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Effect of Distance on Hydraulic Efficiencies of Successively Located Grate Inlets

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Abstract **-** Laboratory experiments were conducted at a recirculating rectangular channel of 12 m long and 0.9 m wide with a longitudinal slope of 1/300. Accordingly, two-grated inlet systems were tested under varying approach flow rates, and the corresponding capturing efficiencies were determined. To do so, two cases were considered where the side grates were successively positioned on the main channel with a distance of 0.2 m and 0.4 m, respectively. The ranges of total flow rate and Froude number were $0.33 < Fr < 0.52$ and $1\ L/s < Q_t < 5.2\ L/s$, respectively. The results revealed that the hydraulic performance of a two-grated inlet system is strongly linked to the longitudinal distance between the grates and it was observed that positioning the grate inlets at a lesser distance was hydraulically more efficient in capturing the total approach flow rate. Moreover, the experimental results have also shown that the total hydraulic efficiency of successively located grate inlets displayed an increased tendency for higher values of upcoming flow rates.

Keywords**:** grate inlet, hydraulic efficiency, urban drainage, physical model, spatially-varied flow.

1. Introduction

Stormwater inlets are an essential part of the urban drainage systems by collecting the surface runoff and thus reducing the environmental impacts on roads which might otherwise threaten both vehicular and pedestrian safety. Therefore, the proper and efficient design of such surface drainage structures plays a key role in minimizing the potential risks in urban streets. Although the efficiencies of stormwater inlets are affected by the hydraulic behavior of grates [1], a comprehensive methodology of hydraulic characteristics and performances of grate inlets is not well-studied in the literature [2]. However, as reported in [3], the focus has recently been given to the investigation of grate behaviors to better understand the parameters affecting the efficiencies of urban stormwater drainage systems. According to the extensive reviews of [4] and [5], the existing literature studies on grate inlets mainly performed laboratory tests to determine the grate efficiencies under varying hydraulic and geometric conditions [3, 6, 7, 8, 9, 10, 11]. Apart from the laboratory tests, grate inlets have also been numerically investigated in various studies to analyze the corresponding hydraulic efficiencies under different approach flow conditions [12, 13, 14, 15, 16], where the numerical results were mostly in agreement with the experimentally obtained data. However, the hydraulic behavior and performance of successively located grates were not taken into account in the above-mentioned studies on stormwater inlets. Thus, to fill this gap in the literature, in this present study, the effect of distance on the hydraulic efficiencies of successively located grate inlets is experimentally investigated under subcritical flow conditions.

When water flows through a grate inlet, the total approach flow rate decreases in the streamwise direction due to the continuous interception of the upcoming flow by the grate openings. Provided that multiple grates are used simultaneously, the water that is not intercepted by the first grate is captured by the subsequent grates. In this regard, the capturing capacity of a single grate is associated with efficiency by the following relation:

$$E = Q_i/Q_t \tag{1}$$

where E is the hydraulic efficiency, Q_i and Q_t stand for the intercepted and total flow rates, respectively. For multiple grate systems, Eqn. (1) can be equally applied where E refers to the total efficiency of the system and Q_i represents the total intercepted flow by all grates.

The void fraction of a grate, η, having a range of $0 < \eta < 1$, is also defined as the fraction of the total area of the openings over the total grate area:

$$\eta = A_V / A_T \quad (2)$$

where A_V and A_T represent the total area of the voids and the grate, respectively.

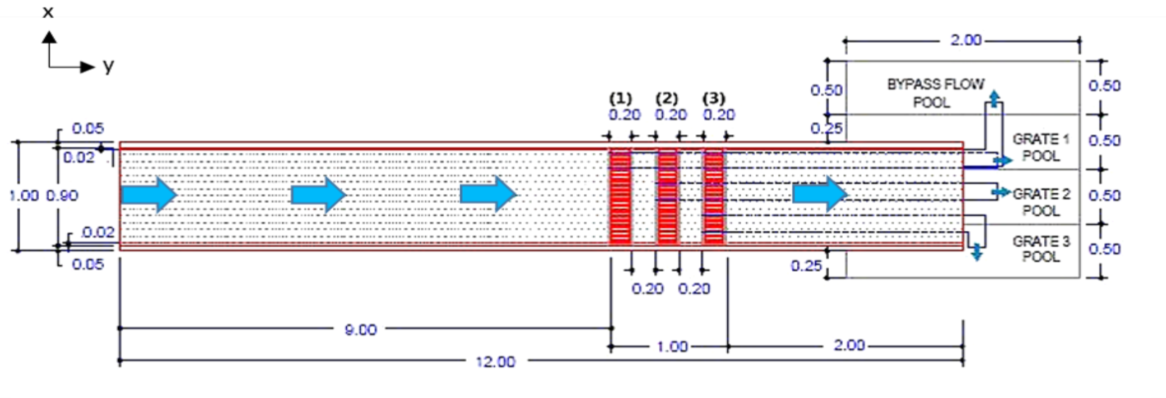
The Froude number is a non-dimensional parameter to describe the flow regime in open channel flows and it is defined as the ratio of the inertial and gravitational forces as follows:

