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INVESTIGATING BED CONFIGURATION ON SANDY BED CHANNEL

دراســه معمليــه لشــكل القــاع فى المجارى (القنــوات) ذات التربه الرمليــه

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الخلاصة:

يهدف هذا البحث لدراسة تأثير عوامل السريان المختلفه مثل ظروف التصرف ورقم فرويد على شكل القاع أمام وخلف المنشأ المائى وكذا أمام وخلف منطقة وجود القفزة الهيدروليكية . فقد تمت دراسة شكل القاع وحركته بأستخدام قيم فرويد مختلفة تتراوح بين ٢,٠ إلى ١٩,٦ أمام القفزه الهيدروليكيه وكذلك عند قيم فرويد تتراوح مابين ٠,٢١ إلى ٠,٦٢ خلف القفزه ولقد أجريت التجارب بإستخدم رمل طبيعى ذو قطر متوسط ٠,٤ مم عند نسبة مرور ٦٠ % . ولقد أجريت هذه الدراسة فى معامل معهد بحوث الهيدروليكا التابع للمركز القومى لبحوث المياه مستخدماً قناتين صناعيتين ذو قطاع مستطيل وذو جوانب زجاجية بأبعاد وسعه مختلفتين حيث تم إمرار عدة تصرفات بسرعات مختلفه وأعماق سريان مختلفه وبالتالى أرقام فرويد مختلفه . وأجريت عدة تجارب (٧٢ تجربة) لدراسة شكل القاع فقد تم إختيار تصرفات مابين ٠,٠٢ إلى ٠,١٣ م٣/ث بزيادة مرحلية ٠,٠١ م٣/ث وتم إختيار (٦) فتحات للبوابات عند كل تصرف للوصول إلى شكل وخصائص القاع وبالتالى تقدير خشونة القاع. وأوضحت نتائج الدراسة أن زيادة السرعة ينتج عنها نتوأت متماثلة والتى تنسطح بعد فترة وعند السرعات العالية > ٠,٥م/ث سجلت نفس النتيجة ولكن النتوأت كانت غير متماثلة . كما تم رسم علاقتين بيانيتين لتوضيح تأثير رقم فرويد فى حالتى كونه أقل أو أكبر من (١) لتلخص العلاقات المستنتجه لأشكال القاع المختلفه المناظره لحالات سريان مختلفه أثناء التجارب . وهذه الأشكال البيانيه يمكن الأستعانة بها لتفسير وأستنتاج شكل قاع المجارى المائية عند محطات الطاقة .

ABSTRACT:

The main objective of this study is to investigate the effect of different flow parameters, mainly flow discharge and Froude number on bed configuration upstream and downstream of hydraulic jump. Bed regression was studied at different Froude numbers ranging from 2.0 to 19.6 upstream the hydraulic jump and ranging from 0.21 to 0.62 downstream the hydraulic jump. The sand used in the experiments was natural and sieving analysis was tested where grain size diameter was found to be 0.4 mm at 60 % passing. This experimental study was conducted at the Hydraulics Research Institute (HRI), the National Water Research Center (NWRC), employing two different rectangular flumes with different capacities and dimensions. Therefore, different velocities; different depths and thus different Froude numbers were obtained. The two sides of the flumes are made of glass to facilitate visualizing and monitoring the bed configuration. Extensive field observations on sediment movements in movable bed flume have been carried out for estimating the bed roughness in river channels.

Seventy two runs were executed at different discharges started from 0.02 to 0.130 m^3/s with an increment of 0.01 m^3/s where each discharge has six different gate openings to get all characteristics of bed configuration. The experimental investigations showed that at low unidirectional velocities (≤0.50 m/s), increasing the flow caused the bed to evolve from small-scale symmetric ripples to large-scale symmetric ripples to dunes and later to plane bed. At higher velocities (>0.50 m/s), a similar trend was observed, but ripples were more asymmetric and moved to standing waves and then anti-dunes. Two phase diagrams are presented, the first diagram at Fr <1 and the second at Fr >1 to summarize the observed relationships of bed configurations to flow conditions. These diagrams assist in the interpretation of bed configuration characteristics.

Keywords: Sand - Bed Channel- Bed Regression – Ripples - Dunes – Configuration.

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1. INTRODUCTION

Studying the bed configuration is vital in predicting flow resistance, sediment transport, and deposition within many rivers. The changes in bed form result from the interaction of the flow, fluid, and bed material. Thus, the resistance to flow and sediment transport is a function of the slope and depth of the flow, the viscosity of the fluid, and the size distribution of the bed material. Bed configurations that are common in natural flow environments can be generated by purely unidirectional flows, combined flows, and purely oscillatory flows. In the natural environment, most bed forms are observed in sands, but they are produced in silts and gravels as well. The bed configurations that may form in an alluvial channel are plane bed without sediment movement, ripples, dunes, plane bed with sediment movement, anti-dunes, and chutes and pools.

Bed configuration changes were generated under low unidirectional velocities. Bed configuration changes were not observed as a distinct bed state but rather appeared to mark transitions in bed-form scale and symmetry. Bed configurations were more prevalent at longer oscillatory periods and in finer-grained sediment.

