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Sediment Flushing Criteria from Inverted Siphon Structures

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Abstract: Deposition of sediments on the horizontal segment of the inverted siphon structure causes several problems such as reduction of hydraulic capacity and increase of frequency of upstream overflow. Control and cleaning of sediment deposited have been and remain a crucial aspect of this structure maintenance and operation. Numerous tools have been applied to clean the deposited sediments. The regular method is to manually transport the deposited sediment to the downstream end of the horizontal segment of the closed conduit and then take out this accumulated sediment. Such method is too costly and time consuming. To speed up the operational procedure, one may apply the flushing technique. In this technique a volume of water is discharging into the closed conduit during a short period of time. The temporary high flow and velocity contribute to transport large amount of sediment. By repeating this procedure, large amount of sediment can be carried out in a very short period of time. In this study such technique has been investigated experimentally. The purpose of this study was to determine the effectiveness of such operation. Four different bed sediment particle sizes under different hydraulic conditions were tested. From analysis of data, relationships between sediment movements length against flushing runs were developed and the main parameters which affect the sediment removal have been introduced.

Key words: Flushing, sediment, inverted siphon, sediment removal

INTRODUCTION

Deposition of sediment, in irrigation canals and related structures such as inverted siphon, can cause many problems. Sediment accumulation can reduce the hydraulic efficiency of siphon by reducing the cross-section area and by increasing the flow resistance through developing the bed form. Therefore, it is necessary to remove the sediments periodically. The traditional way of cleaning inverted siphon usually involve the movement of the sediment by workers to a location at the downstream end of the horizontal segment of inverted siphon and from this location, the sediment is removed by manual or mechanical equipment. This method has drawbacks such as high demand of workers, the working conditions are unacceptable and it takes long period of time.

One alternative way of cleaning of inverted siphon is the flush cleaning with the aid of sudden releasing of a large amount of water in a short period of time. Because of this, a flushing wave is created which can erode the deposited sediment and transport them to the location which then can be removed by suction equipments. This method has been employed for sewer cleaning in recent years. Engineered sewer sediment flushing systems are potentially low cost. By creating high velocity flushing waves to re-suspend deposited sediments, this technique has been applied effectively reduce sediment level, Bertrand-Krajewski (2003). During the last 15 years, new hydraulic flushing systems have been developed and installed in more than 500 locations in Europe, the United States and Canada (Pisano *et al*., 1998).

Bertrand-Krajewski *et al*. (2002) reported a field study on the hydraulic performance of a sewer flushing gate in Lyon, France. A vacuum-flushing device was introduced by Fan (2002), which has a water holding and release mechanism different from the gate flushing device. The historical overview of the sewer sediment control is reported by Fan *et al*. (2003). Pisano *et al*. (2003) also introduce an automated flushing system in Cambridge. Guo *et al*. (2004) conducted experimental tests on a newly designed vacuum-flushing device in removing sediment from combined sewers.

The results of the foregoing studies have indicated a good efficiency of flushing technique for removing sediment in the sewer system. Therefore such technique can be used for removal of sediment in other hydraulic structures such as inverted siphon. To study the hydraulic performance and efficiency of this technique in inverted siphon the present study has been conducted. An inverted siphon is a hydraulic structure which conveys water from one side of natural drainage or a road to the other side.

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DIMENSIONAL ANALYSIS

To develop a general relationship for predicting the length of transported sediment due to a surge, the following relations can be written:

$$L_t = f_1 (L, N, D, d_{50}, h, d_t, r, r_s, g, m) \qquad (1)$$

In which, L_t is the maximum distance which sediment are transported by sudden release of water and is defined as transported length. L is the total horizontal length which the sediment must be transported. N is the number of flushing, D is the size of box of the inverted siphon, d_{50} is the median size of sediment particle, h is the total head above the sediment and d_t is the tail water depth. r, r_s are water and sediment density respectively. In this equation g is the specific weight of water and m is the kenitic viscosity of water.

