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Hydraulic efficiency of road drainage inlets for storm drainage system under clogging effect

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Abstract

Road drainage inlets are used to collect surface runoff from streets and other land surfaces through grate or curb openings and convey it to storm drains. The surface runoff that is not discharged to the urban storm drainage system due to inadequate inlets or attention to inlet capacity can cause flooding, undue hazards to motorists and pedestrians, and disrupt urban activities.

The aim of this study is to determine the hydraulic efficiencies of three grate inlet designs used in Singapore – G2000 (longitudinal bars), G2012 (lateral bars) and G2014 (lateral bars extended over curb opening) under various road configurations (longitudinal and cross slopes) and operating environments (clogging factors and rainfall intensities). In this study, a road model (1/1 scale) was constructed to configure the geometry of a road with simulated rainfalls of various intensities. The rainfalls were simulated by a network of overhanging pipes at 2m intervals to simulate flow conditions where surface runoff approaches the grate inlets from both the gutter and carriageway. The study showed that the hydraulic efficiencies of G2000 and G2012 grate inlets had a range from 70% to 96% under a non-clogged condition and 28% to 83% under a 100% clogged condition. G2000 grate inlets intercepted 2.5% more flow than G2012 grate inlets. When the clogging was greater than 100%, G2014 grate inlets intercepted 50% more flow than G2000 and G2012 grate inlets. The results of the study will serve as a guide for road geometry and grate designs to optimize the hydraulic efficiency of road drainage inlets.

Keywords: hydraulic efficiency, intercepted flow, road drainage inlet.

1 Introduction

The most important objectives of a hydraulic urban study are to understand the discharge runoff related to a specific storm and design an efficient and effective

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drainage system. Surface runoff from a storm event is removed from the road through drainage inlets placed at intervals along road curbs and channelled into the city's drainage network. Drainage systems are typically designed on the assumption of full-flowing pipes/channels, often neglecting for how fast the surface runoff is channelled into the system.

The efficiency of road drainage inlet depends largely on its grate geometry design and the characteristics of the external environment (Comport *et al.* [5] and Guo and MacKenzie [6]). Although there have been several empirical methodologies to estimate inlet hydraulic capacities (Gomez and Russo [3] and Brown *et al.* [7]), the actual hydraulic performance of the inlets used in Singapore have not been determined.

This paper presents an experimental method to determine the hydraulic efficiency of three drainage inlet grate designs used in Singapore on a road model with varying geometry and simulated storm events, and clogging factors.

2 Road drainage system in Singapore

In Singapore, surface runoff on road carriage ways is captured by drainage inlets and connecting pipes placed at regular intervals along the curbs and conveyed to the city's drainage network. The key elements affecting hydraulic performance of the inlets and connecting pipes are road geometry (longitudinal and cross slopes), grate inlet designs and degree of clogging on grates (Comport *et al.* [5] and Guo and MacKenzie [6]). Singapore, a city in a garden [8], has many trees, plants and shrubs growing along the roadsides. During storm events, the surface runoff brings along the leaves shed from the greeneries into the road carriageways and onto the drainage inlets, affecting the performance of the grate inlets.

The current drainage design in Singapore are based on the "Code of Practice on Surface Water Drainage" [1]. The code specifies the design and placing intervals for road drainage inlets. However, there is no specific guidance for varying road geometry.

The design of road drainage grate inlets has evolved with continuous improvements in hydraulic efficiency and road safety. Presently, three grate inlet designs (G2000 – longitudinal bars, G2012 – lateral bars and G2014 – lateral bars extended over curb opening) (as shown in Fig. 1) are used in Singapore. However, the hydraulic efficiencies of these grates have not been determined.


G2000 – longitudinal bars
G2012 – lateral bars
G2014 – lateral bars extended over curb opening

Figure 1: Three grate inlets used in the study.

3 Methods

Three grate inlet designs, regulated by Code of Practice on Surface Water Drainage [1] and Code of Practice on Street Work Proposals Relating to Development Works [2] (G2000 – longitudinal bars, G2012 – lateral bars and G2014 – lateral bars extended over curb opening) were placed on an adjustable road model of varying longitudinal and cross slopes under three simulated rainfall intensities and different degrees of clogging at the grate inlets.