With the introduction of only a small flow velocity, bed configurations evolve into large-scale ripples and the resultant bed forms becomes similar to that produced by low-flow dunes. Accordingly, these experiments suggest that much of the bed configuration changes record is produced by combined flows, long-period, finer grained sand and wide basins to form; bed configurations may therefore serve as a useful indicator of deposition in unrestricted, open-water conditions.

Bed configuration is typically similar to the findings of Simons 1981[12] where at Froude Number (Fr <<1), typical ripple pattern is configured, then transferred to dunes with ripples and when the value is a little increased (Fr < 1) only dunes were formed, later dunes are washed out and plane bed started to be appear. At Fr >1 standing waves and antidunes were formed, Fig. 1.

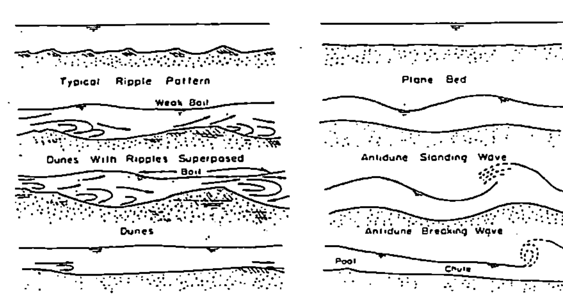


Fig. 1: Forms of Bed Roughness in Sandy Channels [12]

2. LITERATURE REVIEW

Primarily, the literature, in the field of sandy bed configuration, was reviewed. Many researchers were interested in that field. For example, Andreotti et al (2006) published a paper about Aeolian sand ripples; it was an experimental work of fully developed states. This research was concerned more about the effect of Aeolian sand ripples [2]. Blom (2006) published a research about the impact of the variability in dune dimensions on sediment sorting and morph-dynamics [3]. Cataño-Lopera and García (2006) published also a research about Geometric and Migrating characteristics of amalgamated bed forms under oscillatory flows [4]; both of the two researches covered and discussed Coastal and Estuarine. Bartholdy et al (2005) published an experimental work about "Flow and grain size control of depth-independent simple sub-aqueous dunes" [5]; Best (2005) published a research about the fluid dynamics of river dunes [6]. Dumas et al (2005) published a research "experiments on oscillatory-flow and combined-flow bed forms" [7]. Hersen (2005) published a paper about flow effects on the morphology and dynamics of Aeolian and sub-aqueous barchan's dunes [8]. Kleinhans (2005) published a research entitled "upstream sediment input effects on experimental dune trough scour in sediment mixtures" [9].

Based on the surveyed literature, a shortage in the experimental investigations was evident. For that reason, the present research was initiated with set objectives. The main objectives of this research are; to study the effect of flow conditions, mainly the Froude number on bed configuration upstream and downstream of hydraulic jump; to study the effect of unidirectional velocities on wave lengths; and to develop diagrams to summarize the observed relationships of bed configurations to flow conditions to assist in the interpretation of shallow sedimentary environments where unidirectional combined flow is thought to be omnipresent.

4.1. THE EXPERIMENTAL FLUMES

The used flumes have rectangular cross section with different dimensions. The side walls along the entire length of the flume are made of glass with wooden-frames, to allow visual investigation of the flow patterns and stability of bed protection. The horizontal bottom of the flume is made of ceramics and wood. The flumes are fed from a pump with a maximum discharge of 0.05 m^3/s for the smaller flume and 0.130 m^3/s for the larger one. The flume is equipped with a steel wooden radial gate. There is, also, a movable downstream gate located at the end of the flume. The bed material size is less than 0.5 mm. It was checked by sieve analysis before it was used. It is a medium sand type with a size between 0.5 mm to 0.25 mm, Simon 1981 [12].

Laboratory experiments were conducted to investigate bed forms generated under different flow conditions (discharges and Froude numbers). Experiments were carried out in a small and large flumes with glass sides; the smaller one with dimensions 40 m long, 0.4 m wide, and 0.6 m high and the larger one with dimensions 25 m long, 1m wide and 1 m high. Fig. 2 shows 3-D view of the smaller flume, while Fig. 3 shows longitudinal section of the larger flume respectively. Natural sand was selected as a bed material where sieve analysis was performed to get the grain sizes distribution, see Fig. 4. Different flow discharges ranging from 0.02 m^3/s to 0.13 m^3/s were run with corresponding velocities from 0.02 m/s to 1 m/s. Three regimes: appearances of an initial wave length, coarsening of the pattern, and finally saturation of the ripples have been identified.