Applying the M-theorem, the following non-dimensional equation can be obtained:

$$\frac{Lt}{L} = f_2(N, \frac{V}{\sqrt{gD}}, \frac{\rho VD}{\mu}, \frac{\rho_s}{\rho}, \frac{D}{d_{50}}, \frac{D}{d_t}) \qquad (2)$$

V is the entrance velocity and is directly proportional to square root of h ($\sqrt{2gh}$), thus one can write h/d instead of $\frac{V}{\sqrt{gD}}$ since measuring V is difficult and needs sophisticate instruments. The term $\frac{\rho VD}{\mu}$ is Reynolds number and in this study its value is high enough so the flow is fully turbulent and it has no effort on flow conditions. The ratio ρ_s/ρ was also constant, therefore, Eq. (2) is reduced to:

$$\frac{Lt}{L} = f_3(N, \frac{h}{D}, \frac{D}{d_{50}}, \frac{D}{d_t}) \qquad (3)$$

To determine the number of flushing run for transporting the sediment to a desired distance say for example $L_t = 0.95$ L, then Eq. (3) is further reduced to:

$$\frac{h}{D} = f_4(N, \frac{D}{d_{50}}, \frac{D}{d_t}) \qquad (4)$$

This is the general and a basis relationship for analyzing the experimental data.

EXPERIMENTAL SET_UP

As it was mentioned earlier, the main purpose of this study was to investigate the hydraulic criteria of the sediment removal from the bed of horizontal segment of the inverted siphon structure using the flushing technique. To reach such goals, an extensive experimental program was conducted in hydraulic laboratory of Shahid Chamran University. The experimental setup consist of a flushing tank which is a circular cross section pipe installed vertically at the upstream, a flap gate installed at the bottom of flashing tank and test section. The test section is a box, 15×15 cm, closed conduit made of plexi-glass installed on a table. Water is held in flushing tank and is released by sudden opening of the flap gate. Figure 1 shows a scheme of the experimental setup used in this study.

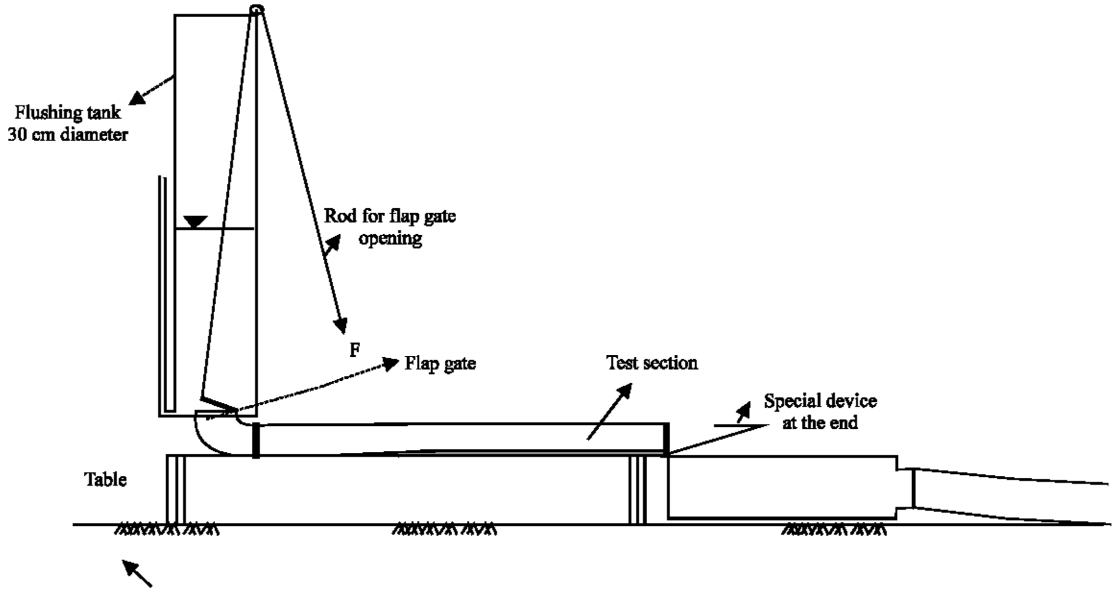

Fig. 1: Experimental setup

Table 1: Sediment properties used in this study

Sediment type	D_{50} (mm)	Φ (degree)
Medium sand	0.7	29
Course sand	1	29
Very course sand	2	30
Very fine gravel	3.3	30

