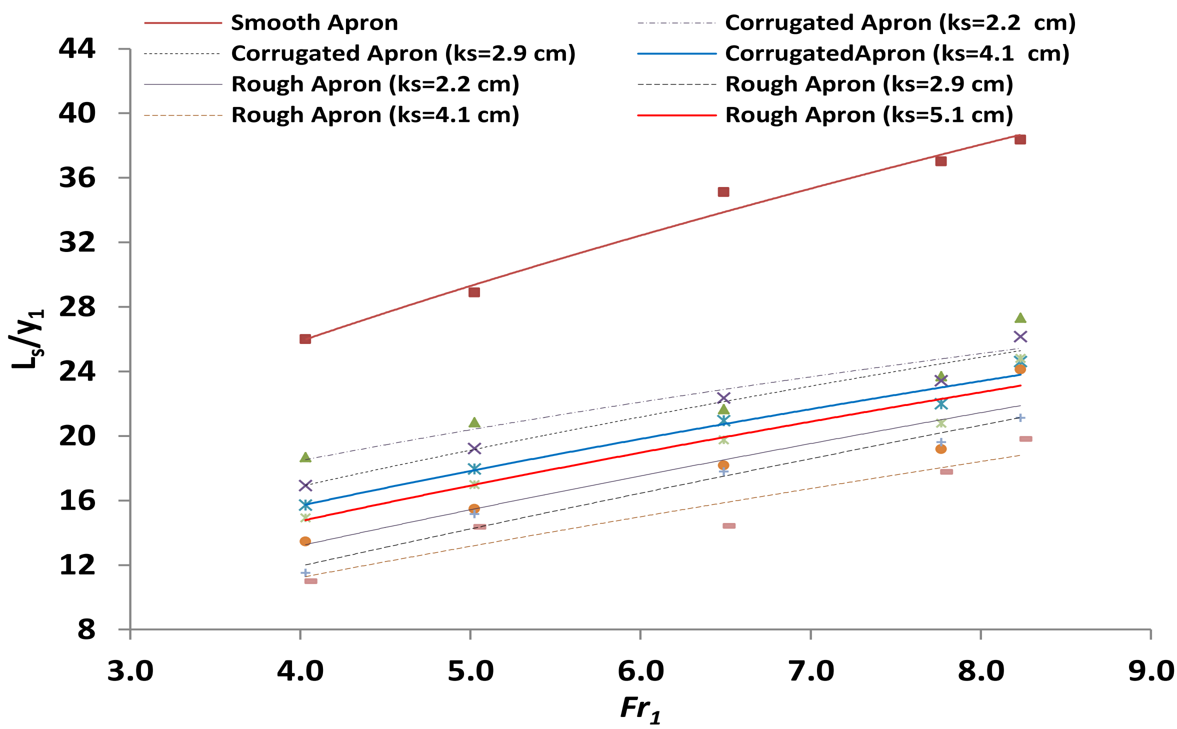

Figure 7. Relationship between observed relative scour length (L_s/y_1) with Fr_1 over smooth, corrugated and rough aprons at submergence factor S=0.4

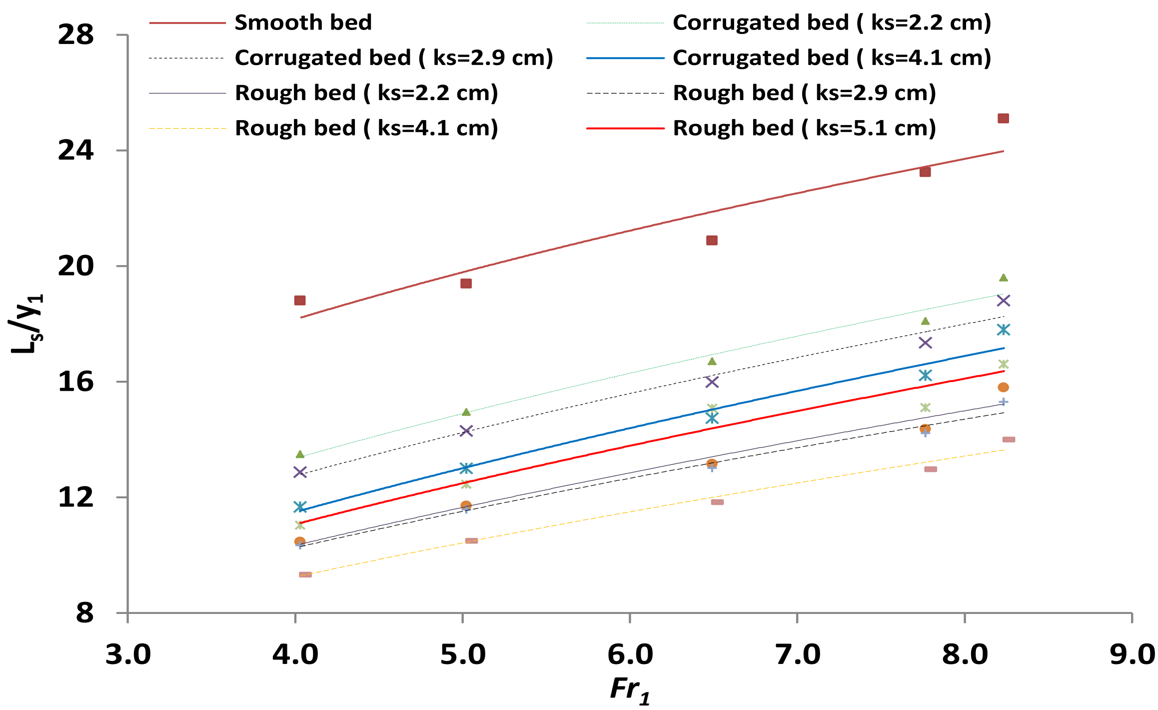

Figure 8. Relationship between observed relative scour length (L_s/y_1) with Fr_1 over smooth, corrugated and rough aprons at submergence factor S=0.1

