Preliminary studies of the development of a clogging prediction method for stormwater infiltration systems

N.R. Siriwardene A. Deletic, T.D. Fletcher

Institute for Sustainable Water Resources, Building 60, Department of Civil Engineering, Monash University, VIC 3800, Australia.
(E-mail: nilmini.siriwardene@eng.monash.edu.au)

Abstract

Infiltration systems have become a popular approach to managing stormwater. However, a high incidence of failure due to clogging has been found in these systems. A study has thus been undertaken to develop a fundamental understanding of the clogging processes, by conducting one dimensional (1D-Rig) and two dimensional (2D-Rig) laboratory experiments, and based on this knowledge, to develop a new method for clogging prediction. So far, constant and fluctuating stormwater level flow regimes in the systems have been studied. This paper presents the methods and compares the results of 1D and 2D rig constant water level experiments. It was found that a clogging layer was formed at the interface between the filter and underlying soil, irrespective of sediment distribution within the filter. It was also found that the very fine sediments were enough to clog the system.

Keywords

Infiltration systems, physical clogging, stormwater, sediments, filter media

INTRODUCTION

Stormwater infiltration systems are basically holes in the ground filled with filter material such as gravel or porous soil, usually wrapped in geotextile. Examples of these systems include infiltration basins, trenches, soakaways, leaky wells and porous pavements. These systems divert urban stormwater away from the surface runoff path, acting to temporarily store and then infiltrate it into the surrounding soils. They help to restore the pre-development hydrology, as they perform as pervious surfaces. Therefore, they have become a very popular approach to manage stormwater. One of the main advantages of stormwater infiltration trenches/soakaways is that they are suitable for areas with limited land availability.

In contrast, there are some limitations in implementing these systems, namely the suitability of surrounding soils and distance to the groundwater level. In addition, there are other disadvantages in these systems, namely potential for soil and groundwater pollution (Mikkelsen et al., 1997) and possible superstructure damage due to the presence of the water in the soil (Alfakih et al., 1999). However, the biggest disadvantage of these systems is the possible failure of the system due to clogging (Galli, 1992; Nozi et al., 1999; Raimbault et al., 1999; Warnaars et al., 1999). Lindsey et al. (1992) conducted a field survey of infiltration systems in Maryland, USA in 1986 (207 systems in 18 cities, most of which were 2 years old) and then again in 1990 (177 systems) and found that the conditions of systems declined significantly during the intervening four years. They reported that 33% of the systems were not functioning as designed in 1986. By 1990, the failure rate had increased to 50%. Infiltration trenches were reported as having the highest failure rate of the systems examined.

Clogging is a process that develops in these systems over time, due to the deposit of sediments from the stormwater. Although clogging has been studied for several decades for other systems such as sand filters (Reddi et al., 2000), recharge basins (Goodrich et al., 1990) and injection wells (Rinck-Pfeiffer et al., 2000), stormwater infiltration through infiltration systems has not been extensively considered. The studies published are on very small scale investigations and are inconclusive (Pokrajac & Deletic, 2002; Raimbault et al., 1999).
It is very important to understand the nature of clogging process in stormwater infiltration systems, whether it is biological, physical, chemical or a combination of all three. Clogging is defined as the processes of reducing porosity and permeability and hence decreasing the infiltration rate of the system due to physical, biological and chemical processes (Bouwer, 2002). A previous field experiment study of well clogging using urban stormwater identified physical clogging as the cause of clogging in their system (Pavelic et al., 1998). This may be due to the presence of high sediment concentrations, and low organic matter content in the stormwater. Another study of stormwater aquifer storage and recovery systems with injecting wells showed physical clogging to be the primary process (Rinck-Pfeiffer et al., 2000). So far, the laboratory studies (Pokrajac & Deletic, 2002) of stormwater infiltration systems have focused on physical clogging processes. Therefore it was decided to focus in the first instance on the physical clogging in stormwater infiltration systems. The study will investigate the importance of the biological clogging in the near future.

The main aim of the project is to investigate the clogging process of stormwater infiltration systems, and based on this knowledge, to develop a new, reliable and robust model for sediment transport and clogging prediction. This paper presents the methods and some of the results of the preliminary laboratory studies.

METHOD
The following laboratory programs are being conducted:

• One dimensional laboratory experiments (1D Rig) have been conducted in order to investigate the transport of sediment particles in stormwater through the filter media, by simulating a typical infiltration system. During these experiments several factors such as stormwater inflow rate, constant and fluctuating water levels were varied. Typical soils investigated were sandy soil, and sandy loam soil, while crushed stones were used as the initial infiltration media.
• Two dimensional laboratory experiments (2D Rig) have been conducted in order to investigate clogging in a typical two dimensional flow regime.