Four different sizes of non-cohesive sediments were used in this study. Table 1 shows the characteristics of these materials. The specific gravity of the sediment was specified equal to 2.65.

EXPERIMENTAL PROCEDURES

The experimental procedure in this study was as follow:

- Sediment material with a constant thickness equal to 1 cm was put on a thin galvanized sheet. This sheet then was entered the test section from the downstream end and placed on the bed of the test section.
- A special device, as shown in Fig. 1, was installed at the downstream end of the test section. The reason for placing such device is to be able to maintain the water level or tail water depth in the test section at any desire level. The top of this device is opened to direct flushing water and flushed sediment to a reservoir.
- Flow was allowed to enter the test section very slowly to a desire flow depth.
- Water entered into the flushing tank to a desired level. The level of water surface indicates the head, h.
- Flushing run was started by sudden opening of the flap-gate through pushing a rod which is connected to the flap-gate as it is shown in Fig. 1.
- Flushing wave transported sediment from the upstream end of the test section to some distance downstream. This distance was recorded after each flushing run and will be called the transported length Lt. Most of the sediments which were transported were deposited on the top of sediment downstream and less sediment washed away from the test section.
- Steps 3 to 6 were repeated. Transported length was recorded after each flushing run. The flushing runs continued until the sediment are transported 95% of the test section length or the sediment did not move any further distance. The later case happened when the head in the flushing tank was low.
- The above procedures were repeated for new head level. In this study tests were conducted for the head equal to 15, 20, 25, 30, 35, 40, 45, 50, 55 and 60 cm.
- Steps 3 to 8 were repeated for new tail water depth. At the beginning of the experimental tests, a few tests conducted under full tail water, 15 cm and head equal to 60 cm. During these flushing runs no sediment movement was observed. Therefore, it was decided to conduct tests under half full tail water, 7.5 cm and no tail water.
- Steps 1 to 9 were repeated for new sediment material. Four different sizes of non cohesive sediment were used in this study. The characteristics of the sediment are shown in Table 1.

Table 2: Range of different variables

Variables	Dimension	Symbol	Number	Range
Sediment size	mm	D_{50}	4	0.7-3.3
Total head	cm	h	10	15-60
Tail water depth	cm	d_t	2	7.5,15

The spatial distribution of flushed sediment in the test section was recorded after a few flushing run. A video camera was also employed to record movement of water and sediment. The recorded video images were digitized to obtained data on speed and shape of the flushing surge along the test section.

In this study 80 different hydraulic and sediment conditions and total of 736 flushing runs were conducted. Table 2 shows the range of variables used in this study.

RESULTS AND DISCUSSION

Time variation: Time variation of water depth in the flushing tank was determined from recorded video images. Figure 2 shows water level lowering during the flushing run for h = 60 cm. The tail water depth during this run was zero and no sediment was placed on the bed.

As it can be seen the flushing tank has been emptied less than 2 sec in almost uniformly drawdown velocity.