The experiment was designed to collect data on gutter flow depths before and after each grate inlet and outflow rates from grate inlets under simulated rainfall intensities. A total of 327 combinations were set up for the study.

3.1 Experiment facility

The experiment facility consisted of an elevated one-lane road model, a one cubic metre water tank, two four-inch pumps, overhanging pipes, flow meters and pressure measurement devices. The layout of the facility is shown in Fig. 2.

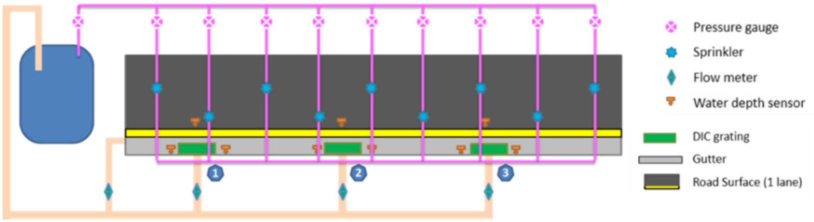

Figure 2: Layout of the experiment facility.

The model of one-lane road (3m width) was constructed with a finished layer of bitumen (roughness coefficient n = 0.015). The road model had features to configure varying longitudinal and cross slopes for the road surface. Three grate inlets were placed at 6m intervals along the gutter and connected to three connecting discharge pipes of 250mm diameter. The characteristics of gutter flows and frontal flows were observed at different positions of the grate inlets during the experiment.

Rainfalls of different intensities were simulated via a network of pipes overhung 1m above the road surface with sprinklers at 2m staggered intervals. The set-up had simulated rainfalls which allowed the surface runoff from gutter and carriageway to approach the grate inlets, similar to actual flow conditions on a road. This differed from earlier studies where the simulated surface runoff was a continuous steady flow (Pezzaniti *et al.* [4]).

The parameters and values configured for the tests are shown in Table 1 (Land Transport Authority [2]).

3.2 Gutter flow, intercepted flow, by-pass flow and grate inlet efficiency

A road gutter is defined as a section of road adjacent to the road curb which conveys water during a storm event. Conventional gutter sections in Singapore

Table 1: Test parameters.

Parameters	Test values			
Longitudinal slopes	1%	2%	3%	-
Cross slopes	1%	3%	4%	-
Rainfall intensities (mm/h)	133	183	250	-
Grate inlet designs	G2000	G2012	G2014	-
Degree of clogging	0%	50%	100%	>100%

road design are 300mm wide concrete surface with a recess of 75mm below the road surface (Land Transport Authority [2]). The surface runoff will be contained mainly in the gutter section before being intercepted by the grate inlets. A typical gutter section of a road is shown in Figs 3 and 4. Water depth in the gutter was measured by pressure measurement devices placed along the gutter, just before and after the grate inlets. Side flow/frontal flow is the amount of flow coming from traffic lanes and approaching the grate inlets at the longer side of the grate. The frontal flow was also computed based on the measured water depth on the road surface just before it was captured by the grate inlets.

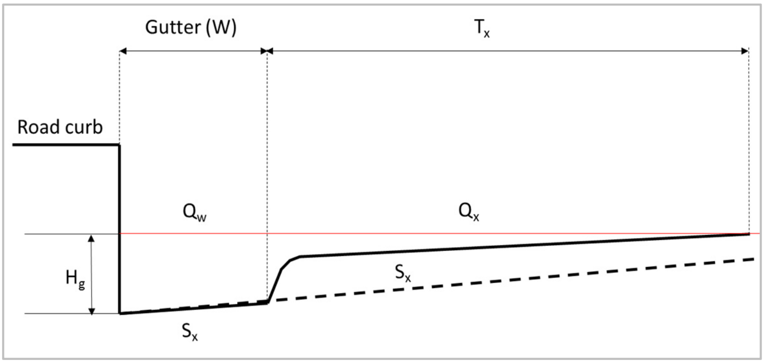

Figure 3: Gutter cross section with water depth higher than gutter depth.