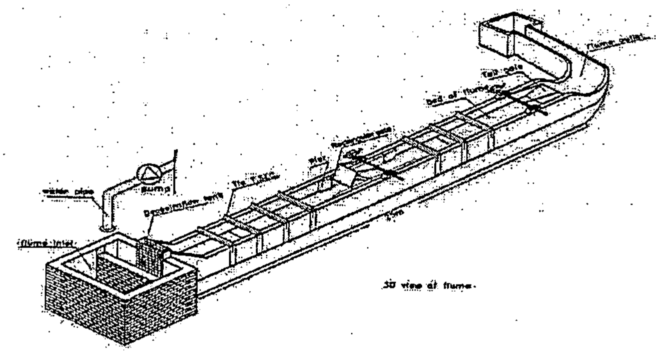


Fig. 2: 3-D View of the Smaller Flume

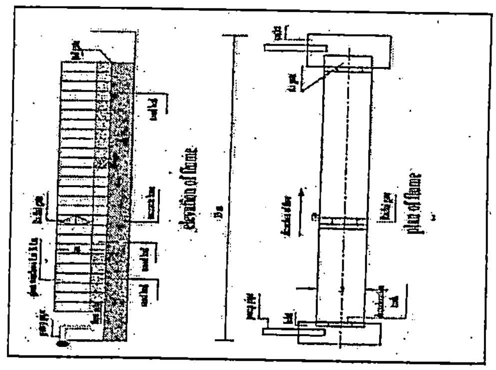


Fig. 3: Longitudinal Section of the Larger Flume

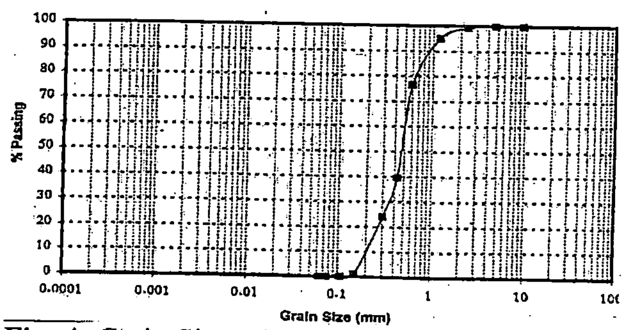


Fig. 4: Grain Size Distribution of the Used Sand

4.2. MEASURING DEVICES

The measuring devices comprised a flow meter, current meter and point gauges. A camera and a video recording were also available.

One ultrasonic flow-meter with an accuracy of $\pm$ 1% was used to determine the flow discharge. It was installed on a 16" diameter feeding pipe, Fig. 5.

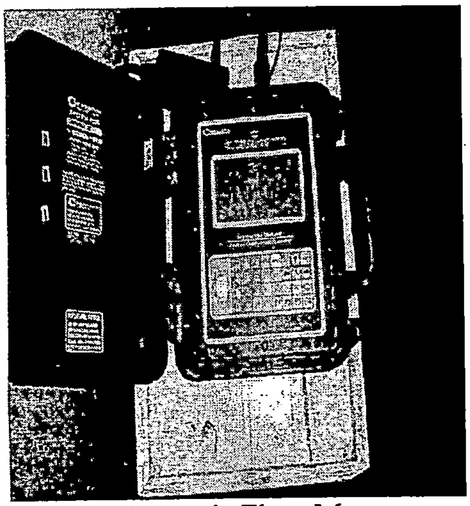


Fig. 5: Ultrasonic Flow-Meter

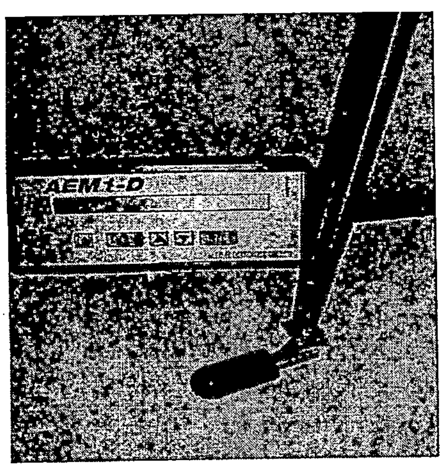


Fig. 6: Electro-Magnetic Current-Meter

The flow velocities were measured using an Electro-Magnetic current-meter type E.M.S. (manufactured by Delft Hydraulics), Fig. 6. The device was connected to a mean value meter to show the average velocity within a selected time period.

To monitor the water levels, two point gauges with side stilling wells were installed. Also, a mobile point gauge with an accuracy of $\pm$ 0.1 mm was used to measure the water and bed level.

Video and photo cameras were also essential to record the flow patterns and to monitor the stability of the rip-rap protection layers. In order to measure the flow discharges, flow meter sensors were installed on the flow feeding pipe.

5. MODEL TEST PROGRAM

A comprehensive model test program was designed to achieve the study objectives covering different flow conditions (different Froude numbers). The first flume was used for low discharges ranged from 0.02 m^3/s to 0.05 m^3/s while the second flume was used for high discharges ranged from 0.06 m^3/s to 0.13 m^3/s.

Two flow regimes were used in the research; the first one is directly downstream of the sluice gate which is called the upper flow regime at flow depth $y_1 < y_c$ and Fr > 1, Fig. 7 at C.S. (1); the second flow regime is the lower flow regime where $y_2 > y_c$ and Fr <1, Fig. 7 at C.S. (2). Table 1. shows the model test program for upper flow regime (Fr > 1) while Table 2. shows the model test program for lower flow regime (Fr <1). At each flow discharge, six different gate openings were used to control the flow depth downstream of the gate at supercritical flow conditions (Fr > 1) and also the conjugate depth (Fr <1) so as to control the value of Froude numbers. For the first (small) flume, the discharge starts from 0.02 m^3/s to 0.05 m^3/s and gate openings started from 0.01 m to 0.06 m; on the contrary, the second (large) flume starts from 0.06 to 0.13 m^3/s with gate openings from 0.03 m to 0.08 m.

