Hydraulics characteristics of tipping sediment flushing gate

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ABSTRACT

This paper highlights the preliminary study on the potential of a tipping flush gate to be used in open storm drain to remove sediment. The investigation was carried out by using a plasboard model of the tipping flush gate installed in a rectangular flume. Steady flow experiment was carried out to determine the discharge coefficients and also the outflow relationship of the tipping flush gate. The velocity produced by the gate at various distances downstream of the gate during flushing operation was measured using a flowmeter and the velocity at all the points was higher than the recommended self-cleansing design available in the literature. Preliminary experiment on the efficiency of flushing was conducted using uniform sediment with $d_{50}$ sizes of 0.81, 1.53 and 4.78 mm. Results generally showed that the number of flushes required to totally remove the sediment from the initial position by a distance of 1 m increased by an average of 1.50 times as the sediment deposit bed thickness doubled. An equation relating the number of flushes required to totally remove the sediment bed for 1 m with the sediment bed deposit thickness was also developed for the current study.

Key words | flushing, open storm drain, sediment, self-cleansing design, tipping gate

INTRODUCTION

Sedimentation in sewer systems and open storm drains had caused problems such as a reduction of hydraulic capacity (Bong et al. in press), odours due to anaerobic processes and source of pollutants during storm events (Bertrand-Krajewski et al. 2003). Various techniques have been developed to clean sewers of sediments which are based on both mechanical and hydraulic principles. However, for most developing countries, removal of sediments from open storm drains often involves manual handling which is costly.

Among the various techniques, the one based on hydraulic effects mainly consists of creating a flushing effect by discharging a volume of water during a short period of time. The flushing effect could be created by storing water in upstream chambers and discharged through a gate or tipping bucket located above water level or mobile tipping plates like the Hydrass gate (Chebbo et al. 1996; Lorenzen et al. 1996). These devices allow the production of successive flushing waves at high velocities sufficient (Bong et al. 2013) to scour and transport sediments and represent an automated cost-effective solution for sewer cleansing. Various experimental studies are also available in the literature on the effect of flushes from flushing devices such as sluice gates/lifting gates (Campisano et al. 2004, 2008), vacuum flushing (Guo et al. 2004) and the Hydrass gate (Bertrand-Krajewski et al. 2005). Figure 1 shows examples of flushing devices used in sewers for sediment flushing.

This paper describes a preliminary study on the potential of using a tipping flush gate in an open storm drain to flush out sediments. A preliminary model of a self automated tipping gate with a scale reduction 1:2 from the original one to be installed in an onsite open drain for the next part of the study has been designed and tested in an experimental flume for the hydraulics characteristics. Preliminary experiments on the efficiency of flushing have also been conducted in the same experimental flume using uniform non cohesive sediment with $d_{50}$ sizes of 0.81, 1.53 and 4.78 mm. Results from this preliminary study could provide better understanding of the tipping flush gate characteristics for further study.
THE TIPPING SEDIMENT FLUSH GATE

The model tipping flush gate operation is made up of two phases. The first phase is the storage phase during which water is stored behind the gate until the water level reaches a value that leads to the rotation and opening of the gate. At the moment when the gate opens, the flushing phase starts and the stored water is rapidly discharged. The gate was designed to open at 30° from the horizontal and the gate starts to tip when the water level behind the gate reaches 0.27 m. After the flush, the receding water level upstream of the gate rotates the lower part of the gate and the gate starts to close when the water level reaches 0.19 m with another storage phase being started. Figure 2 shows the front view and the isometric view of the model tipping flush gate while Figure 3 shows the photographs of the general view of the tipping flush gate when open and closed respectively. Plasboard (density = 1,092 kg/m³) was used as the main material for the gate.

METHODOLOGY

The tipping flush gate was fixed at 2.2 m from the inlet of a rectangular flume with the dimensions 0.6 m (width) × 0.5 m (depth) × 0.57 m (effective length). The material for the bottom of the flume was plasboard with the lateral walls made of glass. To study the outflow conditions of the tipping flush gate, the gate can be modelled as an inclined weir (see Figure 4) as defined by Bertrand-Krajewski et al. (2005). Different outflow conditions will depend on the upstream water level. For higher water level, the outflow occurs through both the upper and lower part of the tipped gate. For lower values of the upstream water level, the outflow occurs only through the lower part of the gate.