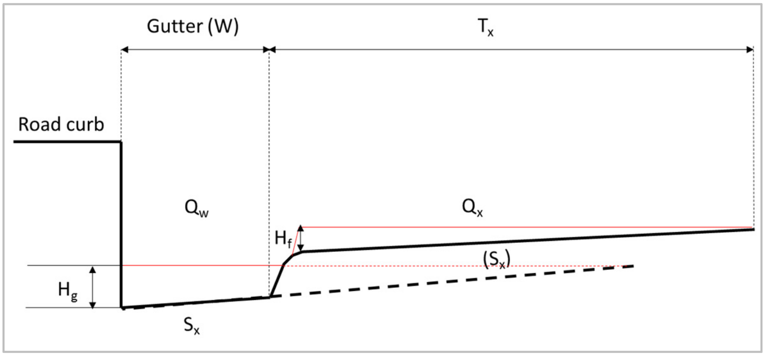

Figure 4: Gutter cross section with water depth lower than gutter depth.

Intercepted flows (Q_i) were measured for individual grate inlets at position 1, 2 and 3 and for the entire system of three inlets. The hydraulic efficiencies of the road system consisting of three grate inlets and of individual grate inlets were calculated for each configuration of road profile, rainfall intensity, grate design and clogging factor.

$$E = Q_i/Q_{total} \quad (1)$$

where:
E = Efficiency of the grate inlet,
Q_i = Intercepted flow by the inlet,
Q_{total} = Total discharge approaching the inlet.

Gutter flows, frontal flows and intercepted flows on the experimental model is shown in Fig. 5.

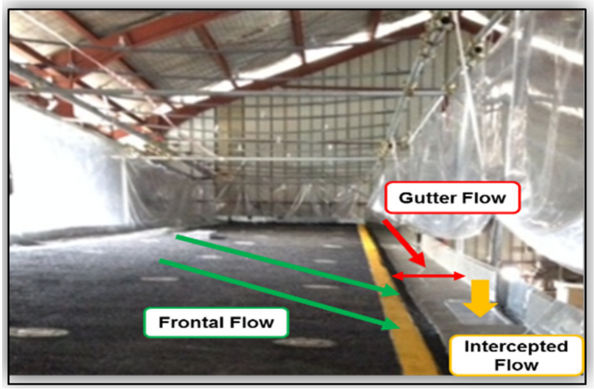

Figure 5: Gutter flow, frontal flow and intercepted flow in the experiment model.

4 Grate inlet efficiency under non-clog condition

The grate inlets were tested at different road configurations and rainfall intensities under non-clogging and clogging conditions. The hydraulic efficiencies for grate G2012 and G2014 do not vary for the same experiment set-up. Observations during the experiments also revealed that the water depth within gutter section did not exceed the gap under the road curb, all the run-off being intercepted by the grate inlets.

It was expected as G2012 and G2014 grate inlets have similar grate geometry, the only difference being the curb opening for G2014. Therefore, G2014 grate inlets were not included in the tests to determine hydraulic performance for grate inlets under non-clogging conditions.

4.1 Effect of road configuration

The experiment results show that hydraulic efficiencies of the grate inlets range from 70% to 96% for rainfall intensities simulated at 133mm/h, 183mm/h and 250mm/h. The highest efficiencies were at 4% cross slope and the lowest efficiencies were at 1% cross slope.

The intercepted efficiencies reduced at steeper longitudinal slopes and increased at steeper cross slopes (as shown in Fig. 6). The results are consistent with the hypothesis that (1) steeper cross slopes will allow more run-off to be channelled to the gutter where the surface run-off is contained hence increasing the efficiency; and (2) steeper longitudinal slopes will cause more run-off to by-pass the grate inlets, hence reducing the efficiency.

