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Investigation of Live-Bed Scour at Labyrinth Side Weirs

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Abstract

Side weirs, also known as lateral weirs, and overflow dams are free overflow regulation and diversion devices commonly encountered in hydraulic engineering. The lateral loss of water is reducing the sediment transport capacity in the main-channel and the formation of a local sediment deposit in the downstream of weir. The head over the side weir rises and the side overflow discharge as well. The design discharge to be diverted over the weir is increased by this flow-sediment transport interaction. Although there were no studies that scrutinized the scouring depth and geometry that occurs around the labyrinth side weirs in channels with movable bed, there are limited number of studies that examined the scouring geometry around the classical side weir. In the present study, local scour depths formed in the periphery of triangular labyrinth side weir mounted in a live-bed rectangular cross-section straight channel were experimentally investigated under steady state flow and free overflow from the side weir conditions. To provide for live-bed conditions, the sediment was added to bed material in the experiments. A series of experiments were conducted for live-bed scouring conditions (for flow intensity greater than one) to determine the maximum scour depths that occur around the triangular labyrinth side weir with different flow depths, different main channel discharges, different volumetric amounts of sediment feed, different crest heights, different Froude numbers, different flow intensities and using uniform bed material. In the experiments, the dimensions of the scours and sediment deposits that occur upstream and downstream of the weir exhibited a periodic change (increase and decrease). The maximum depth of scour occurred at the downstream end of the triangular labyrinth side weir frequently.

Keywords: Triangular labyrinth side weir, Flow intensity, Local scour, Live-bed scour, Sediment transport.

Labirent Yan Savaklarda Hareketli Taban Oyulmasının İncelenmesi

Özet

Yan savaklar; baraj, bağlama ve tersip benti gibi su yapılarında serbest savaklama akım yönünü değiştirme gibi amaçlarla hidrolik mühendisliğinde yaygın olarak kullanılmaktadırlar. Yanal savklanmadan dolayı, ana kanaldaki sediment taşınım kapasitesi azalmakta ve savağın mansap bölgesinde sediment birikimi gözlenmektedir. Yan savak yüksekliğine bağlı olarak savaklanma debisi de artmaktadır. Literatürde klasik yan savaklardaki oyulmayı inceleyen sınırlı sayıda çalışma bulunurken, labirent yan savaklarda oluşan oyulma derinliğini ve geometrisini inceleyen hiç bir çalışmaya rastlanmamıştır. Mevcut çalışmada dikdörtgen enkesitli alüvyal tabanlı bir kanalda kararlı akım şartları ve serbest savaklanma durumu için üçgen labirent yan savak civarındaki yerel oyulma derinlikleri deneysel olarak araştırılmıştır. Deneylerde hareketli taban koşullarını sağlamak için, kanala belirli miktarlarda taban malzemesi ilavesi yapılmıştır. Üçgen labirent yan savak etrafında oluşan maksimum oyulma derinliklerini belirlemek için; farklı akım derinlikleri, farklı ana kanal debileri, farklı hacimlerde beslenen sediment miktarları, farklı kret yükseklikleri, fraklı Froude sayıları, farklı akım şiddetleri ve nüiform taban malzemesi dikkate alınarak hareketli taban oyulması koşulları altında (akım şiddetinin birden küçük olduğu durum) bir dizi deney gerçekleştirilmiştir. Deneylerde savağın membasında ve mansabında farklı boyutlarda oyulma ve kum birikintileri oluştuğu gözlemlenmiştir. Maksimum oyulma derinliğinin, çoğunlukla üçgen labirent yan savağın mansap ucunda oluştuğu gözlenmiştir.

Anahtar Kelimeler:

1. Introduction

A structure, located in a stream bed or built later, could change certain properties of the flow. If these changes in flow could be predicted beforehand, the structure would be designed in a sounder manner, or necessary precautions against the problems that are caused by these changes would be taken. Otherwise, this case leads to damages in the structure or to the failure in fulfilling its function. The scouring observed in the intake structure, scouring formed in the downstream of the spillway, and the scouring occurring in the abutment wall and midfoot of the bridges and the scouring observed in the downstream of the baffle structures are of major problems encountered in hydraulic engineering.