Transported length: Measured transported length under 32 of total 80 hydraulic and sediment conditions are shown in Fig. 3-6. In Fig. 3-6 transported length (L_t) are plotted against number of flushing runs (N). It is obvious that as number of flushing run increases, the transport length increases until it is almost equal to the test section length. For h = 15 cm, d_{50} = 0.7 mm and d_t = 7.5 cm, Fig. 3a, the sediment was moved for the first few flushing runs then, the value of L_t remained constant. The reason is that sediment are removed from upstream and deposited on top of the sediment at the downstream. Because of this the sediment thickness is increased and upcoming surge, for the head equal 15 cm, is not able to move the sediment further downstream. Almost the same behavior can be seen for other bed material sizes, Fig. 4a-6a. When the tail water is kept equal to zero, sediment can be transported much faster and will reach to the downstream end after a few flushing runs as it can be seen in Fig. 3b-6b. A comparison between results in these figures and the former figures indicate that the transported length increases with decreasing the tail water depth. The transported length is doubled when the tail water is reduced from 7.5 cm to zero. The reason is that for higher initial tail water depth in the test section provided the bottom sediment with better sheltering against the flush wave released from the flush tank resulting in a lesser transported length. Guo *et al.* (2004) also found that when the tail water increases the weight of transported sediment decreases. Their results indicate that increasing tail water depth from zero to 2.5 cm, the weight of transported sediment is reduced by 51%.

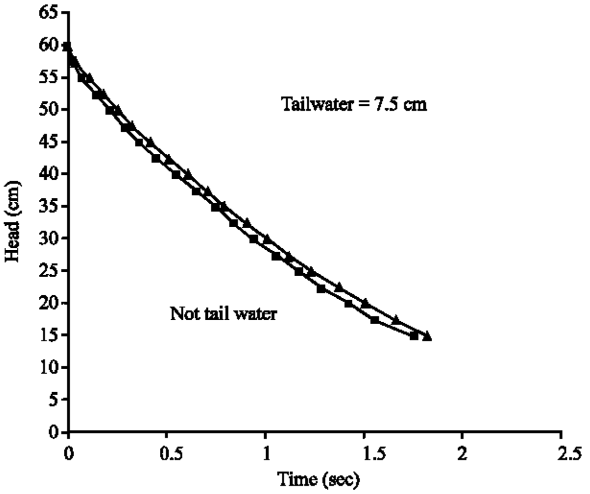

Fig. 2: Time variation of water level in flushing tank for h = 60 cm and d_t = 0

Head of the flushing tank is another important parameter which affects the sediment movement. A comparison between results in Fig. 3a-d indicates that the transported length increases as head of flushing tank increases. For example in Fig. 3a, h = 15 cm and for no tail water, sediment reaches to the downstream end after 15 flushing runs, in Fig. 5b, h = 30, sediment reaches after 7 flushing runs, in Fig. 3c, h = 45 cm, it reaches after 3 flushing runs and in Fig. 3d, h = 60 cm only two flushing runs can transport the whole sediment to the downstream end. In general for the few initial runs, the required number of flushing runs is decreases by half as the head doubled. The values of transported length after two flushing runs from Fig. 6a-c are obtained as 67.5, 145.5, 167.5 and 171.5 cm, respectively. Almost the same trend can be obtained from Fig. 3, 4 and 5. The above results indicate that as the flushing head is increased, the sediment is transported faster. Guo *et al.* (2004) also found that when head is doubled, the weight of the flushed sediment about tripled. The rate of movement is much faster when the head is increased from 15 to 30 cm