$$Fr = V / \sqrt{g D_h} \quad (3)$$

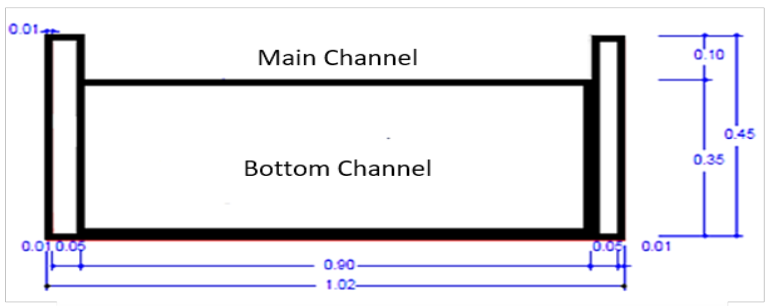
where V is the approach flow velocity, D_h refers to the hydraulic depth which corresponds to the flow depth in rectangular channels, and g is the gravitational acceleration.

2. Experimental Procedure

An experimental study was carried out at the Hydraulics Laboratory of Middle East Technical University (METU) to investigate the hydraulic efficiencies of successively located grate inlets under different flow rates. A recirculating rectangular flume of 12 m long and 0.9 m wide was utilized to represent a small road or street (Fig. 1a) where the water was supplied from a constant head tank. The maximum flow depth that could be tested on the main channel was 10 cm (Fig. 1b). The entire flume and all tested grate inlets were made from fiberglass and rectangular grate bars oriented in the main flow direction were used during the tests. The longitudinal and cross slopes of the main channel were kept constant throughout the experiments at 1/300 and 0%, respectively. All tests were performed under steady flow conditions and the Froude number range was $0.33 < Fr < 0.52$, corresponding to subcritical flow regime. The experimental setup consisted of three different sections to test the grates (Fig. 1a) where multiple grate inlets could be tested simultaneously on the main channel. Accordingly, the flow intercepted by each grate was separately conveyed in the bottom channel (Fig. 1b), whereas the bypassed flow remained as a surface runoff. Both flows were then collected at the pools where the volumetric flow rates were determined by measuring the water level rise in a certain duration.



(a)



(b)

Fig. 1: (a) Plan view of the experimental setup showing the three grate sections, and collective pools for the intercepted and bypassed flows, (b) details of the channel cross-section, all dimensions are in meters. Adapted from [17].

Within the scope of this present study, two cases were investigated where the side grates were located (i) at sections (1) and (2) having a distance of 0.2 m apart and (ii) at sections (1) and (3) having a distance of 0.4 m apart, both in a crossing pattern. Thus, the intercepted flow rates of both cases were measured to observe the effect of distance between two successive inlets on grate efficiency. Each test was repeated five times to decrease the errors in the discharge measurements. Moreover, for each case, the flow depth at 0.5 m upstream of section (1) was measured by a limnimeter with 1 mm accuracy, leading to calculating the Froude number from Eqn (3). Accordingly, the bar details of the isolated side grates covering almost one-fifth of the channel cross-section and the system with the grates successively located at sections (1) and (2) are shown in Figure 2 and Figure 3, respectively.