To determine the outflow through the upper part of the gate assuming a steady flow condition, the experiment was conducted by sealing the lower part of the gate and allowing water to pass only through the upper part of the gate. Since the inclined weir shape for the upper part can be considered
as rectangular, the outflow over the upper weir $Q_{\text{Wup}}$ [m$^3$/s] can be evaluated as (Ghetti 1984; Bertrand-Krajewski et al. 2005):

$$Q_{\text{Wup}} = \mu_{\text{Wup}} B_{\text{Wup}} \sqrt{2g \left( h - h_{\text{Wup}} + \frac{V^2}{2g} \right)^{3/2} - \left( \frac{V}{\sqrt{g}} \right)^{3/2}}$$ (1)

in which $\mu_{\text{Wup}}$ is the discharge coefficient of the upper weir, $h$ [m] and $h_{\text{Wup}}$[m] are the water level at 0.5 m upstream of the gate and height of crest of upper weir respectively; $B_{\text{Wup}}$[m] is the upper weir width which is into the page in Figure 4; $V$[m/s] is the average upstream flow velocity and $g$[m/s$^2$] is the gravity acceleration. From the experiment, for different values of flow rate, the upper weir coefficient $\mu_{\text{Wup}}$ was evaluated from Equation (1).

The outflow through the lower part of the gate can be considered as flow through pressurized orifice or flow over a weir depending on the upstream water level. If the upstream water level $h$[m] is greater than the height of the gate hinge $h_{\text{hng}}$[m], the outflow would be under head through the lower orifice and evaluated as (Ghetti 1984; Bertrand-Krajewski et al. 2005):

$$Q_H = \mu_H A_H \sqrt{2g \left( h - h_{\text{bar}} + \frac{V^2}{2g} \right)}$$ (2)

in which $\mu_H$ is the discharge coefficient of the lower orifice under head; $A_H$[m$^2$] is the outflow area and $h_{\text{bar}}$[m] is the barycentre of the outflow area from the bottom. To determine the discharge coefficient of the lower orifice $\mu_H$, the experiment was performed by allowing water to pass through both over and under the gate at the same time.

If the upstream water level $h$[m] is lower than $h_{\text{hng}}$[m], the outflow can be modelled as the flow over a rectangular weir (Carlier 1986; Bertrand-Krajewski et al. 2005):

$$Q_{\text{Wrect}} = \mu_{\text{Wlow}} \sqrt{2g \left( h - h_{\text{Wlow}} + \frac{V^2}{2g} \right)^{3/2} - \left( \frac{V}{\sqrt{g}} \right)^{3/2}}$$ (3)

in which $\mu_{\text{Wlow}}$ is the discharge coefficient of the lower weir; $h_{\text{Wlow}}$[m] is the lower weir height and $b$[m] is the weir width. To determine the discharge coefficient of the lower weir, the
experiment was conducted with the flow through the lower weir only. Figure 5 shows the three flow conditions during the experiments to determine the outflow discharge coefficients.

To determine the flushing characteristics, velocity of the flush waves during the flushing operation (without sediment bed) was measured using an electromagnetic flowmeter at the centreline of the flume at the distances of 0.5, 0.75, 1.0, 1.25, 1.5, 1.75, 2.0, 2.25, 2.5, 2.75, 3.0, 3.25 and 3.5 m from the gate. Using the Fixed Point Average option in the flowmeter, the velocity reading was taken continuously and the average velocity was updated every 2 s. The flowmeter has an accuracy of ±2% of the true velocity value. The highest velocity during the flushing period for each of the distances from the gate was recorded. Changes of water level at 0.5 m upstream of the gate and 1.0 m downstream from the gate were recorded using a digital camera and digital frames for each second during flushing were extracted from the video clips relative to the sections. The water level was measured with respect to the bottom of the flume.

Experiments were also conducted using uniform non-cohesive sediments with $d_{50}$ sizes of 0.81, 1.53 and 4.78 mm with a specific gravity of 2.54, 2.55 and 2.57 respectively. The sediment sizes were within the range observed by Bong et al. (in press) from site sampling of sediment in urban open concrete storm drain. The sediment bed was laid starting from 0.5 m downstream of the gate and building up a deposit bed of 1.0 m long and 25 mm thick. No sediment was laid in the remaining downstream length in order to examine the deposit bed advancing. Flushing was conducted until all the sediment has been removed from the 1 m length where initially the sediment was laid. Since the changes of water level behind the gate was the same during the opening and closing of the gate for each of the flush, the gate dynamics and flow volume was the same for each flush. The volume of water flowing through the gate during each flush was calculated to be 0.106 m$^3$. The number of flushes needed was recorded. At the end of each flushing operation, the heights of sediment bed along the flume were measured at every 0.25 m interval and at every 0.15 m for each cross section with a ruler with uncertainty of 0.5 mm. The mean height in each cross section was calculated. The experiment was repeated with the sediment bed laid starting from 1.5 m downstream from the gate. Another set of experiment using the same sediment but at a sediment bed deposit thickness of 50 mm was also conducted. All the experiments as mentioned in this section were conducted at a channel slope of 0.001.