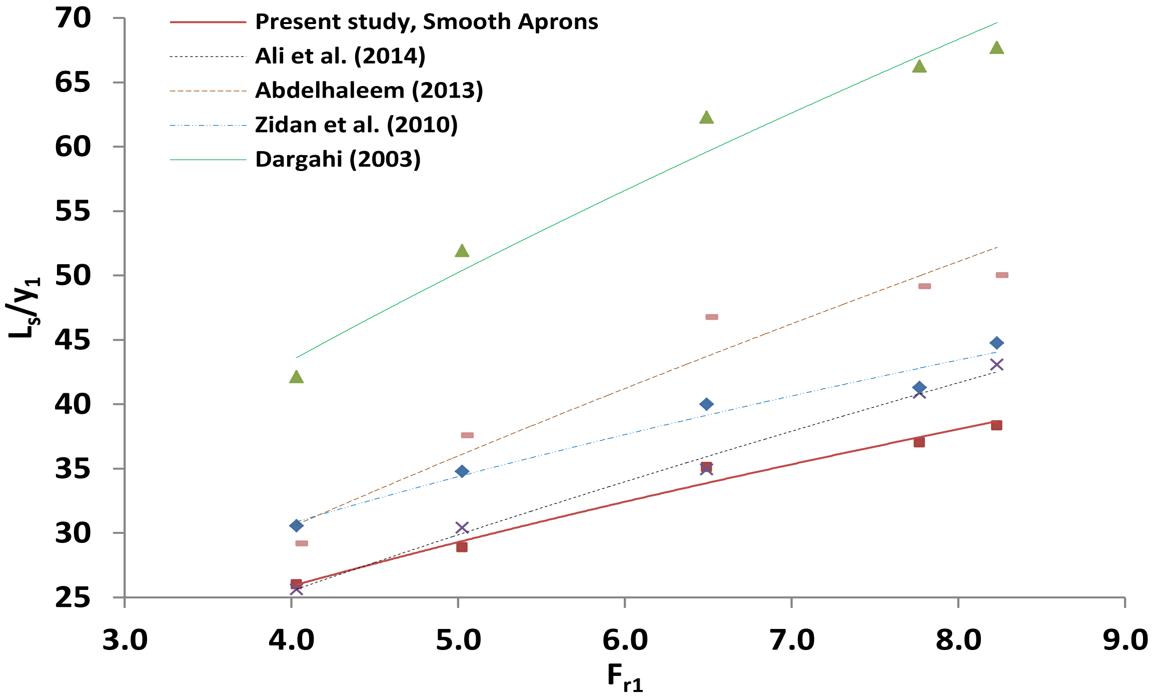

Figure 9. Relationship between (L_s/y_1) and Fr_1 over smooth apron for the present study and previous research works.

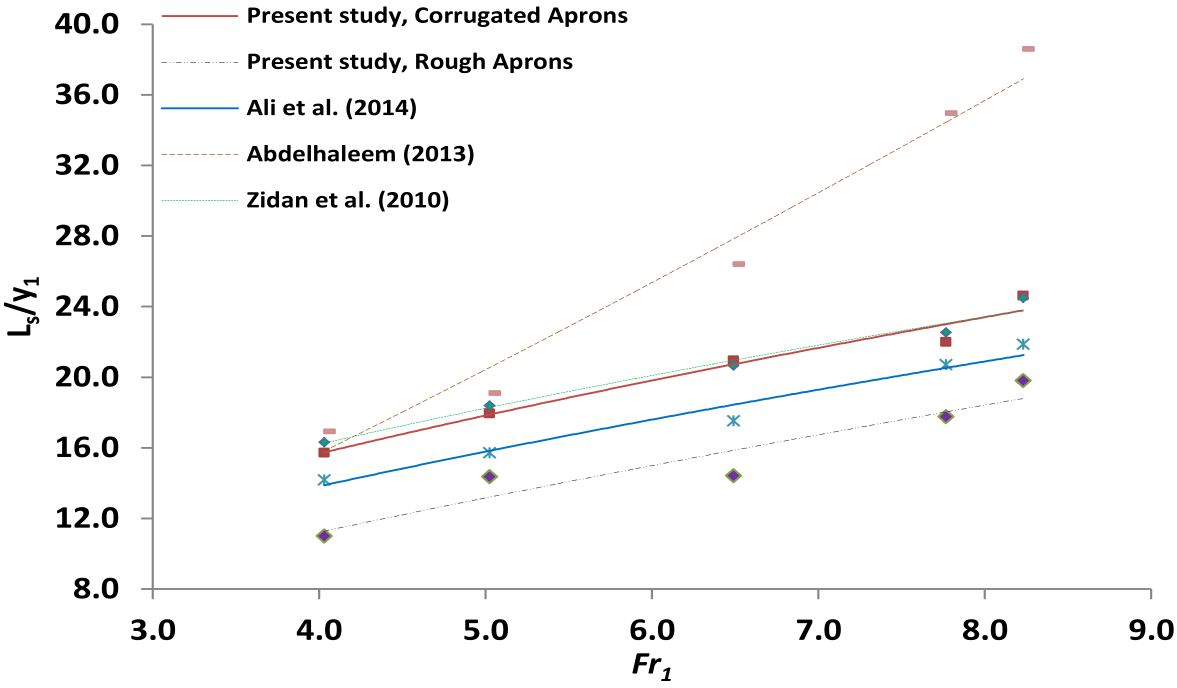

Figure 10. Relationship between (L_s/y_1) and Fr_1 over corrugated and rough aprons for the present study and previous research works.