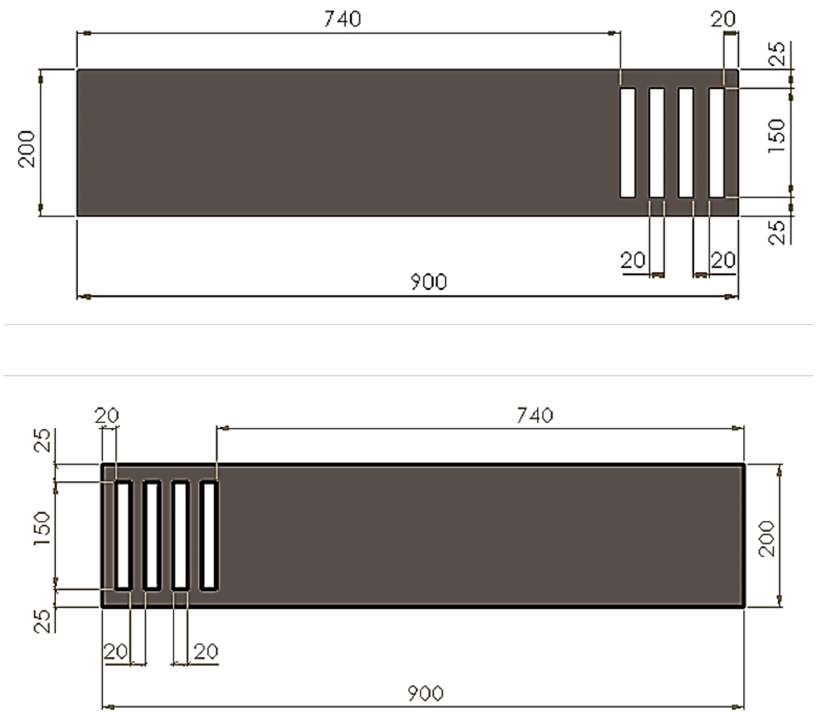


Fig. 2: Geometric details of successively-located side grates, all dimensions are in mm.

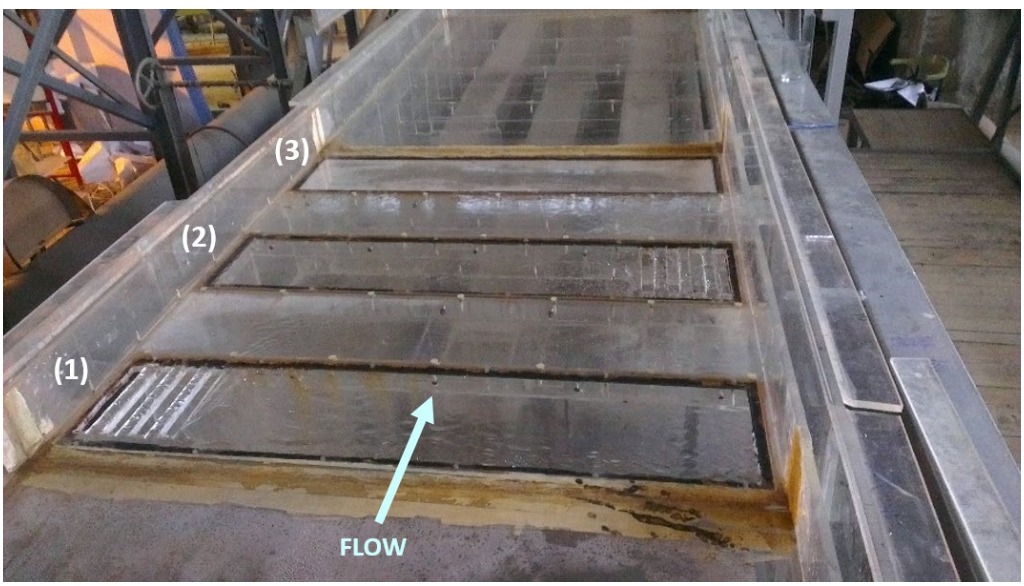


Fig. 3: The surface runoff on the main channel where successive side grates are located at sections (1) and (2) with a distance 0.2 m apart. No grate is located in section (3).

3. Results and Discussion

Table 1 summarizes the hydraulic efficiencies of side grates that were successively located at sections (1) and (2) on the on the main channel. It can be seen that the lowest value of the total efficiency (i.e., 71.2%) was obtained when the approach flow rate was 1.15 L/s. However, the total efficiency of the system was the highest (i.e., 78.95%) for the flow rate of 4.74 L/s, which does not correspond to the highest value. Although a very similar tendency was observed for the individual efficiency of the grate at section (2), a fluctuating efficiency pattern was found for the grate at section (1) in accordance with the increasing approach flow rate.

Table 1: Hydraulic efficiencies of successive side grates located at sections (1) and (2) on the main channel. All cases correspond to subcritical flow conditions.