The decrease in velocity and shear stress due to the lateral over flow causes the realization of a reverse current via creating a stagnation region in the downstream of the side weir. Scouring is formed between the main channel axis in the downstream region of the side weir and the outer bank, as a result of the changes in the shear stress.

Although there were no studies that scrutinized the scouring depth and geometry that occurs around the labyrinth side weirs in live-bed channels, there are limited number of studies that examined the scouring geometry around the classical side weir. Rosier et al. (2011) conducted an experimental research on the geometrical behavior of bed forms in a classical side weir region placed in a rectangular channel [1]. Paris et al. (2012) researched the applicability of De Marchi hypothesis on the determination of discharge capacity of side weirs under subcritical flow regime and live-bed conditions. This study presents experiments demonstrating the relationship between bed morphology and overflow discharge. The experiments were conducted in a main channel with small dimensions (0.30 m x 5 m x 0.30 m) and within a small discharge range (2-12 L/s). Studies reported that De-Marchi approach could be used in live-bed channels [2]. Onen and Agaccioglu (2013) conducted an experimental research examining clear-water scouring and live-bed scouring conditions in rectangular cross-section side weirs with L = 0.25, 0.40 and 0.50 m weir opening and p = 0.07, 0.12 and 0.17 m crest height from the sand bed in a live-bed 180o curved channel, considering subcritical flow regime and overfall conditions [3].

Since there are limited number of studies in the literature on the change in bottom topography and the scouring problem, which both occur around the labyrinth side weir that are placed in the streams, a complete theoretical basis on this subject was not constituted. Therefore, it is considered that it would be useful to examine the scouring problem, especially in our country that is rich in rivers. The aim of the present study is; to investigate the maximum scouring depth and the bottom geometry in the labyrinth side weirs, under the live-bed scouring conditions.

2. Hydraulics of Side Weir Flow

The most important function of the side weir is to discharge the excessive water, when the optimum capacity, determined by taking into account the requirement and economy, is exceeded. Side weirs are used in numerous engineering applications. As the water level in the reservoir reaches a level that could damage the dam, side weirs are used to discharge the water (Fig. 1). Although they are built next to the reservoir due to the flow conditions in the reservoir, these weirs act as normal weirs. This condition should be taken into consideration while conducting the hydraulic design.

Figure 1. Walshaw Dean Reservoir [4]

Figure 2 presents the side weir plan and section. It is stated that; y_1 = flow depth at the upstream end of the side weir at the centerline of the main channel (m), y_2 = flow depth at the downstream end of the side weir at the centerline of the main channel (m), y = flow depth at any point in the main channel (m), Q_1 = main channel discharge (m^3/s), Q_2 = main channel discharge after the side weir (m^3/s), Q_w = total flow over side weir (m^3/s), V_1 = mean approach flow velocity at the upstream of the side weir in thw main channel (m/s), V_2 = mean approach flow velocity at the downstream of the side weir in the main channel (m/s), V_s = mean approach flow velocity of the side weir in the collection channel (m/s), B = main cahnnel width (m), L = around a triangular labyrinth side weir of width (m), Ψ = angle of deflection (°), p = weir crest height (m), x = longitudinal coordinate (m).

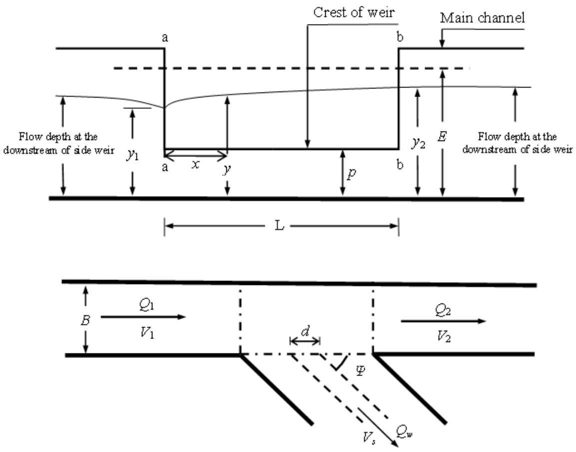


Figure 2. Plan and section of the side weir flow [5].