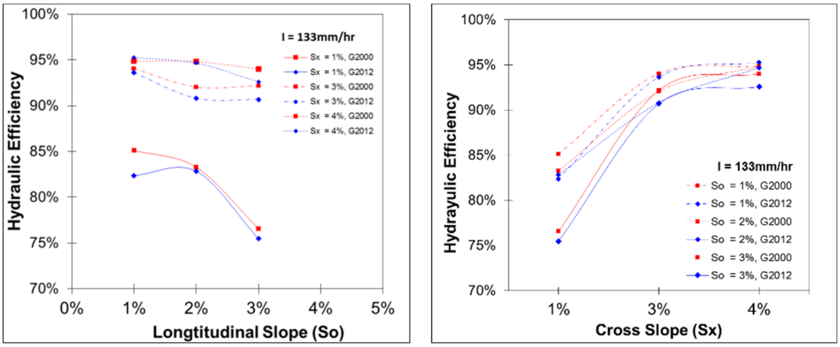

Figure 6: Hydraulic efficiencies under non-clogging condition for rain intensity of 133mm/h.

It also shows that change in cross slopes has higher impact to the hydraulic efficiency of grate inlets than change in longitudinal slopes. When longitudinal slope is adjusted from 1% to 3%, inlet hydraulic efficiency only drops 1%–2% at steep cross slopes and 7%–8% at flat cross slopes. However, when cross slope is adjusted from 1% to 3%, inlet hydraulic efficiency can be increased from 10%–20%. The change in hydraulic efficiency with respect to the change in road configuration is shown in Table 2.

Table 2: Change in hydraulic efficiency with respect to change in road configuration under non-clogging condition.

Longitudinal slope	**Cross slope**	**Hydraulic efficiency**
▲ (1%–3%)	-	▼ (1%–8%)
-	▲ (1%–3%)	▲ (10%–20%)

4.2 Effect of rain intensities

At varying simulated rainfall intensities for the same experimental set up, the intercepted flow increases as the rainfall intensifies. However, the hydraulic efficiency tends to drop at higher rainfall intensity, although the difference is not significant (Fig. 7). Based on this result, we can conclude that the rain intensity has minimal impact to the inlet hydraulic efficiency under non-clogging condition.

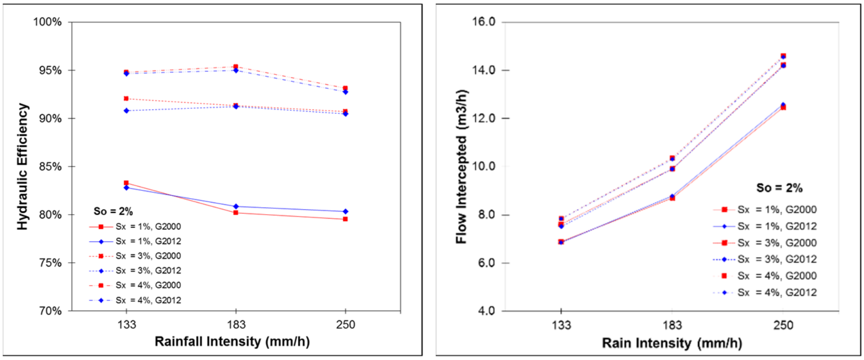

Figure 7: Inlet hydraulic efficiencies and intercepted flows at different rain intensities under non-clogging condition (So = 2%).

4.3 Effect of grate inlet geometry design

The hydraulic performance for the two grates tested does not vary significantly under non-clogging condition. We observed that grate G2000 tends to achieve slightly higher efficiency (1%–3%) than grate G2012 (Fig. 8).

