Hydraulic Performance and Reliability Assessment of Street Inlet with Enhancement of Pervious Concrete Curb

SPEAKER:
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Winner of Best Thesis Award MSc Category

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BACKGROUND OF STUDY

1. Urbanization replaced *pervious* with *impervious* surface
2. Pervious vegetated land to impervious street pavement
3. Reduced natural infiltration and *increase rate of runoff* on the street
4. Pavement drainage system *exceed* designed capacity
5. Street *inlet* is the main *key*
BACKGROUND OF STUDY

WHAT IS STREET INLET?

- Opening to collect and remove stormwater from street into underground drainage

- Each country may use different design standard in terms of patterns, sizes and configurations
BACKGROUND OF STUDY

Impervious street curb

Pervious street curb
BACKGROUND OF STUDY

WHAT IS NEW PERVIOUS CONCRETE CURB (CURBVIOUS)?

- A technology for curb developed from pervious concrete which allow more interception of excess stormwater runoff on the street
PROBLEM STATEMENT

During heavy stormwater events, grate and curb-opening inlets are often found inefficient in collecting and conveying the excess stormwater runoff away from the street.

CONCERN ARISES

1. How much efficiency of street inlets used in Malaysia?
2. Is it possible to assess inlet performance using probabilistic method?
3. Can Curbvious technology enhance the inlet performance and reduce ponding/flooding?
OBJECTIVES

1. To conduct experimental investigation and assess the current hydraulic performance of several typical type of grate and curb-opening inlets.

2. To assess reliability of several typical type of grate and curb-opening inlets using probabilistic approach.

3. To develop and assess the hydraulic performance of a new pervious concrete curb (Curbvious) in reducing excess stormwater runoff on the street.
Experimental Studies
1. Full scale (1:1) model
2. Fixed slopes: Longitudinal slope = 0.5 %, Cross slope = 2.5%, Gutter slope = 4%
3. 3 grate and 4 curb-opening inlets used in Malaysia
4. Flows: 0.0004 to 0.03 m³/s
5. Froude number, $F$ less than 0.50 ($F<1$)

SCOPE OF STUDY

- **Reliability Assessment**
  1. Limit state function
  2. Probability of density function
  3. Monte Carlo simulation technique
  4. 2R rel software

- **Curbvious Technology**
  1. Typical size, shape and material used for the curb
  2. Reported and established properties, design mix proportions of pervious concrete
<table>
<thead>
<tr>
<th>Authors</th>
<th>Country/States</th>
<th>Inlet tested</th>
<th>Investigation mode</th>
<th>Inlet Efficiency/Capacity</th>
<th>Inlet Characteristics/Behaviour/Pattern</th>
<th>Inlet Design Curve/Equation</th>
<th>Numerical model</th>
</tr>
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<tbody>
<tr>
<td>Bauer &amp; Woo (1964)</td>
<td>Colorado, US</td>
<td>Curb-opening</td>
<td>Experimental</td>
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<td>Lehigh, US</td>
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<td>Singapore</td>
<td>Grate &amp; combination</td>
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<td>✓</td>
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<td>Catalonia, Spain</td>
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<td>Barcelona, Spain</td>
<td>Grate</td>
<td>Experimental &amp; Numerical</td>
<td>-</td>
<td>✓</td>
<td>✓</td>
<td>-</td>
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<tr>
<td>Beg et al. (2016)</td>
<td>Portugal</td>
<td>Grate</td>
<td>Experimental &amp; Numerical</td>
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<td>✓</td>
<td>✓</td>
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<td>Hammond &amp; Holley (1995), Qian et al. (2013), Schalla (2017)</td>
<td>Austin, Texas</td>
<td>Curb-opening</td>
<td>Experimental</td>
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<td>-</td>
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<td>✓</td>
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</tbody>
</table>

Inlet tested: Grate/Curb/Combination inlets
Country: US, UK, Spain, China, Singapore
Investigation mode: Experimental/Field/Numerical
Type of findings:
1. Inlet design curve/equation
2. Inlet efficiency/capacity
3. Inlet behavior/characteristics/flow pattern
4. Numerical model
Most of the previous research focused on improving the design of street inlet (dimensions & geometry), increasing the number of inlet and inlet spacing (Gomez et al., 2016).

No research introduced the application of pervious concrete on street curb. Pervious concrete = high porosity, allowing water to infiltrate through it (Abdel-Aziz et al., 2015).

Widely used for pervious street pavements applications (Gupta, 2014), however it is challenging to implement – lack of expertise, insufficient information and costly (Harvey & Smith, 2018).