At each gate opening corresponding to specific discharge, the flow depth (Y) was measured employing point gauges and also using rulers sticked with the flume glass walls. The flow velocity was measured using electro-magnetic current meter with high accuracy. More double checks for velocity measuring were done applying Bernoulli's equation at the upstream section of the gate and the downstream section of the gate, Equation (1). The ripples lengths and heights were measured using vernier caliper devices and rulers. It was more realistic to get dimensionless parameters to be applied for any dimensions of streams, so ripple length to ripple height, ripple length to flow depth, and ripple height to flow depth were determined and plotted.

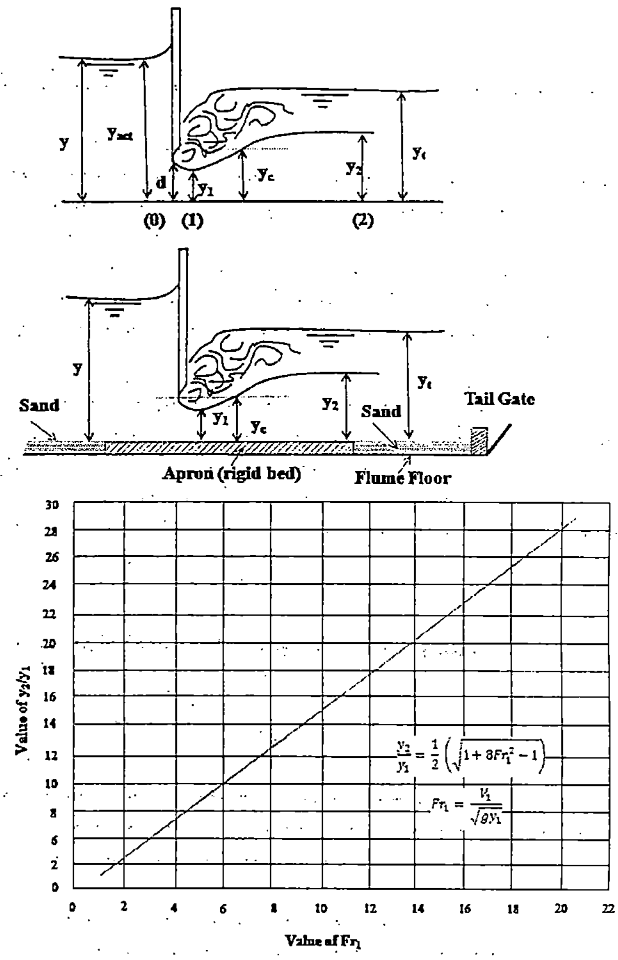


Fig. 7: Flow Depth upstream and downstream of the Gate and Conjugate Depths

Applying Bernoulli's Equation between C.S. (1) and C.S. (2):

$$y_d + \frac{V_1^2}{2g} = y_2 + \frac{V_2^2}{2g} \qquad (1)$$

Applying Momentum Eq. and Continuity Eq., the conjugate depths are given by:

$$\frac{y_2}{y_1} = 0.5\,\{\sqrt{(1+8Fr_1^2)}-1\} \qquad (2)$$

The minimum apron length (L_{apron}) required to retain the hydraulic jump on the apron with existing tail-water can be determined by El-Masry and El-Gamal [1]. The Empirical formula for determination of scour length based on Bligh is depending on bed material C_B, upstream water level and bed level H_{max}.

$$L_{Bligh} = 1.2\ C_B \sqrt{(H_{max}/3.9)} \quad (3)$$

Where : (C_{Bligh}) is a coefficient depending on bed material (for fine is 15 and for coarse sand is 12 in case of Bligh Formula [1]
(Hmax) is the difference between upstream water level and dry downstream level (m).

Lane's formula for percolation length (L_p) may be written as follows:

$$L_p = C_L \cdot H_{max} \quad (4)$$

Where : (C_L) is a coefficient depending on bed material (for fine is 7 and for coarse sand is 5 in case of Lane Formula [1]

5.1. RIPPLES AND DUNES HEIGHT (H) AND LENGTH (λ) USING DIMENSIONAL ANALYSIS THEORY

It is technique to study fluid flows, to plan experiments and present data completely. It is also method for reducing the numbers and complexity of experimental variables and then saving time and money. Using Buckingham Pi (π) Theorem: $\varphi(h, \lambda, y, \rho, v, \mu, g) = 0$

Then n = 7 which are h, λ, y, v, ρ, μ, and g   k =3 which are M, L, T

Where : h = ripples and dunes height (m), λ = ripples and dunes length (m), y = water depth (m), v= water velocity (m/s), and (ρ, μ, and g) are constants

Number of Pi (π) = n - k = 4 ($\pi_1, \pi_2, \pi_3, \pi_4$)