Q_t (L/s)	Q_{i1} (L/s)	Q_{i2} (L/s)	E_1 (%)	E_2 (%)	E_{t12} (%)	Fr_1
1.156	0.466	0.357	40.30	51.74	71.19	0.333
1.580	0.598	0.553	37.85	56.31	72.85	0.357
2.291	0.868	0.848	37.89	59.59	74.90	0.383
3.488	1.291	1.397	37.02	63.59	77.06	0.472
4.741	1.763	1.980	37.19	66.49	78.95	0.515
5.092	1.935	2.083	38.02	65.98	78.91	0.518
5.156	1.945	2.102	37.71	65.46	78.49	0.508

NOTE: Q_t = total flow rate, Q_{i1} = intercepted flow rate by the grate located at section (1), Q_{i2} = intercepted flow rate by the grate located at section (2), E_1 = efficiency of the grate located at section (1), E_2 = efficiency of the grate located at section (2), E_{t12} = total efficiency of the system with successive grates at sections (1) and (2), and Fr_1 = approach Froude number.

The hydraulic efficiencies of the side grates that were positioned at sections (1) and (3) are presented in Table 2. Accordingly, the total efficiency of the system was observed to display an increasing trend within the total flow rate range of $1\ L/s < Q_t < 2\ L/s$. However, due to the limitations in the laboratory conditions, the hydraulic performance of the system could not be tested for higher flow rates, preventing to compare the efficiencies of the two tested cases for the flow rate range of $2\ L/s < Q_t < 5.2\ L/s$.

Table 2: Hydraulic efficiencies of successive side grates located at sections (1) and (3) on the main channel. All cases correspond to subcritical flow conditions.

Q_t (L/s)	Q_{i1} (L/s)	Q_{i3} (L/s)	E_1 (%)	E_3 (%)	E_{t13} (%)	Fr_1
1.201	0.590	0.228	49.20	37.32	68.11	0.345
1.426	0.677	0.321	47.46	42.86	69.99	0.341
1.625	0.739	0.412	45.47	46.50	70.83	0.368
1.825	0.832	0.487	45.59	49.04	72.27	0.371

NOTE: Q_t = total flow rate, Q_{i1} = intercepted flow rate by the grate located at section (1), Q_{i3} = intercepted flow rate by the grate located at section (3), E_1 = efficiency of the grate located at section (1), E_3 = efficiency of the grate located at section (3), and E_{t13} = total efficiency of the system with successive grates at sections (1) and (3).

Figure 4 plots the total hydraulic efficiencies of successive side grates at sections (1) and (2) with respect to the approach flow rates. As can be seen, the capturing efficiencies were found to be highly dependent on the flow rate values which is also consistent with the experimental studies of [1, 7, 8, 10]. Accordingly, the total efficiency of the system exhibited an increasing tendency as the flow rate increases and this result is also in strong agreement with the laboratory findings of [1, 2, 18]. However, the interception capacity of the two-grated system was observed to decrease when the flow rate further increased. This might be attributed to the fact that the maximum capturing capacity of the system was reached where the so-called hydraulic behavior was also reported in the experimental study of [19].

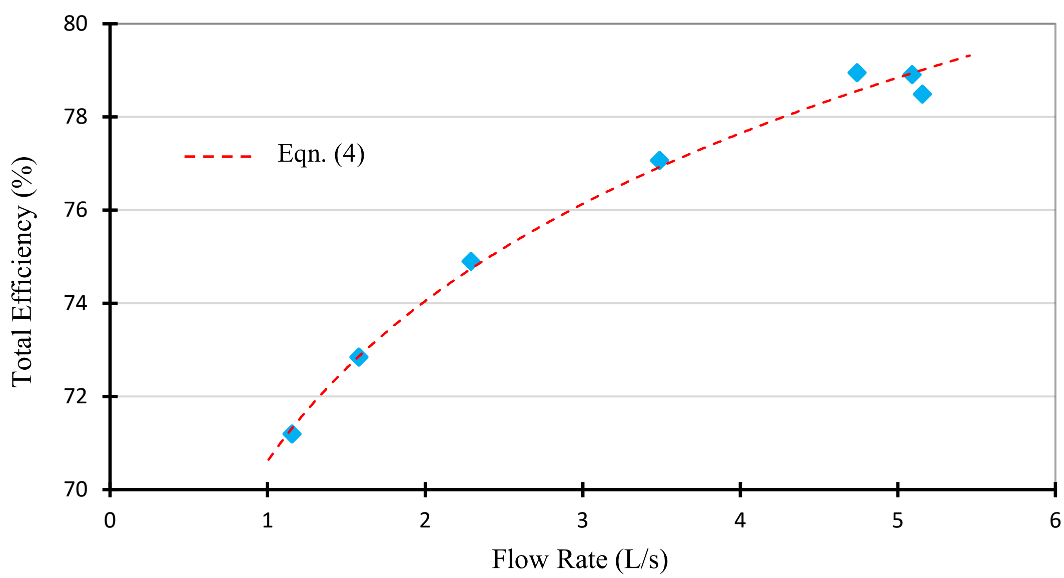


Fig. 4: Total hydraulic efficiencies of the side grates successively located at sections (1) and (2). All cases correspond to subcritical flow conditions. The coefficient of determination, R^2=0.992.