![Figure 5](image-url) | Flow conditions: (a) flow over upper weir; (b) flow through pressurized orifice; and (c) flow through under the gate.
RESULTS AND DISCUSSION

Evaluation of the discharge coefficients

Figure 6 shows the results of the experiments to determine the discharge coefficients of the flushing gate. As shown in Figure 6(a), the discharge coefficients $\mu_{W_{up}}$ for the outflow through the upper part of the gate seem to be almost constant for different values of head $h-h_{W_{up}}$ with an average value of 0.65. Same for the case of outflow through the lower part of the gate for orifice under pressurized head as shown in Figure 6(b) where the discharge coefficients $\mu_{H}$ also almost constant with the variation of head $h-h_{bat}$ with an average value of 0.47. The discharge coefficient for outflow through the lower weir is as shown in Figure 6(c) where the average value for $\mu_{W_{low}}$ is 0.31. These discharge coefficients are valid for the gate in this study and it is yet to be tested whether these values are transferable to other similar gate but with different dimensions.

By substituting the discharge coefficient values obtained into Equations (1)–(3), the following Equations (4)–(6) were

Figure 6 | Discharge coefficients as functions of upstream water level for: (a) upper weir; (b) orifice under head; and (c) lower weir.

Figure 7 | Global outflow relations $Q(h)$ for the tipping flush gate in the current study.

Figure 8 | Variation of water level during flushing operation at: (a) 0.5 m upstream of the gate; and (b) 1.0 m downstream of the gate.
obtained for outflow through upper part of the gate, outflow through pressurized orifice and outflow through lower part of the gate respectively.

\[ Q_{\text{Wup}} = 0.65B W_{\text{up}} \sqrt{2g \left[ \left( h - h_{\text{Wup}} + \frac{V^2}{2g} \right) \right]^{\frac{3}{2}} - \left( \frac{V^2}{2g} \right)^{\frac{3}{2}}} \]  

(4)

\[ Q_H = 0.47A H \sqrt{2g \left( h - h_{\text{bar}} + \frac{V^2}{2g} \right)} \]  

(5)

\[ Q_{\text{Wrect}} = 0.31b \sqrt{2g \left[ \left( h - h_{\text{Wlow}} + \frac{V^2}{2g} \right) \right]^{\frac{3}{2}} - \left( \frac{V^2}{2g} \right)^{\frac{3}{2}}} \]  

(6)

The global outflow relation \( Q(h) \) relative to the upstream water level \( h \) for the gate used in the current study was calculated using the previous Equations (4)–(6) and is plotted in Figure 7. In Figure 7, the dashed line shows the theoretical outflow calculated using Equations (4)–(6) while the data point markers show the outflow measured in the current study. From Figure 7, a good agreement was observed between the theoretical and the measured outflow for the current study.

**Flushing results**

The variation of water level with time as extracted from the video clips by playing back in slow motion for the distance of 0.5 m upstream of the gate and 1.0 m downstream of the gate is shown in Figure 8. In Figure 8(a), the water level upstream of the gate just before the gate opening was 0.27 m at 0 s. When the gate opens, the water level recedes to 0.19 m at 4 s, then the gate closes and the water level rises up a bit and up to 0.2 m. In Figure 8(b), at 1.0 m downstream of the gate, the time it took by the flush waves to reach this distance was approximately 1 s, thus the water level at this

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**Figure 9** | Sediment bed profiles of \( d_{50} = 0.81 \text{ mm} \) after flushes for (a) 25 mm initial sediment bed deposit thickness and (b) 50 mm initial sediment bed deposit thickness.
point had a sudden surge after 1 s the gate opened. 4 s after the gate had closed, the water level continues to recede until (at 7 s) the water level starts to maintain at 0.01 m.

The highest velocity achieved during flushing was at the distance of 2.5 m from the gate with a velocity of 1.37 m/s while the lowest velocity was at the distance of 0.5 m from the gate with the velocity of 1.08 m/s. The velocity was observed to be lowest for the point nearest to the gate and had an increasing trend until the distance of 2.5 m from the gate where the velocity reached the highest value. After the distance of 2.5 m, the velocity had a decreasing trend with the lowest value of 1.22 m/s at distance of 3.5 m from the gate (the last point the velocity reading was taken before the end of the flume). Nevertheless, the velocity achieved along the flume during flushing was higher than the critical velocity recommended by the Drainage and Irrigation Department, Malaysia which is 0.9 m/s (Ab. Ghani et al. 2008) for the purpose of self-cleansing design of open drain and also by various authors for self-cleansing design of sewers (Nalluri & Ab. Ghani 1996; Vongvisessomjai et al. 2010). This means that the velocity produced during flushing should be able to scour the sediment deposit and remove the deposit from the flume. Further study was needed either in longer flume or using the one on site to determine until what length the velocity generated from the flush is above the recommended self-cleansing velocity of 0.9 m/s, thus verifying the effective flushing length of the gate.