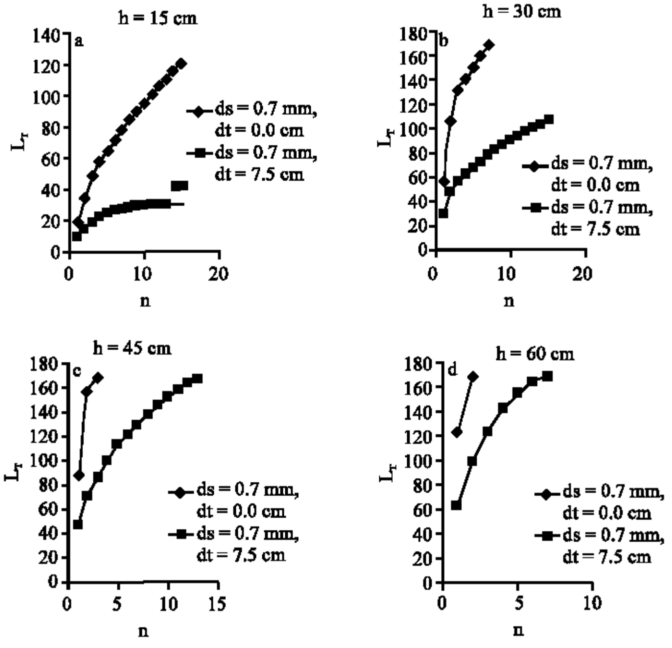

Fig. 3: Variation of transported length L_t versus flushing runs for d_{50} = 0.7 mm

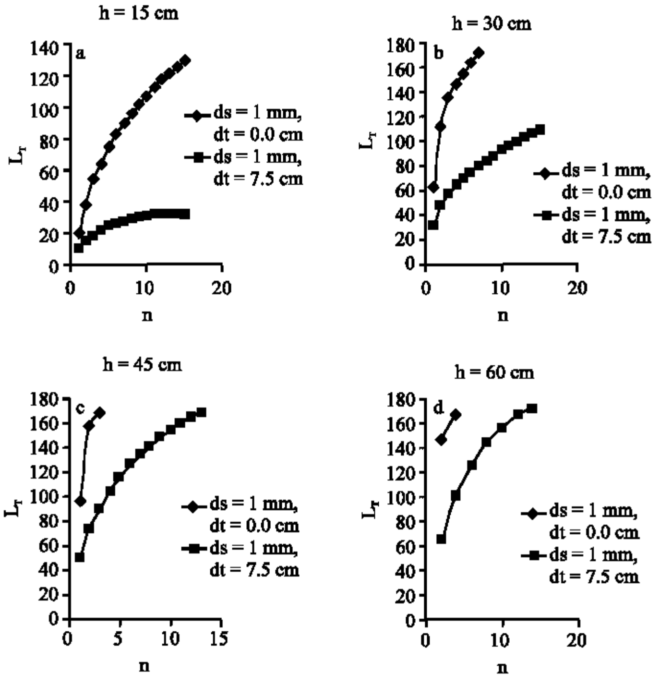

Fig. 4: variation of transported length L_t versus flushing runs for d_{50} = 1.0 mm

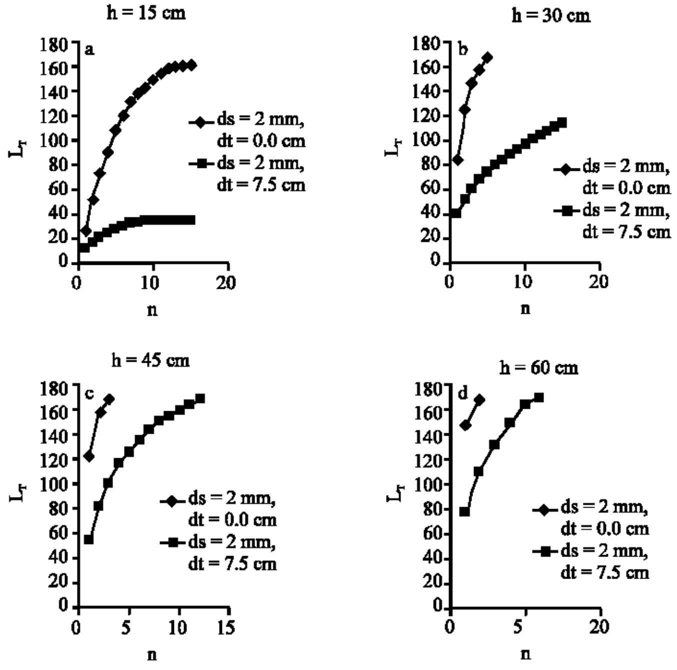

Fig. 5: variation of transported length L_t versus flushing runs for d_{50} = 2.0 mm

and then the rate of movement is decreased. One explanation for this behavior is that as the head increases the volume of water inside the flushing tank increases and when the water is released, accumulation of more volume of water in the test section can force the upcoming surge and therefore some of the kinetic energy of the surge is dissipated by increasing tail water depth during the flushing time.