$\pi_1 = y^{a1}\, v^{b1}\, \rho^{c1}\, h$

$M^o L^o T^o = L^{a1} (LT^{-1})^{b1} (M l^{-3})^{C1} L$

For M $0 = C_1$

$\therefore C_1 = 0$

For T $0 = -b_1$

$\therefore b_1 = 0$

For L $0 = a_1 + b_1 - 3C_1 + 1$

$\therefore a_1 = -1$

$$\therefore \pi_1 = \frac{h}{y} \quad (5)$$

$\pi_2 = y^{a2}\, v^{b2}\, \rho^{c2}\, h$

$$\therefore \pi_2 = \lambda / y \quad (6)$$

$\pi_3 = y^{a3}\, V^{b3}\, a^{c3}\, M$

$$\therefore \pi_3 = \mu / \rho v y \quad (7)$$

Since π_3 is dimensionless and $\pi_3 = \rho v y / \mu = Re$

$\therefore$ Re (π_3) can be neglected since it doesn't have significant effect in open channel flow

$$\therefore \pi_4 = y^{a4} v^{b4} \rho^{C4} g \quad (8)$$

$\pi_4 = gy/v^2$ since π_4 is dimensionless

$\therefore \pi_4 = v^2/gy = Fr$

$$\Phi\left(\frac{h}{y}, \frac{\lambda}{y}, \frac{\rho v y}{\mu}, \frac{v}{y}, 1\right) = 0$$

$\therefore \Phi\left(\frac{h}{y}, \frac{\lambda}{y}, Fr\right) = 0$ π_3 is neglected

$\therefore$ Ripples or dunes relative height (h/y) = φ (Fr)

Ripples or dunes relative length ($\frac{\lambda}{y}$) = φ (Fr)

This is the theory which our experiment is based on.

Table 1: Sample of the model test program

Test No.	Flow Discharge (m^3/s)	Gate Opening d (cm)	Gate Type	Upstream Gate Flow Depth, y (cm)	"Measure Gate Opening" Downstream Gate Flow Depth y_1 (cm)
1	0.02	1	Sluice Gate -------- Flume Width =0.4 m	14.0	0.9
2		2		13.7	1.9
3		3		13.3	2.8
4		4		12.8	3.5
5		5		12.6	4.0
6		6		12.1	4.8
7	0.03	1		14.8	0.85
8		2		14.3	1.80
9		3		13.5	2.70
10		4		13.1	3.30
11		5		12.8	3.80
12		6		12.5	4.80
13 to 18	0.04				
19 to 24	0.05				
25 to 30	0.06		Radial Gate ------- Flume Width =1.0 m		
31 to 36	0.07				
37 to 42	0.08				
43to 48	0.09				
49 to 54	0.10				
55 to 60	0.11				
61 to 66	0.12				
67	0.13	2		95	1.65
68		3		84	2.60
69		4		76	3.20
70		5		70	3.60
71		6		66	4.65
72		7		50	5.60

Table 1: Sample of the model test program (continued)

Test No.	Flow Discharge (m^3/s)	Gate Opening d (cm)	Gate Type	Conjugate Depth y_2 (cm)	Flow Velocity Downstream Gate V_1 (m/s)	Froude No. $Fr_2 << 1$ $V_2/\sqrt{(g\ y_2)}$	Froude No. $Fr_1 >> 1$ $V_1/\sqrt{(g\ y_1)}$
1	0.02	1	Sluice Gate ------- Flume Width =0.4 m	23.30	5.55	0.21	18.7
2		2		15.50	2.63	0.32	6.1
3		3		12.14	1.79	0.41	3.4
4		4		10.26	1.43	0.49	2.4
5		5		9.50	1.25	0.53	2.00
6		6		8.10	1.05	0.62	1.5
7	0.03	1		36.24	8.82	0.21	30.5
8		2		24.32	4.17	0.31	9.90
9		3		19.31	2.78	0.39	5.40
10		4		20.53	2.27	0.36	4.74
11		5		15.56	1.97	0.48	3.23
12		6		13.19	1.56	0.57	2.27
13 to 18	0.04						
19 to 24	0.05						
25 to 30	0.06		Radial Gate ------ Flume Width =1.0 m				
31 to 36	0.07						
37 to 42	0.08						
43to 48	0.09						
49 to 54	0.10						
55 to 60	0.11						
61 to 66	0.12						
67	0.13	2		44.9	7.9	0.29	19.6
68		3		35.1	5.0	0.37	9.9
69		4		37.3	4.1	0.41	7.3
70		5		29.3	3.6	0.44	6.1
71		6		24.7	2.8	0.53	4.1
72		7		21.9	2.3	0.59	3.1

5. RESULTS AND DISCUSSIONS

From the model outputs, with the aid of Tables (2, 3) and Figs. (8 to 16), it can be concluded that:

- Bed configuration changes are generated more under low Froude number, Figs. 14, 16.
- Much of the observed bed configuration cross-layers changes are produced by either high discharges or long period flow, Figs. 12, 15.
- The lower flow regime shifts to the upper flow regime at a Froude number of 0.4 for larger flume, Fig. 16, and at Froude number of 0.7 for smaller flume where the depth is shallower and velocity is higher., Fig. 14.