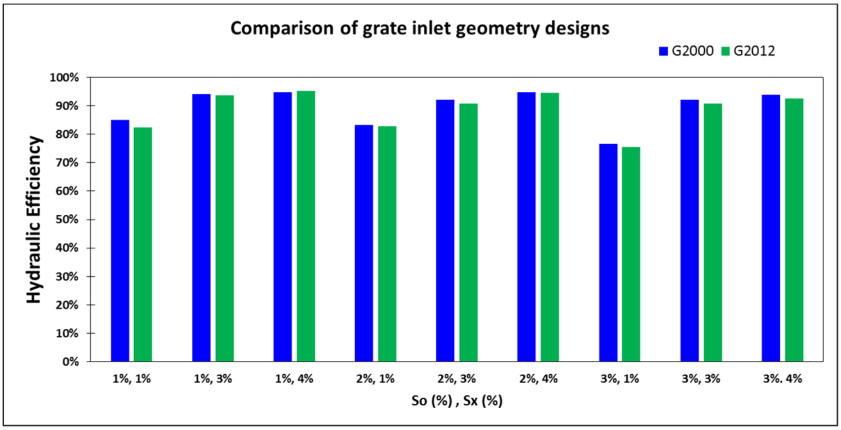

Figure 8: Inlet hydraulic efficiencies for different grates inlet under non-clogging condition (I=133mm/h).

5 Grate inlet efficiency under clogging conditions

Tests on the grate inlets were repeated at the same combinations of road geometry and rainfall intensity as used under non-clogging condition. The three grate inlets and the curb gap were covered to simulate the clogging levels of 50%, 100% and >100% (clogging above the horizontal plane) (as shown in Fig. 9).

Figure 9: Simulated clogging levels of 50%, 100% and >100%.

5.1 Effect of road configuration and rain intensities

Under horizontal plane clogging situation (50% and 100%), the behaviour of grate inlet hydraulic performance is similar to what was observed under non-clogging experiments. However, when the clogging was beyond the horizontal plane, the road configuration had a different impact on the efficiency (Fig. 10).

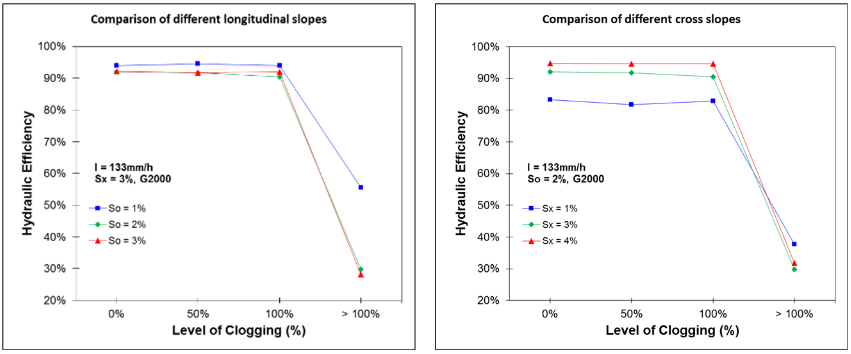

Figure 10: Hydraulic efficiencies at different longitudinal and cross slopes under clogging condition.

The hydraulic efficiency drops 2%–3% only when longitudinal slope is steeper under horizontal plane clogging. A 27% reduction in efficiency was observed at steeper longitudinal slopes under >100% clogging condition. On the other hand, the impact of cross slopes was totally reversed at steeper cross slopes. The hydraulic efficiency increases 8%–10% under horizontal plane clogging, but

Table 3: Change in hydraulic efficiency with respect to change in road configuration under clogging condition.

Clogging level	Longitudinal slope	Cross slope	Hydraulic efficiency
50%, 100%	▲ (1%–3%)	–	▼ (2%–3%)
>100%	▲ (1%–3%)	–	▼ (27%)
50%, 100%	–	▲ (1%–3%)	▲ (8%–10%)
>100%	–	▲ (1%–3%)	▼ (8%)

efficiency reduces 8% under clogging beyond horizontal plane for steeper cross slopes.

Similar to non-clogging conditions, the study shows that the rainfall intensities have little impact on the grate inlet hydraulic efficiencies. The change in efficiency is only less than 3% under all conditions tested (50%, 100% and >100% clogging) for rain fall intensities of 133mm/h, 183mm/h and 250mm/h (Fig. 11).