For further discussion the volume of released water was plotted against the transported length after two flushing runs. Figure 7 shows the results. Data plotting from Fig. 6a-d for tail water equal to zero. By considering

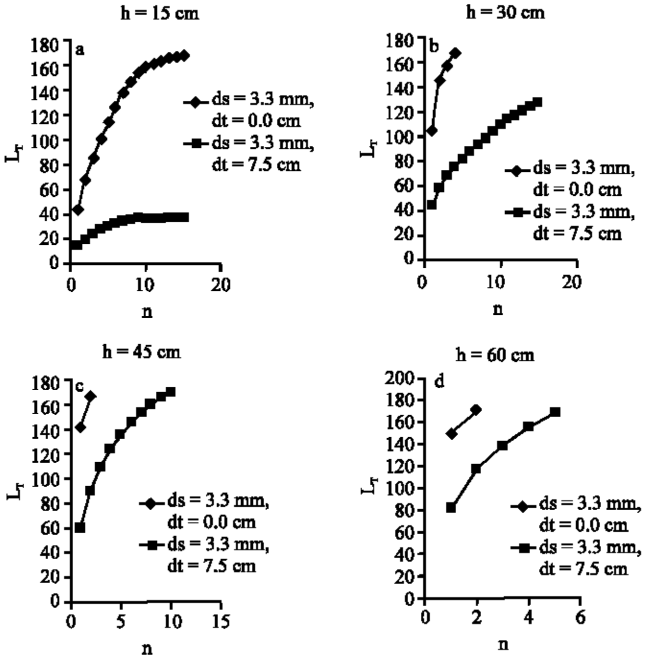

Fig. 6: variation of transported length L_t versus flushing runs for d_{50} = 3.3 mm

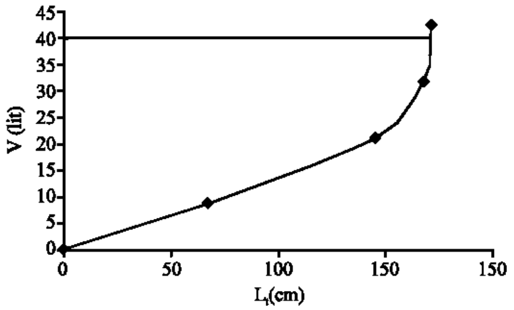

Fig. 7: Volume of the flushed water versus the transported length for flushing run = 2

that the total volume of the test section is 39.82 L, it can be seen that when the volume of flushed water is equal to half volume of the test section, the slope of the curve suddenly is changed and remained almost constant.

Sediment material size also is another parameter which was investigated in this study. A comparison between results in Fig. 3a-6a or Fig. 3b-6b etc. indicates that the larger sediment size, the larger transported length and less flushing runs required for transporting sediment to the downstream end. The reason for this behavior is that as the sediment size is larger, the sediment void ratio increases and the flushed water is penetrated into the sediment more easily and more sediment particles are suspended by incoming surge and transported to the downstream end.