Figure 9 shows the variation of the mean sediment bed profiles for sediment size $d_{50}$ of 0.81 mm after flushes for both the sediment deposit thicknesses of 25 and 50 mm laid starting from 0.5 m downstream of the gate and building up a deposit bed of 1.0 m long. For both cases, during the first flushes, the scouring process was observed to produce lowering and lengthening of the initial bed deposit. Subsequent flushes caused the advancement of the sediment bed. Sediment was totally flushed out of the 1 m length where the initial sediment bed was laid after 13 flushes for thickness of 25 mm and 17 flushes for thickness of 50 mm. Almost similar trend of sediment bed profiles changes but

![Figure 9](image-url)

Figure 9 | Sediment bed profiles of $d_{50} = 0.81$ mm after flushes for (a) 25 mm initial sediment bed deposit thickness and (b) 50 mm initial sediment bed deposit thickness.

![Figure 10](image-url)

Figure 10 | Sediment bed profiles of $d_{50} = 1.53$ mm after flushes for (a) 25 mm initial sediment bed deposit thickness and (b) 50 mm initial sediment bed deposit thickness.
with different total number of flushes required were observed for sediment sizes $d_{50}$ of 1.53 and 4.78 mm as shown in Figures 10 and 11 respectively.

Table 1 shows the number of flushes required to remove the sediment bed deposit from the 1 m length where initially the sediment was laid. The flush ratio was the ratio of the number of flushes required for 50 mm sediment bed deposit thickness with the number of flushes required for 25 mm sediment bed deposit thickness for the same sediment size and distance of initial sediment bed from the gate. From Table 1, generally the number of flushes required increased by an average of 1.50 times as the sediment bed deposit thickness doubled.

To determine the effect of sediment size $d_{50}$, sediment bed deposit thickness $t_s$ and the initial position of the sediment bed from the gate $L$ on the total number of flushes required to totally remove the sediment bed for a distance of 1 m where the bed was initially laid, a correlation analysis was performed. Results from the correlation analysis have shown that the total number of flushes has strong correlation with the sediment bed deposit thickness $t_s$ with Pearson correlation value of 0.902 ($p$-value = 0.000) and no correlation with the sediment size $d_{50}$ with Pearson correlation value of 0.267 ($p$-value = 0.356) and initial position of the sediment bed from the gate $L$ with Pearson correlation value of 0.022 ($p$-value = 0.940). Using linear regression, an equation relating the number of flushes $n$ required with the sediment bed deposit thickness $t_s$ [mm] was developed for the current study and as shown in Equation (7). Equation (7) has an $r^2$ value of 0.813. The graphical representation of Equation (7) is as shown in Figure 12.

$$n = 251.43t_s + 6.57 \quad (7)$$

Future study on the gate flushing could include sediments with different specific gravity since the different sediment sizes used in the current study with almost similar sediment specific gravity values did not have significant

![Figure 11](image)

**Figure 11**: Sediment bed profiles of $d_{50} = 4.78$ mm after flushes for (a) 25 mm initial sediment bed deposit thickness and (b) 50 mm initial sediment bed deposit thickness.
effect on the number of flushes required. Longer flume is also recommended to study the effect of sediment initial distance from the gate since this effect was not significant in the current study due to the limitation of the length of the flume used. The effect of different gate opening angles could also be included in future study.

**CONCLUSIONS**

This paper presents a preliminary study on the potential of a tipping flush gate to be used in open storm drain for sediment flushing. The investigation was carried out using a model plasboard tipping flush gate fixed at 2.2 m from the inlet of a rectangular flume. Steady flow experiment was carried out to determine the discharge coefficients for the outflow of the tipping flush gate and a global \( Q(h) \) was obtained to relate the upstream water level with the discharge through the gate. The variation of water level at 0.5 m upstream and 1.0 m downstream of the gate during flushing operation was captured by video and the velocity produced during flushing at various distances downstream of the gate was determined using flowmeter. The velocity produced was higher than the recommended critical velocity available in the literature for the design of self-cleansing of sewers and open drains. Preliminary study on the efficiency of flushing was also conducted using uniform non cohesive sediment with \( d_{50} \) sizes of 0.81, 1.57 and 4.78 mm. Result shows that generally the number of flushes required to totally remove the sediment from the initial position increased by an average of 1.50 times as the sediment bed deposit thickness doubled. An equation relating the number of flushes required to totally remove the sediment bed for 1 m with the sediment bed deposit thickness for the current study was also developed.

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**REFERENCES**


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<th>Sediment initial distance from gate ( L ) (m)</th>
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Average flush ratio 1.50


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