3. Labyrinth Weirs

Increasing the flow rate that could overflow in a particular lake level or transmitting a constant flow rate by a smaller crest water load is aimed via the labyrinth spillways, through increasing the effective length of the spillway crest. These weirs could be considered as an alternative, which are advantageous in conditions where the space in the upstream is restricted for the reservoir water level that would especially be created by the flood discharge or in conditions where the spillway width is limited due to topography. Labyrinth weirs could be constructed in trapezoidal, triangular, and circular-shaped (Fig. 3). Most preferred type is the trapezoidal-shaped type. Equation (1) is used to find the rate of flow, that pass over the labyrinth weir. Total crest length should be considered instead of the distance "L" in Eq. (1) [6].

$$Q = 1.83.(L-0.2h).h^{3/2} \quad (1)$$

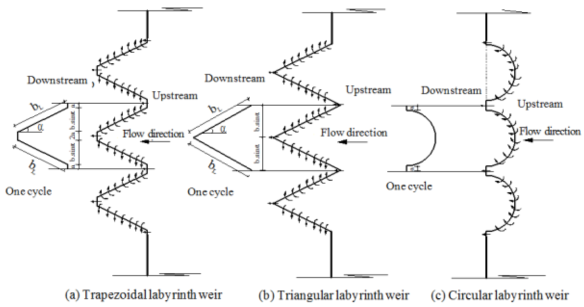


Figure 3. Labyrintyh weirs [7].

4. The Deterioration of Equilibrium in Sediment Transportation

In the case that the amount of solid material transported in an alluvial stream changes locally, changes such as sediment deposit in the bed and scouring could occur. As the amount transported increases scouring is observed, and when decreases, sediment deposit is observed.

The construction of a hydraulic structure such as a weir might cause changes in the stream bed. Such changes in the bed of the stream are observed either as sediment deposit in some parts or as scouring in others, depending on the amount of material that comes from the upstream, on the amount of material that is transported and on the amount of material that is over flown (Fig. 4). Both the sediment deposit and the scouring phenomena continue until they obtain a stable cross-sectional shape. Sediment deposit starts primarily with the sediment deposit of coarse particles, with their departure from the bed the velocity increases and the suspension discharge increases due to the decrease of the mean diameter of the material transported in suspension. Thus, due to the increase in the transported material, equilibrium condition is approximated. On the other hand, as the material coming from the upstream is smaller than the discharge transport capacity, the coarse particles remain in the bed since initially the fine particles in the bed would be scoured. In addition, occurrence of ripples in the bed would as well cause the decrease of the discharge transport capacity. Thereby, either in case of scouring or in sediment deposit, several secondary degree factors accelerate the achievement of the equilibrium condition [8].

Figure 4. Sediment deposit and scouring observed in the present study.

In a bed with cohesionless loose-material, the movement starts when the bed conditions reach a critical value required for movement. The particles that depart the bed due to the bed movement are washed away along the bed by depositing.

Bed shapes encountered in the rivers are as follows:

a. Ripples
b. Dunes
c. Plane bed
d. Antidunes

The order of the bed shapes provided above is made according to the change depending on the velocity of the flow. In other words, sand ripples occur with lower velocity flows, and as the velocity increases the bed has the shapes of ripple, dune, plane bed and antidune, respectively. Various shapes that the bed could take are given in Fig. 5 [9].

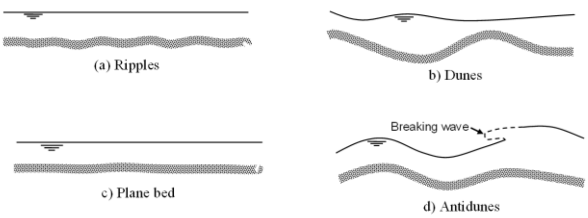


Figure 5. Bed forms developed in alluvial channels [9].