- Bed configuration changes height is more observed at low Froude number, Figs. 11, 12, 14 and 16.
- Bed configuration changes height and length, ratio of length to height, length and height to upstream normal flow depth have insignificant increasing after specific value of Froude number (Fr_1>6), Figs. 13, 15.
- For low Froude number ripple and dunes length and height have significant increase with Froude number (Fr_2 <1), Fig. 14.
- Bed changes length, height and ratio of length to height (L/H) increase with increasing Froude number, Figs. 13 to 16.
- Ratio of bed changes length and height to upstream normal flow depth (L/Y and H/Y) increase with increasing Froude number.
- Decreasing actual water depth downstream of the gate (y_1) leads to increasing the flow velocity and increasing Fr_1.
- For lower flow regime (Fr_2<<1), the ripple and dune height and length at Fr_2= 0.2 at discharge 0.02 m^3/s are 3 and 11 cm respectively while at discharge 0.13 m^3/s are 4.6 and 25 cm respectively. At Fr_2= 0.4, the ripple and dune height and length at discharge 0.02 m^3/s are 5 and 24 cm respectively while at discharge 0.13 m^3/s are 6.5 and 44 cm respectively, Figs. 14, 16.
- For upper flow regime (Fr_2>>1), the ripple and dune height and length at Fr_2= 2 at discharge 0.02 m^3/s are 5 and 25 cm respectively while at discharge 0.13 m^3/s are 9.2 and 35 cm respectively. At Fr_2= 4, the ripple and dune height and length at discharge 0.02 m^3/s are 6.5 and 28 cm respectively while at discharge 0.13 m^3/s are 11 and 47 cm respectively, Figs. 13, 15.

5.1 SAMPLE OF RESULTS ANALYSIS AT THE UPPER FLOW REGIME

Table 2: Sample of the study results at the upper flow regime ($Fr_1 >>1$)

Test No.	Flow Discharge (m^3/s)	Gate Opening d (cm)	Gate Type	Upstream Normal Depth y (cm)	Antidunes Length L (cm)	Antidunes Height H (cm)	L/H	L/Y	H/Y
1	0.020	1	Sluice Gate	14.0	35	8.0	4.37	2.50	0.57
2		2		13.7	32	7.2	4.44	2.33	0.52
3		3		13.3	28	6.1	4.59	2.10	0.46
4		4		12.8	26	5.5	4.73	2.03	0.43
5		5		12.6	25	5.0	5.00	1.98	0.40
6		6		12.1	20	3.5	5.71	1.65	0.29
7	0.030	1		14.8	41	9.0	4.55	2.77	0.61
8		2		14.3	38	8.1	4.69	2.66	0.57
9		3		13.5	33	7.0	4.71	2.44	0.52
10		4		13.1	30	6.3	4.76	2.29	0.48
11		5		12.8	28	5.6	5.00	2.19	0.44
12		6		12.5	25	4.8	5.21	2.00	0.38

Table 2: Sample of the study results at the upper flow regime ($Fr_1 >>1$) (continued)

Test No.	Flow Discharge (m^3/s)	Gate Opening d (cm)	Gate Type	"Water Flow Depth Downstream Gate Opening" y_1 (cm)	Velocity Downstream Gate Opening V_1 (m/s)	Froude No. $Fr_1 >>1$ $V_1/\sqrt{g.\ y_1}$
1	0.020	1	Sluice Gate	0.9	5.55	18.7
2		2		1.9	2.63	6.1
3		3		2.8	1.79	3.4
4		4		3.5	1.43	2.4
5		5		4.0	1.25	2.00
6		6		4.8	1.05	1.5
7	0.030	1		0.85	8.82	30.5
8		2		1.80	4.17	9.90
9		3		2.70	2.78	5.40
10		4		3.30	2.27	4.74
11		5		3.80	1.97	3.23
12		6		4.80	1.56	2.27

5.2. SAMPLE OF RESULTS ANALYSIS AT THE LOWER FLOW REGIME

Table 3: Sample of the study results at the lower flow regime ($Fr_2 <<1$)

Test No.	Flow Discharge (m^3/s)	Gate Opening d (cm)	Gate Type	"Water Flow Depth Downstream Gate Opening" y_1 (cm)	Conjugate Depth y_2 (cm)	Velocity Downstream Gate Opening V_1 (m/s)	Conjugate Water Velocity V_2 (m/s)
1	0.020	1	Sluice Gate	0.9	23.30	5.55	0.32
2		2		1.9	15.50	2.63	0.39
3		3		2.8	12.14	1.79	0.45
4		4		3.5	10.26	1.43	0.49
5		5		4.0	9.50	1.25	0.51
6		6		4.8	8.10	1.05	0.55
7	0.030	1		0.85	36.24	8.82	0.40
8		2		1.80	24.32	4.17	0.48
9		3		2.70	19.31	2.78	0.54
10		4		3.30	20.53	2.27	0.51
11		5		3.80	15.56	1.97	0.59
12		6		4.80	13.19	1.56	0.65

Table 3: Sample of the study results at the lower flow regime ($Fr_2 << 1$) (continued)