SEDIMENT MOVEMENT CRITERIA

It is very important in cleaning of inverted siphon to investigate the relation between the head and required number of flushing runs. To do so, Fig. 8 was developed. In Fig. 8, the ordinate shows the relative head required for transporting sediment to a distance up to 95% of test section length number of flushing runs are shown in x-axis. The top most three curves represent data for tail water equal to 7.5 cm and the three curves on the bottom; represent data for no tail water conditions. It is clear from this curve that the relative head (h/D) decreases as the flushing run increase. Or on the other words, as the available head for flushing decreases, the number of flushing to transport bed sediment increases. From this Fig. 8 one may conclude that D/d_s have no significant affect on sediment movement. In this Fig. 9 two distinguish curve can be plotted in which each curve represents the affect of tail water depth. From analyzing data, the following two sets of equations can be fitted by least-square methods:

$$h/D = 5.124\,N^{-0.529} \quad r^2 = 0.95 \tag{5}$$

For no tail water depth and:

$$h/D = 7.86\,N^{-0.385} \quad r^2 = 0.96 \tag{6}$$

For tail water depth of 7.5 cm.

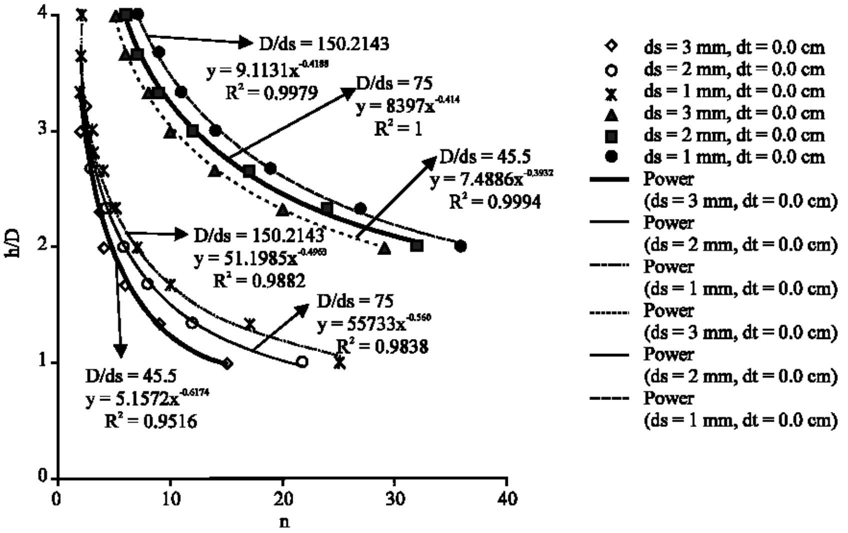

Fig. 8: Variation of h/D versus number of flushing for different sediment sizes

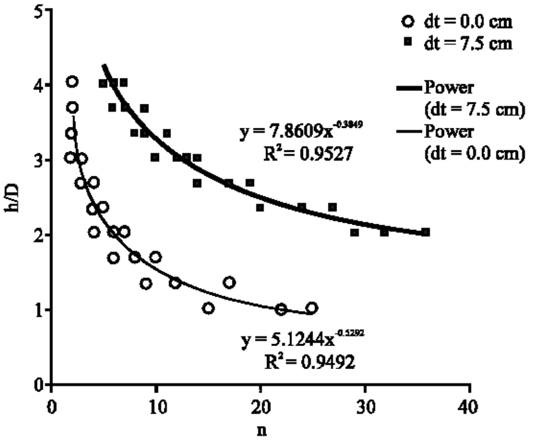

Fig. 9: variation of H/D versus number of flushing all sediment sizes

Equation (5) or (6) can be apply to predict the required head for known number of flushing or vise versa to determine number of flushing for available head.

CONCLUSIONS

Behavior of sediment movement in horizontal segment of inverted siphon due to flushing technique was investigated by a physical model in the laboratory under 80 different hydraulic and sediment conditions. Results from total of 736 flushing runs are shown that:

- Both tail water depth and head of flushing tank found to be important parameters which affect the sediment movement.
- Sediment size was found to have no significant affect on the length of flushed sediment.
- Transported length increases with increasing the flushing head.
- Transported length decreases with increasing the tail water depth.
- Transported length increases with increasing the sediment size.
- For best efficiency, the volume of flushed water should not be greater than half of the volume of horizontal segment of the inverted siphon.

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