Ripple and dune formations observed in this study are presented in Fig. 6.

Figure 6. Ripple and dune formations observed in this study.

5. Experimental Study

This study was conducted at the Firat University Hydraulics Laboratory using the experimental setup depicted in Figure 7. The experimental setup was 18.20 × 0.50 m and the side wall of the main channel was made of glass. The slope of the main channel bottom was approximately 0.1%. The collection channel was 0.50 m wide and 0.70 m high. The main channel and collection channel were separated by a steel wall. The section of the collection channel where the side weirs would be *installed* was built in a circular form with a diameter of 1.30 m to provide free nape overflow from the labyrinth side weir (Fig. 7).

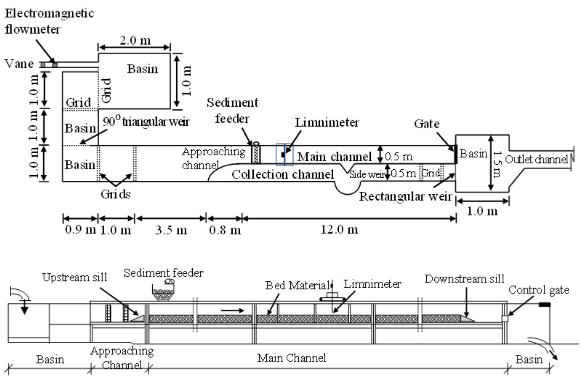


Figure 7. Experimental setup plan and longitudinal cross-section: Plan view (a), Longitudinal section (b).

The experiments are conducted in a linear channel with a rectangular cross-section; for a side weir opening of L = 0.25 meters, and for triangular labyrinth side weirs, with crest height of p = 0.07, 0.12 and 0.16 meters from the sand bed and with an apex angle of $\theta = 90^0$. The experiments were carried out under steady flow conditions, and in the case of bed scouring (V_1/V_c>1) for free over flowing condition. The experiments were conducted at a discharge of 50

- 90 L/s. The flow depth (y_1) was measured at the channel axis at the upstream end of the side weir. The water depth at the main channel axis upstream of the side weir was used as the side weir upstream water depth. Novak and Cabelka (1981) suggested a minimum upstream water depth of 30 mm [10]. Thus, in this study a minimum upstream water depth of 30 mm was used to prevent surface tension affects.

Two sills of 20 centimeters height are placed at the upstream and downstream ends of the main channel, as seen in Figure 8. Quartz sand was placed between the upstream and downstream sills on the main channel. For this sand laid on the channel bed, following values are determined, d_{50} = 1.16 millimeters and γ_s = 26 kN/m^3. The parts before the upstream sill and after the downstream sill are made up of sheet metal with an approximate slope angle of 15^0, reaching the channel bed. Thus, the provided sand base was protected against deterioration. In order to ensure stable flow conditions (i.e. to provide time-invariant flow conditions), hollow bricks are placed at the upstream part of the channel and in front of the specific points at the end of the collecting channel. The aim is to ensure taking accurate measurements over the weir.

This experimental study was carried out for the labyrinth side weirs placed in the middle part of a linear channel. The bed material was laid 4 meters forth and 4 meters backwards from the center of the side weir, covering 8 meters of the channel. Experiment system application assembly is shown in Fig. 8.

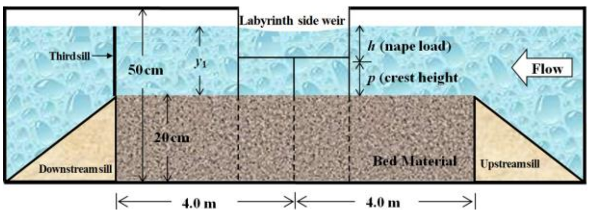


Figure 8. Experiment system application assembly.