1D experiment
A 1D rig was built from several mountable perspex segments, each having 19 cm internal diameter and 20 cm or 10 cm height as shown in Figure 1. Perforated small tubes wrapped in geotextile were placed inside each segment to allow water sampling and pressure monitoring. Pressure sensors were attached to the end of these tubes. The typical height of the crushed stone (filter) layer used was 90 cm and soil layer used was 70 cm. A tipping bucket rain gauge was used to monitor the system outflow. Artificial stormwater was prepared in the water tank to represent the characteristics of typical urban stormwater by mixing sediments less than 300µm (collected from a stormwater retarding basin) and tap water. Air was injected from the bottom of the water tank to keep sediment concentrations uniformly mixed within the tank. Inflow from the water tank to the rig (i.e. the pump) was controlled by a computer.

At the start of each experiment the soil layer was saturated with clean water. Then for 2 to 5 days, the clean water inflow was introduced to the rig from the top continuously through a sprinkler system before introducing artificial stormwater, which was applied until the system was clogged. Water samples were collected from the inflow and along the filter layer to analyse for total suspended solids (TSS) and for particle size distribution (usually 2-3 times a week). Outflow rate and pressures were recorded, while the pump was automatically operated to keep the water level in the stones as prescribed. Each experiment was run until the outflow rate was reduced to 10% of its
initial value. The column was then carefully dismantled and sediments trapped along the filter were measured for each segment separately.

The water samples collected from the inflow and along the filter (i.e. 0m - inflow, 0.3m, 0.5m, 0.7m and 0.85m -just above interface) were analysed to determine the sediment particles’ contribution to the clogging layer. A Malvern particle size sampler was used to analyse the particle size distribution of the sediments and TSS was also analysed separately. Sediment particles were classified under five categories, namely clay (< 2 µm), fine silt (2-6 µm), medium silt (6-20 µm), coarse silt (20-63 µm) and fine/medium sand (63-300 µm).

2D experiment
A 2D rig was built from several mountable perspex segments (each segment of 0.35m height and 2.1m long, Figure 2.) A trench of 0.5m length x 0.8m height x 0.25m width was built in the corner of the rig, from the same crushed stones that were used in 1D experiment. To achieve steady state flow conditions, clean water was introduced continuously to the crushed stones for between two and four weeks. 10 pressure sensors and 6 transducers for monitoring water content around the trench were installed. The system was operated in a similar manner to the 1D Rig.

RESULTS AND DISCUSSION

1D experiments
So far, 9 experiments have been carried out successfully and clogging occurred within 2-6 weeks. They were carried out with two flow regimes, namely constant and fluctuating water levels. The experimental details of the 1D rig experiment are presented in Table 1.

The experiments have confirmed that the clogging occurred on the interface between the stones and the soil, as reported earlier (Siriwardene et al., 2005). The relative hydraulic conductivity of the clogging layer, $k/k_0$ (where $k$ is the hydraulic conductivity at the time of measurements and $k_0$ is the initial hydraulic conductivity before sediment was introduced) versus the number of pore volumes of stormwater introduced into the column is presented in Figure 3, for the constant water level experiments (CWL). From this graph it is clear that hydraulic conductivity decreased continuously with the volume of stormwater introduced into the system. Similar results were obtained with fluctuating water levels experiments, except that clogging was achieved with much lower volumes of introduced stormwater (Siriwardene et al., 2005).
Table 1. Experimental details

<table>
<thead>
<tr>
<th>Type</th>
<th>Constant water levels - CWL</th>
<th>Fluctuating water levels</th>
</tr>
</thead>
<tbody>
<tr>
<td>Name</td>
<td>E1</td>
<td>E2</td>
</tr>
<tr>
<td>Water level above soil (cm)</td>
<td>45</td>
<td>45</td>
</tr>
<tr>
<td>Initial soil hydraulic conductivity (k_0) (\times 10^{-5}) m/s</td>
<td>0.8</td>
<td>3.25</td>
</tr>
<tr>
<td>Initial Q ((\text{cm}^3/\text{s}))</td>
<td>0.4</td>
<td>1.5</td>
</tr>
<tr>
<td>Final Q ((\text{cm}^3/\text{s}))</td>
<td>0.04</td>
<td>0.41</td>
</tr>
<tr>
<td>Duration (Days)</td>
<td>15</td>
<td>35</td>
</tr>
</tbody>
</table>

In the CWL experiments, most of the sediments were deposited around the water level, as shown in Figure 4 (which presents the distribution of sediment in the column after clogging occurred). This could suggest that where the infiltration system does not empty completely between wetting cycles, the sediment accumulates mainly around the minimum water level of the system.

Figure 3. Relative \(k/k_0\) vs. Number of pore volumes introduced for CWL

The degree of clogging was also expressed as hydraulic resistance, \(R = l_c/k_c\) (\(l_c\) and \(k_c\) are the thickness and the hydraulic conductivity of the clogging layer respectively). Figure 5 and 6 show the relative hydraulic conductivity \((k/k_0)\) and relative hydraulic resistance \((R/R_0\), where \(R_0\) is initial hydraulic resistance) versus inflow cumulative mass of sediment respectively. It is clear that the hydraulic conductivity decreased and hydraulic resistance increased with an increase of inflow sediment mass. However, the water level in the column made a big impact on the speed of clogging; the experiment with the constant 5 cm of water in the stones clogged much faster than experiments with 45 cm, while the experiment with 75 cm of water experienced very slow clogging. It appears that the ‘plug’ of sediment which forms at the constant water level acts to reduce the accumulation of sediment in the clogging layer that normally forms at the interface of the infiltration media and the underlying soil.