Research Gap
a) No report on Malaysian inlets efficiency
b) No study presents reliability assessment of street inlet
c) No work on pervious concrete curb
RESEARCH METHODOLOGY

Start

Design Experimental Set Up Half Roadway Model

Experimental Testing

Hydraulic Performance Analysis on Street Inlet

Reliability & Sensitivity Analysis on Street Inlet

Hydraulic Performance Analysis on Pervious Curb

End

PART A

PART B

PART C

Design New Infiltration Rate Testing

Design New Pervious Concrete Curb
Part A: Experimental Investigation on Street Inlets

Halfway Road Model (Design As Per JKR Standard)

- $S_o = 0.5\%$
- $S_x = 2.5\%$
- $S_w = 4\%$

- $Q_a =$ Approaching flow
- $Q_i =$ Intercepted flow
- $Q_b =$ Bypass flow

- Roadway Flume
- Ratio 1:1
- Supply Tank
- Bypass Tank
- Collection Tank

Grate inlet

- Grate 1
- Grate 2
- Grate 3

Curb opening inlet

- Curb 1
- Curb 2
- Curbs 3 & 4
Part A: Experimental Investigation on Street Inlets

1. Approaching flow (Inflow)
   \[ Q_a = C_d \frac{2}{3} \sqrt[3]{2gLH^2} \]

2. Intercepted & Bypass flows (Outflows)
   \[ Q_i=Q_b = C_d \frac{8}{15} \tan \frac{\theta}{2} \sqrt[5]{2gH^2} \]

3. Efficiency
   \[ \eta = \frac{Q_i}{Q_a} \times 100\% \]

4. Other measurement
   Water depth, water spread, velocity,
Part B: Reliability Assessment of Street Inlet

Limit State Function

\[ Z = R - S \]

where, \( R \) is strength/resistance to failure & \( S \) is load or known as that which is conducive to failure

Developed Limit State Function

\[ Z = Q_i(\text{theory}) - Q_i(\text{measured}) \]

LSF grate inlet: 

\[ Z = C_wPD^{1.5} - C_d \frac{8}{15} \tan \frac{\theta}{2} \sqrt{2gH^{5/2}} \]

LSF undepressed curb-opening inlet: 

\[ Z = C_wLd^{1.5} - C_d \frac{8}{15} \tan \frac{\theta}{2} \sqrt{2gH^{5/2}} \]

LSF depressed curb-opening inlet: 

\[ Z = C_w(L + 1.8W)d^{1.5} - C_d \frac{8}{15} \tan \frac{\theta}{2} \sqrt{2gH^{5/2}} \]

Solve LSF model using Monte Carlo Simulation (MCS) Techniques

Probability of failure
Part C: Development and Experimental Investigation of a New Pervious Concrete Curb (*Curbvious*)

Mixture proportions of pervious concrete (*¹*Liu et al. (2018), ²*Gesogslu et al. (2014))

<table>
<thead>
<tr>
<th>Mix</th>
<th>OPC</th>
<th>Water</th>
<th>Coarse agg.</th>
<th>Fine agg.</th>
<th>SP</th>
<th>FCR</th>
<th>CCR</th>
</tr>
</thead>
<tbody>
<tr>
<td>¹A</td>
<td>480</td>
<td>144</td>
<td>1503</td>
<td>0</td>
<td>3.84</td>
<td>9.6</td>
<td>0</td>
</tr>
<tr>
<td>¹B</td>
<td>480</td>
<td>144</td>
<td>1503</td>
<td>0</td>
<td>3.84</td>
<td>0</td>
<td>9.6</td>
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<tr>
<td>²C</td>
<td>450</td>
<td>121.5</td>
<td>1434.6</td>
<td>0</td>
<td>0</td>
<td>28.1</td>
<td>0</td>
</tr>
<tr>
<td>¹D</td>
<td>480</td>
<td>144</td>
<td>1503</td>
<td>9.6</td>
<td>3.84</td>
<td>0</td>
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<td>¹E</td>
<td>450</td>
<td>121.5</td>
<td>1434.6</td>
<td>28.1</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

*Mix with the highest infiltration rate was selected for Curbvious application*

Newly designed infiltration rate testing device
RESULTS & DISCUSSION

Part A: Hydraulic performance of grate & curb-opening inlets

Part B: Reliability assessment of grate & curb-opening inlets

Part C: Hydraulic performance of Curbvious
Part A: Hydraulic performance of grate & curb-opening inlets

Graph of approaching flow against efficiency for grate inlets
Part A: Hydraulic performance of grate & curb-opening inlets

Graph of approaching flow against efficiency for curb-opening inlets
**Part A: Hydraulic performance of grate & curb-opening inlets**

<table>
<thead>
<tr>
<th>Inlet type</th>
<th>Range of efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grate 1</td>
<td>51 – 90</td>
</tr>
<tr>
<td>Grate 2</td>
<td>44 – 88</td>
</tr>
<tr>
<td>Grate 3</td>
<td>46 – 89</td>
</tr>
<tr>
<td>Curb 1 (undepressed)</td>
<td>37 – 78</td>
</tr>
<tr>
<td>Curb 2 (undepressed)</td>
<td>46 – 73</td>
</tr>
<tr>
<td>Curb 3 (depressed)</td>
<td>51 – 84</td>
</tr>
<tr>
<td>Curb 4 (depressed)</td>
<td>54 – 84</td>
</tr>
</tbody>
</table>