Prior to each experiment, the sand was mixed and compacted and the bed was leveled. After the channel bed is compressed and flattened, water was supplied slowly to the channel by turning on the valve very little. As the water slowly flowed over the sand by rising slowly from the ramp in front of the sill of the upstream end of the channel, a third sill is placed 20 centimeters above the sill on side of the downstream (i.e., as it should be 40 centimeters high from the channel bed). In such way, deformation the flat shape of the sand in the bed is prevented. Then, it was waited until the depth of water in the next section of the downstream sill of the main channel reached the same water depth in the main channel. After all water level along the channel became even, the requirement flow was attained and the experiment was commenced by slowly removing the third sill that prevented the deformation of the shape of the sand in the bed, on the sill at the downstream part. By keeping the flow rate constant, flow height in the channel (y_1) was adjusted to the required level via the radial caps at the end of the channel.

Once the experiment is completed, the valve was slowly turned off, and the third sill was placed back on the downstream sill of the channel in order to preserve the topography that was formed on the bed, and thus the discharge of the water from the channel was provided. Consequent to all these processes, maximum scouring depth that occurred at the side weir area was measured via a digital limnimeter. In addition, for the bed topography, bed level measurements were taken at the side weir area at 268 points with particular intervals through the aid of the digital limnimeter. Figure 9 presents the points, at which the bed topography measurements were taken.

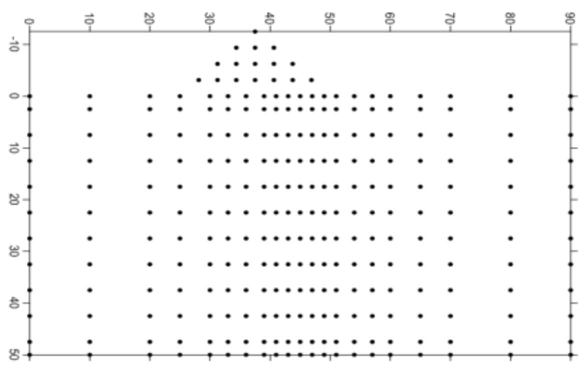


Figure 9. The demonstration of the points of topography measurements at the labyrinth side weirs that were tested: L = 0.25 m.

Initially pilot experiments were conducted in order to determine the bed load flow for various flow conditions. In case of a moving bed (V_1/V_c >

1), since bed ripples occur in a short time, and the bed is constantly in a movement, solid material transportation occurs at a high level, and the amount of the overflown material increases constantly due to the increase in the flow rate (V_1/V_c). Thus, in order to provide the moving bed condition, constant supply of solid material was provided in the channel via the portative machine, which is designed in the Hydraulics Laboratory of the Firat University's Civil Engineering Department, seen in Fig. 10. The velocity of the volumetric amount of sediment feed ($Q_{s,up}$) was adjusted by taking into consideration the "V_1/V_c" values through this machine.

Figure 10. Portative machine that provide solid material supply to the channel.

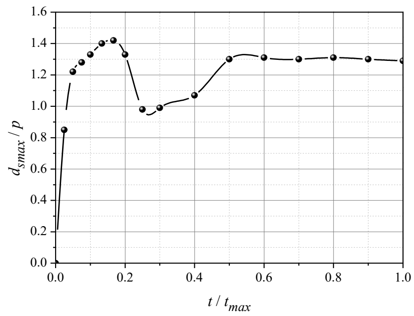
Side weir properties and flow conditions in this study are presented in Table 1.