To compare the two cases of this present study with respect to identical flow rates, a power-law formula was obtained from the measured data (Fig. 4) to predict the hydraulic efficiency of the system where side grates are located at sections (1) and (2):

$$E_{t12}\,(\%) = 70.62\ x\ Q_t^{0.068} \tag{4}$$

where E_{t12} refers to the total efficiency of the system with grates at sections (1) and (2), and Q_t stands for the total upcoming flow rate to the first grate. Accordingly, Figure 5 compares the total efficiencies of both cases with respect to the same approach flow rate values. The results have revealed that within the flow rate range of $1\ L/s < Q_t < 2\ L/s$, the total hydraulic efficiency of the successive grates located at sections (1) and (2) was found to increase on average by 3.3% compared to grates at sections (1) and (3). Considering the fact that the void ratios, η, of the grates located at section (1) are the same in both systems, for an identical approach flow rate, the bypass flow rates would be expected to be equally identical at the immediate downstream region of the first grate. However, since the spatial acceleration of the flow due to the channel bottom slope would be lower at a relatively shorter distance, lower approach flow rates are created at the immediate upstream of the second grate. Hence, the system with a lesser distance between the grates was found to capture more water (Fig. 5). The so-called discussion is consistent with [3], where the capturing efficiencies of grate inlets were found to be higher for lower approach flow rates.

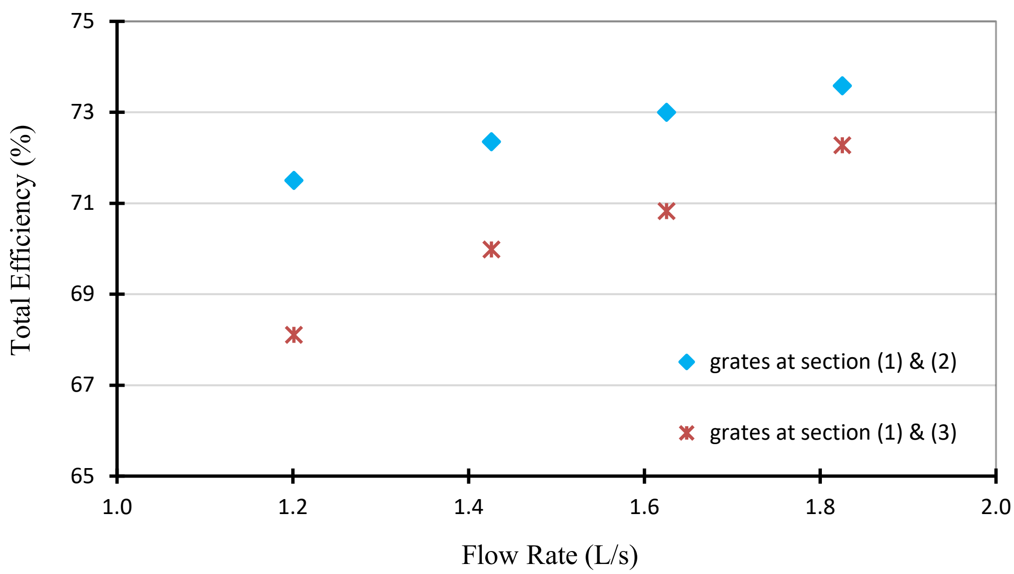


Fig. 5: Total hydraulic efficiencies of both two-grated systems for identical flow rate values. The data for grates at sections (1) and (3) are experimentally obtained, whereas the data for grates at sections (1) and (2) are predicted from Eqn. (4). All cases correspond to subcritical flow conditions.

4. Conclusion

The hydraulic performances of the successively positioned grate inlets were experimentally investigated under varying approach flow rates. All tests were conducted under subcritical flow conditions. Within this context, two systems were tested on a rectangular channel where the distances between two successive side grates were 0.2 m and 0.4 m, respectively. According to the results, the grate efficiencies were found to be strongly correlated with the total approaching flow, mostly yielding an increasing tendency with a corresponding increase in the flow rate. Moreover, the results have revealed that the capturing capacity of a system having a shorter distance between two successive grates was noticeably higher under identical approach flow rates. It can be concluded that the findings of this present study might provide useful information for the design of urban drainage systems in a more effective manner.

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