(a) Efficiency of grate inlets

Overall range of efficiency: **44 – 90 %**

Grate 1 ➔ Grate 3 ➔ Grate 2

(b) Efficiency of curb-opening inlets

Overall range of efficiency: **37 – 84 %**

Curb 4 ➔ Curb 3 ➔ Curb 2 ➔ Curb 1

The grate inlet proves to have higher efficiency as compared to curb-opening inlet.
Part B: Reliability assessment of grate & curb-opening inlets

1. The higher the approaching flows, the higher the tendency inlet towards failure.

2. $P_f$ of grate inlets: 0.00001($10^{-5}$) to 0.1($10^{-1}$)

3. $P_f$ of curb-opening inlets: 0.00001($10^{-5}$) to 0.1($10^{-0}$)

4. Ranking of failure

   Grate 2  ➔  Grate 3  ➔  Grate 1

   Curb 1  ➔  Curb 2  ➔  Curb 3  ➔  Curb 4
### Part C: Hydraulic performance of *Curbvious*

#### Average infiltration rate for each pervious concrete mix design

<table>
<thead>
<tr>
<th>Mix</th>
<th>Infiltration rate on side surface of pervious concrete (l/m²/min)</th>
<th>Avg. Infiltration Rate of a Pervious Concrete (l/m²/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Side 1</td>
<td>Side 2</td>
</tr>
<tr>
<td>A</td>
<td>1089</td>
<td>1078</td>
</tr>
<tr>
<td>B</td>
<td>1780</td>
<td>2218</td>
</tr>
<tr>
<td>C</td>
<td>1214</td>
<td>1214</td>
</tr>
<tr>
<td>D</td>
<td>1653</td>
<td>1991</td>
</tr>
<tr>
<td>E</td>
<td>1954</td>
<td>1724</td>
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</table>

#### Infiltration Performance

1. Mix D is the most appropriate to be applied on *Curbvious*

2. Avg. Infiltration rate Mix D = 1864 l/m²/min

3. Total % of max. infiltration flow net area (%) of Mix D = 76.54%
Part C: Hydraulic performance of *Curbvious*

Despite being red, Mars is a cold place. Venus has a beautiful name, but it’s terribly hot. Neptune is the farthest planet from the Sun.

Range of efficiency of grate inlets with and without *Curbvious* at moderate flow conditions

<table>
<thead>
<tr>
<th>Type</th>
<th>Efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grate 1</td>
<td>51 – 90</td>
</tr>
<tr>
<td>Grate 2</td>
<td>44 – 88</td>
</tr>
<tr>
<td>Grate 3</td>
<td>46 – 89</td>
</tr>
<tr>
<td>Grate 1 with <em>Curbvious</em></td>
<td>68 – 95</td>
</tr>
<tr>
<td>Grate 2 with <em>Curbvious</em></td>
<td>65 – 91</td>
</tr>
<tr>
<td>Grate 3 with <em>Curbvious</em></td>
<td>69 – 93</td>
</tr>
<tr>
<td><em>Curbvious</em></td>
<td>11 – 27</td>
</tr>
</tbody>
</table>

Graph approaching flow against efficiency *Curbvious* with and without grate inlets.
CONCLUSION

1. Efficiency of street inlet decreases as the approaching flow increases.

2. Grate inlet has higher efficiency than curb-opening inlet.

3. Overall range of efficiency grate inlets 44-90%, curb-opening inlets 37-84%.

4. Reliability model of grate and curb-opening inlets

\[ Z = Q_i(\text{theory}) - Q_i(\text{measured}) \]

5. Probability of failure of street inlet gradually increases with the increase of approaching flows on the street.

CONTRIBUTIONS

1. **NEW** street inlet design guidelines

2. Stormwater drainage system **ENHANCEMENT** through Curbvious

1st curb fabricated using pervious concrete

Curbvious efficiency was **within 11 to 27%**

Dual functions:
1. Road furniture
2. Drain excess storm water
RESEARCH ACHIEVEMENT

**Paper Publications**
2. Probabilistic Assessment for the Capacity of Grate and Curb-Opening Inlets During Floods [ASCE Journal Published in J. Irrig. Drain. Eng. (Q2)]
3. Infiltration Rate of Pervious Concrete on Street Curb Application [Status: Published in Int. J. Recent Technol. & Eng. (Q4)]
4. Efficiency of Simple Curb Inlet Design in Malaysia [Status: Published in IOP Conf. Ser. Earth Environ. Sci.]

**Intellectual Property**
1. Curbvious Design Concrete Material (Class 25-01), Filling ID: 19-00381-0101/
2. Infiltration Rate Testing (Class 10 – 04), Filling ID: 19 – E0018 – 0101 / -
3. New Infiltration Rate Test for Lateral Flows in Pervious Concrete, Filling ID LY2019003391/-
4. Curbvious Trademark – Status: Submitted

**New Pervious Concrete Curb (Curbvious) Awards**
1. Gold Medal, 30th International Invention, Innovation and Technology Exhibition (ITEX 2019)
2. Best Invention in Design for Japan Intellectual Property Association Award, 30th International Invention, Innovation and Technology Exhibition (ITEX 2019)
5. Silver Medal, International Eureka Innovation Exhibition (i-EiE 2019)
6. Bronze medal, Malaysia Technology Expo (MTE 2020)
THANK YOU