Table 1. Side weirs and flow conditions tested in the experiments

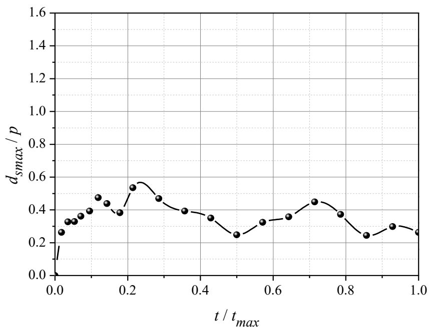
Experiment No	p (m)	L (m)	Q_1 (L/s)	y_1 (m)	$Q_{s,up}$ (m^3/s)	V_1/V_c (-)	F_1 (-)
1	0.07	0.25	50	0.12	0.00075	1.94	0.77
2	0.12	0.25	55	0.16	0.00019	1.52	0.55
3	0.16	0.25	90	0.19	0.00020	2.06	0.69

6. Evaluation of the Experiment Results

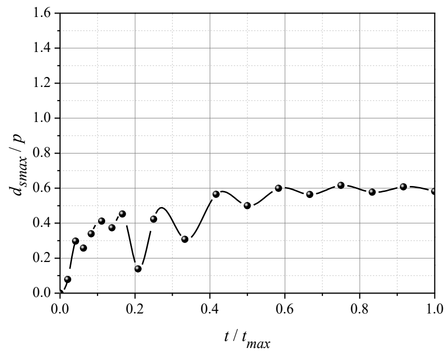
In this section, non-dimensional maximum scouring depth's (d_{smax}/p) change in non-dimensional time (t/t_{max}) was investigated in case of moving bed scouring, for side weirs with L = 0.25 meters opening and p = 0.07, 0.12, 0.16 meters crest height, and is presented in Figure 11(a-c). For moving bed scouring, "V_1", which is the velocity value in the main channel, is selected greater than the "V_c" value, which is the initial velocity of the movement in the bed. The experiments were carried out in the range between V_1/V_c = 1.0-3.0 and each experiment were carefully elaborated to be sustained for 1080 minutes. Figure 4 presents the areas in which maximum scouring depths were observed. The experiments pointed out that the duration required to obtain the maximum scouring depth during equilibrium for moving bed scouring is approximately 480 minutes. For larger "V_1/V_c" values, this duration was around maximum 900 minutes. After this duration, maximum scouring depths were observed to exhibit amplitudes close to the equilibrium scouring depths (Fig. 11). On the other hand, for the same "V_1/V_c" values in side weirs with larger crest heights, scouring depth at the time of equilibrium was observed to be smaller, and the equilibrium time was attained in a shorter duration. Scouring depth-duration graphics for each experiment is presented in Figs. 11 (a-c) and the flow characteristics are presented in Table 1. The tendency of the experiment results is parallel to the change of scouring depth as a function of time graphics in the studies of Tsujimoto and Mızukami (1985) and Yanmaz and Altinbilek (1991) [11 and 12].



a) No.1 experiment



b) No.2 experiment



c) No.3 experiment

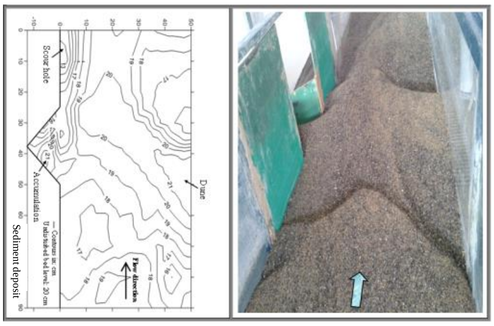
Figure 11. Time-dependent change of the scouring depth for L=0.25 m in the maximum scouring area: p=0.07 m (a), p=0.12 m (b), p=0.16 m (c).

Bathymetric contour lines of the bed occurrence as a result of the experiment for L = 0.25 m and p = 0.07, 0.12 and 0.16 m and the related images are presented in Figs. 12 (a-c).

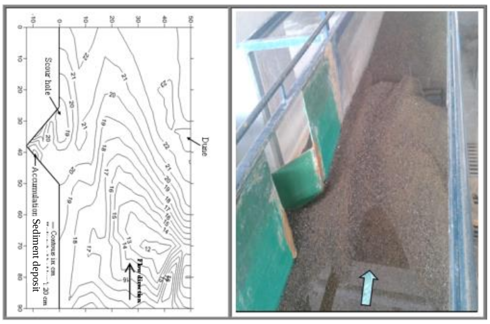
In Figure 12 (a), it is possible to observe that the topography at the interior edge of the channel did not change significantly. Scours and peaks were observed in the labyrinth triangular side weir area placed at the exterior edge. Scouring depth at equilibrium time occurred at a certain distance from the weir area.