Test No.	Flow Discharge (m^3/s)	Upstream Normal Depth y (cm)	Froude no. $Fr_2 << 1$ $V_2/\sqrt{g.\ y_2}$	Ripple and Dunes Length L (cm)	Ripple and Dunes Height H (cm)	L/H	L/Y	H/Y
1		14.0	0.21	10	3.0	3.3	0.71	0.21
2		13.7	0.32	20	4.2	4.7	1.46	0.31
3	0.020	13.3	0.41	25	5.1	4.9	1.88	0.38
4		12.8	0.49	32	5.5	5.8	2.50	0.44
5		12.6	0.53	36	6.0	6.0	2.81	0.48
6		12.1	0.62	45	7.5	6.0	3.72	0.64
7		14.8	0.21	12	3.2	3.7	0.81	0.22
8		14.3	0.31	21	4.2	5.0	1.47	0.29
9	0.030	13.5	0.39	26	4.9	5.3	1.93	0.36
10		13.1	0.36	28	4.8	5.8	2.14	0.37
11		12.8	0.48	33	5.5	6.0	2.58	0.43
12		12.5	0.57	41	6.8	6.0	3.28	0.54

5.3. SAMPLE OF MONITORING AND VISUALIZING THE FLOW AND BED CONFIGURATION IN THE FLUME

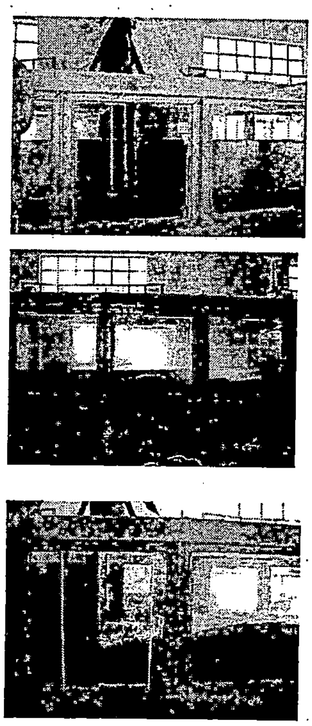


Fig. 8: Monitoring and Visualizing the Flow and Bed Configuration in the Flume

Fig. 9: Flatten the Bed

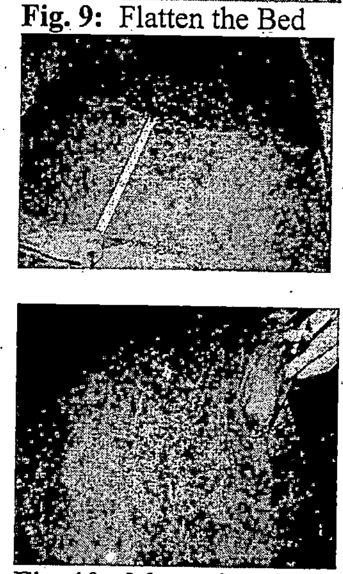
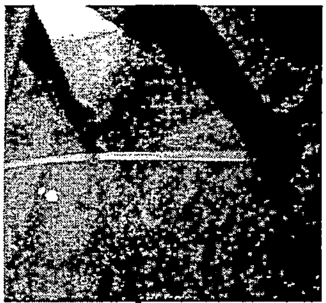
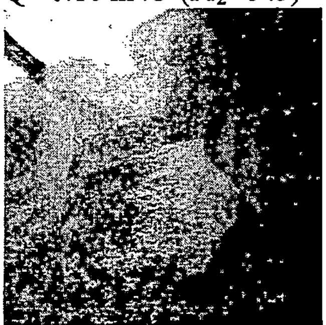


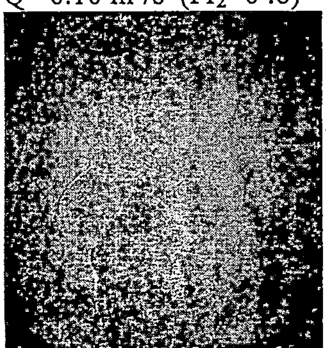
Fig. 10: Measuring the Ripple Bed Length and Height



Q= 0.10 m^3/s (Fr_2=0 .5)

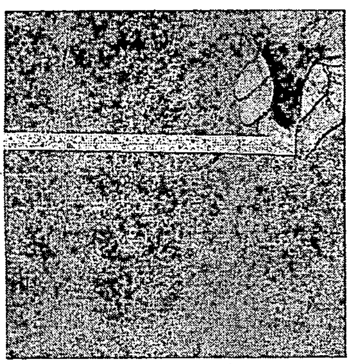


Q= 0.10 m^3/s (Fr_2=0 .6)

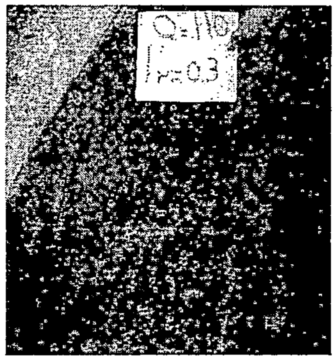


Q= 0.10 m^3/s (Fr_2=1)

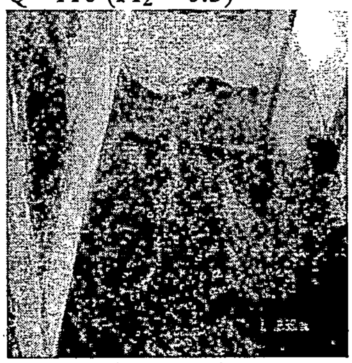
Fig. 11: Ripples and Dunes at Discharge 0.10 m^3/s with Different Froude Numbers