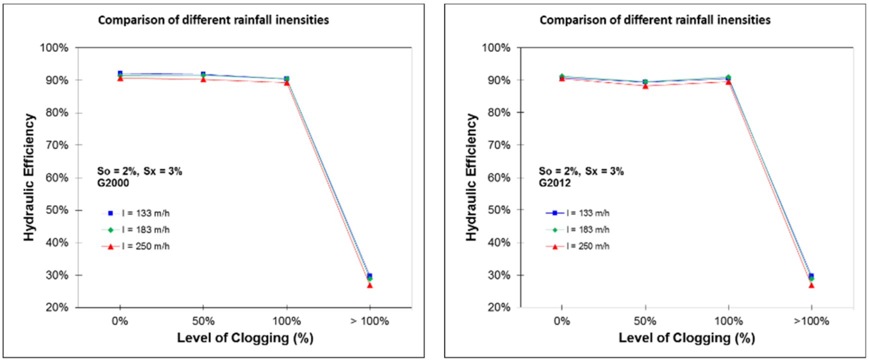

Figure 11: Hydraulic efficiencies at different longitudinal and cross slopes under clogging condition.

5.2 Effect of grate inlet geometry design

A comparison between three grate inlet designs at different road configurations and operating environment showed that G2000 grate inlets intercepted more flows than G2012 grate inlets under non-clogging and horizontal plane clogging condition. The performance of these two grate inlets drops significantly when the clog is beyond horizontal plane, from about 90% to 30% interception efficiency.

The efficiency of G2014 grate inlets was the same for G2012 grate inlets if the clogging was below 100%. When the clogging was above the horizontal plane, hydraulic efficiency of grate inlet G2014 was more than twice as it is for grate inlet G2012 (Fig. 12).

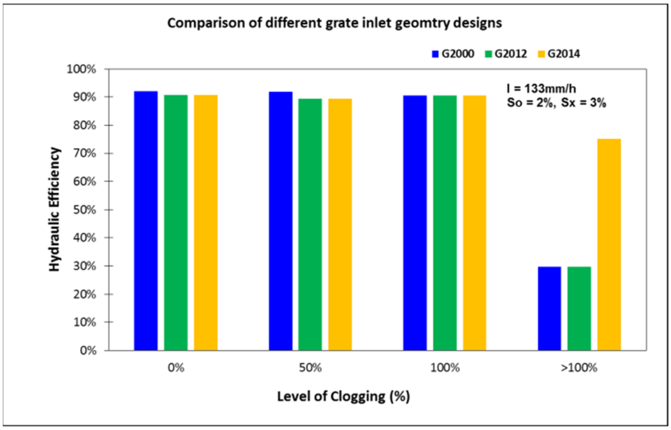

Figure 12: Hydraulic efficiencies for different grate inlets under clogging condition.

6 Discussion

The experimental set-up had three (3) grates with simulated rainfalls which allowed the surface runoff from gutter and carriageway to approach the grate inlets, similar to actual flow conditions on a road. This differed significantly from earlier studies where the simulated surface runoff was a continuous steady flow.

The geometry of the clogging on the grates presented in previous studies were done by covering the grates uniformly by 50% and 100% (Guo and MacKenzie [6]). For this study, the geometry of the clogging on the grates resembled the actual conditions observed after a storm event including a geometry where the clogging was beyond the horizontal plane (Fig. 9).

The study depicted grate inlets operating in real environment, thus hydraulic efficiencies obtained are more representative than earlier experimental studies.

7 Conclusion

A study using a network of overhanging pipes to simulate storm events was developed to determine the hydraulic efficiencies in terms of flow interception into different grate inlets. This methodology allows for similar flow conditions where the surface runoff approaches the grate inlets from both the gutter and carriageway.

The study showed that the existing grate inlet designs can intercept up to 96% of the surface run-off. A comparison between three grate inlet designs also showed that G2000 grate inlets intercepted more flows than G2012 grate inlets. Under clogging condition of more than 100%, G2014 grate inlet's hydraulic efficiency in terms of flow interception is much higher than G2000 and G2012 grate inlets. This results ascertained that G2014 grate inlets should be used in locations where there is a tendency of grate inlets being clogged.

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