Scouring depth at equilibrium time in Figure 12(b) was formed in an elliptical shape from the center of the downstream of the weir to the downstream end. At the upstream overflow part, a small peak formation was observed. Due to the increasing crest height and decreasing flow rate (V_1/V_c), less material was transported to the collection channel.

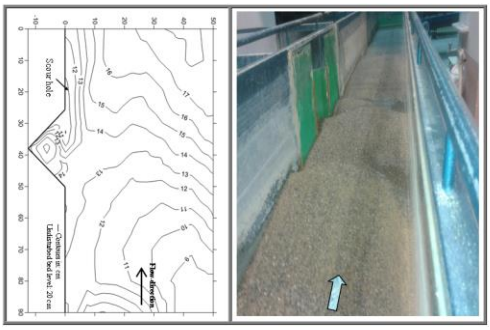
In Figure 12(c), it was observed that the topography at the interior edge of the channel did not alter significantly and small-dimensioned sand ripples were formed. However, at the exterior edge of the channel, it was observed that scours and peaks were formed. Scouring depth was formed with an elliptical shape at the weir's downstream end. Bed ripple formation is observed. Maximum scouring formation is observed at the downstream overflowing part. Due to the large crest height and lower side weir length of the side weir used for this experiment, little amount of material was overflown.



a) No.1 experiment



b) No.2 experiment



c) No.3 experiment

Figure 12. Bed bathymetry and related images for L=0.25 m: p=0.07 m (a), p=0.12 m (b), p=0.16 m (c).

7. Conclusions

Along a linear, rectangular cross-section channel with a moving bed, in constant flow and free overflowing conditions; following results are obtained from this study, which scrutinized the topographical changes that occur around the side weir and at the main channel bed and the scouring depths at the non-dimensional equilibrium time, in conditions of moving bed scouring in labyrinth side weirs with L = 0. 25 m length and p = 0.07, 0.12 and 0.16 m crest height from the sand bed.

- In this experimental study (V_1/V_c = 1.0 - 3.0), it was observed that scouring depth became evident after a short duration from the initiation of the experiment and this duration shortened due to the increase of the flow rate.

- For the flow rate V_1/V_c = 1.52 value, while usually ripple formation was observed in the bed, mostly dune formations were observed at 1.94 and 2.06 values.
- The transformation of the channel bed from ripple form to dune form, scatterings were observed in the scouring depths due to the changing bed roughness.
- While the duration to reach the maximum value of the scouring pit decreased due to the increase of the side weir crest height, the duration for obtaining the maximum value in larger "V_1/V_c" values increased.
- The place of the scouring pit formation was determined as around the side weir and close to the downstream end. As the "V_1/V_c" value increased, it was observed that the place of the scouring pit was shifted from the downstream end of the side weir to the downstream.
- With the larger values of flow rate (V_1/V_c), scouring depth at the non-dimensional equilibrium time (d_{se}/p) also reached larger values.
- Larger scouring depths were obtained in side weirs with large crest heights.
- When the flow conditions were considerably same, bed scouring started earlier as the side weir crest height decreased, and bed scouring started later as the side weir crest height increased.
- It was determined that scouring shape that occurred in the bed was directly related to the flow rate (V_1/V_c) and non-dimensional side weir crest height (y_1/p) in the rectangular cross-section linear channel, under moving bed flow conditions.
- While the side weir height is 0.07 meters, the shape of the scouring in the bed is formed with circular cross-sections due to the vortex occurrence, and when the side weir crest height increases to 0.12 and 0.16 meters, the scouring was observed to have an elliptical shape.
- It was determined that the scouring depth at non-dimensional equilibrium time (d_{se}/p) changed directly with the increase in flow rate (V_1/V_c) and after a certain period it presented an amplitude around the peak values.

8. References

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