Q = 110 (Fr_2 = 0.2)



Q= 110 (Fr_2 = 0.3)



Q = 110 (Fr_2 = 0.6)

Fig. 12: Ripples and Dunes at Discharge 0.110 M^3/S with Different Froude Numbers

5.4. SAMPLE OF RESULTS ANALYSIS FOR BED CONFIGURATION

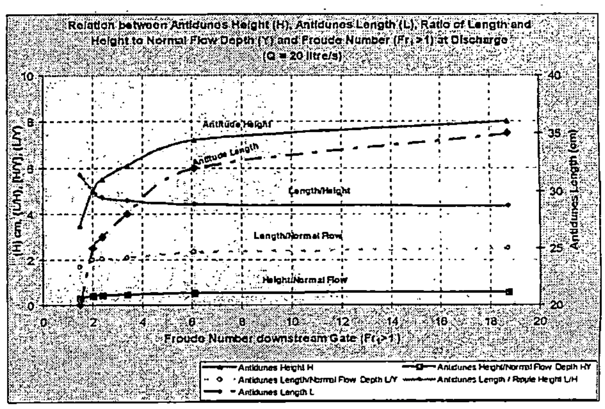


Fig. 13: Sample of Bed Configuration Characteristics at the Upper Flow Regime (Fr_1>>1) At Q=0.02 M^3/S on the Smaller Flume

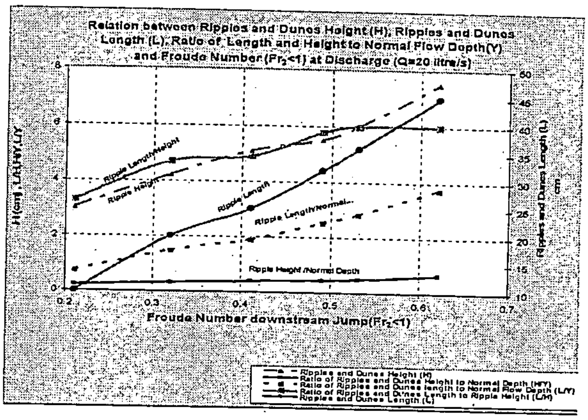


Fig. 14: Sample of Bed Configuration Characteristics at the Lower Flow Regime (Fr_2<<1) At Q= 0.02 M^3/S on the Smaller Flume

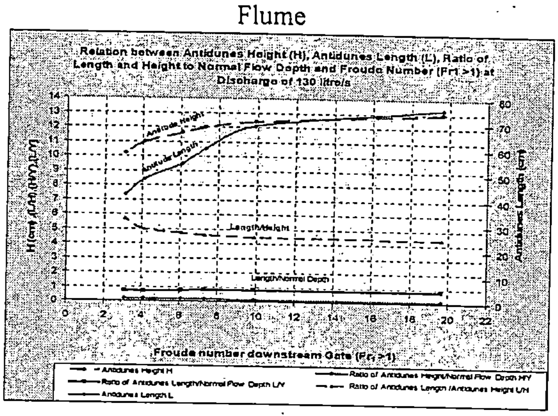


Fig. 15: Sample of Bed Configuration Characteristics at the Upper Flow Regime (Fr_1>>1) At Q= 0.13 M^3/S on the Larger Flume

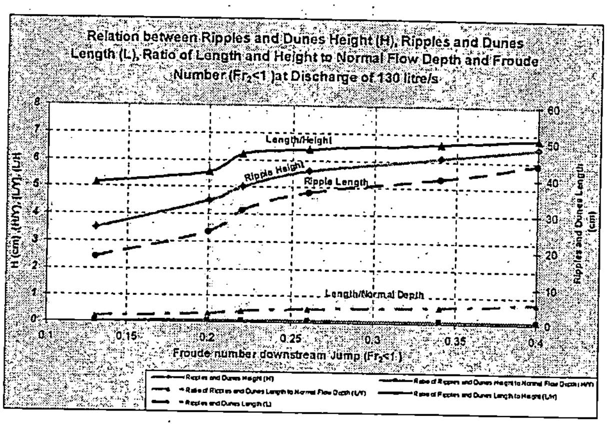


Fig. 16: Sample of Bed Configuration Characteristics at the Lower Flow Regime (Fr_2<<1) at Q= 0.13 m^3/s on the Larger Flume

7. CONCLUSIONS

From the study results and analysis, it can be concluded that:

- Much of the observed bed configuration changes are produced by either high discharges or long period flow.
- At low unidirectional velocities, when increasing the flow rate, the bed begins to evolve from small-scale symmetric ripples to dunes and then to plane bed.
- At higher velocities, similar trends can be observed, but ripples were more asymmetric and moved to standing waves and then to anti-dunes.
- Standing waves and anti-dunes bed configuration only occurs with Froude number greater than 1.0 (the upper flow regime Fr>1).
- Ripples and dunes only occur at Froude number less than 1.0 (the lower flow regime Fr<1).
- The lower flow regime (Fr<1), ripples and dunes, transfers to upper flow regime, standing waves and anti-dunes, at a Froude number of 0.4 at the larger flume but in the smaller flume at Froude number of 0.7 where the depth is shallower and velocity is higher.

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