Figure 4. Filter height vs. sediment density for CWL

The E2 and E11 experiments were conducted with the same constant water level (ie. 45cm), but two different inflow sediment concentrations; 141 mg/L and 85 mg/L, respectively. From Figures 5 and 6 it is clear that clogging occurred at a similar total mass of sediment introduced in both cases. Figure 7 shows the inflow cumulative sediment mass of sediments versus the water volumes pass through the system for CWL experiments. It is clear from Figure 7 that double the amount of stormwater had to pass through the system in E11 compared to E2. This suggests that the sediment mass introduced, not the volume of water, is the main factor determining system clogging.
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Figure 5. Relative k vs. Inflow cumulative mass of sediment for CWL

Figure 6. Relative k vs. Inflow cumulative mass of sediment for CWL

Figure 7. Inflow cumulative mass of sediment vs. Inflow cumulative water volume

Graphs in Figure 8 (a), (b), (c) and (d) represent the concentration depth profiles for the clay, fine silt, medium silt and coarse silt respectively over time for experiment E10 (each graph shows the particle size concentrations along the filter depth for different days throughout the experiment).

Figure 8 Filter depth vs. Sediment concentration
It is clear from Figure 8(a) that almost all the clay particles reached the interface. The fine and medium silt particles also contributed to the clogging layer creation. However, particle greater than 20µm did not reach the interface and hence did not contribute to the clogging.

**2D experiments**

So far, only two 2D experiments have been conducted, one with fluctuating water levels (2D-E1) and one with a 75cm continuous constant water level (2D-E2).

The relative hydraulic conductivity versus number of pore volume for 2D-E2 is presented in Figure 9. Similar to the 1D Rig experiment results, the hydraulic conductivity decreased with the increase of stormwater volume that passed through the system. Similar to the 1D experiments, the sediment was accumulated around the CWL, forming a plug (Figure 10), as well as the formation of a clogging layer at the interface, irrespective of the sediment distribution within the filter.

![Figure 9. Relative hydraulic conductivity vs. Number of pore volumes](image1)

![Figure 10. Filter height vs. sediment density](image2)

The water samples collected along the filter were also analysed as per the 1D Rig experiments, to determine the sediment particles’ contribution to the clogging layer. Figure 11 shows the filter depth versus sediment concentration for experiment 2D-E2. Similar to the 1D CWL experiments, the particles greater then 20µm did not contribute to clogging of the system. Therefore, it can be concluded that the sediments less than 20µm are primarily causing the system clogging.

It should be noted that the 2D-E2 was conducted with only 62 mg/L of sediment in the inflow and had a much finer particle size distribution than in other experiments (see Figure 8 and Figure 11). It is important to note that the system was clogged faster (i.e. 21 days) in 2D-E2 compared to 1D-E10 (i.e. 43 days), despite the fact that less sediment was introduced in the system. This could be due to the presence of more fine sediment in the stormwater. It could suggest that the trapping efficiency of fines were decreased in 2D-E2 due to the presence of less coarse particles, which were formed around the constant water levels. This indicates that the amount of fine particles (less than 20µm) present in the stormwater is a crucial factor for infiltration system clogging.

The next stage is to develop a physically based model using these results (and those from future experiments), to simulate the physical clogging of traditional stormwater infiltration systems. For modelling of the hydraulic conductivity of the clogging layer, the initial approach will be to test the data collected during 1D experiments by using an established method (Reddi et al., 2000), developed for sand filters based on the Kozeny model (Leonard, 1962). To derive the Kozeny model, porous medium was represented as a series of capillary tubes and basic principles of flow in cylindrical tubes were used.
CONCLUSIONS

One and two-dimensional laboratory experiments showed that the performance of infiltration systems could fail easily by the formation of a clogging layer at the infiltration media/soil interface. However, it appears that the degree of clogging of the system depends mostly on the amount of fine sediment particles present in the stormwater. The experiments have shown that the sediment particles less than 20 µm are the main driver in the development of the clogging layer and hence causing system failure. The preliminary 2D experiments show the same trends observed in 1D clogging experiments apply for 2D flows, giving confidence to the results.

Although a design criterion is to make these systems fully empty between storm events, it was found that the systems which have some permanent pool level (a permanent water at the bottom of the trench) could help to delay the clogging process, as most of the sediments tend to accumulate around these water levels, thus delaying the formation of the ultimate clogging layer at the interface of the infiltration media and the underlying soil. Future work will use the presented results to test some of the clogging models that have been used for prediction of clogging in sand filters.

REFERENCES


