Exploring the effects of geotextiles in the performance of highway filter drains

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Abstract

Highway Filter Drains (HFD) are one of the most utilised drainage systems for roads, being considered as an environmental solution for sustainable drainage in transport infrastructures. However, little research has been done to understand their performance, representing a significant knowledge gap. This article therefore determines the hydraulic and clogging response of 3 different HFD designs in the laboratory; one standard design with British Standard Type B aggregate, and 2 new designs including a geotextile located at 50 mm and 500 mm depth from the surface of the HFD structure in order to assess the effect of the geotextile. The laboratory models were initially subjected to 9 rainfall scenarios with 3 rainfall intensities (2.5, 5 and 10 mm/h) and 3 storm durations (5, 10 and 15 minutes). Subsequently, the equivalent of 2-years' worth of pollutants were added to test possible clogging issues under the highest intensity rainfall event, corresponding to a 1 in 1 year return period for the West Midlands, UK. No clogging issues were found in any of the models although the majority of the sediments were concentrated in the first 50 mm of the HFD profile, with higher percentages (>90% of the sediment added) in those models with an upper geotextile. Location of the geotextile significantly influenced (p-value = 0.05) the hydraulic performance of the HFD.

Keywords: Geosynthetics; Clogging; Geotextile; Highway Filter Drains; Road Safety; Sustainable Drainage Systems (SuDS).

1. Introduction

Vehicle traffic in the UK has increased dramatically since the 1950s to more than 300 billion vehicle miles in 2014 (UK Department of Transport, 2015). To cope with this high volume of traffic, the UK has a road network of nearly 1.8 km road/km^2 of land area with a total length of 419,596 km, of which 3,674 km are motorways and 49,040 km are main roads (Nicodeme et al. 2013).

The Strategic Road Network (SRN) (including motorways and A roads) (UK Department for Transport, 2012) and local road networks are England's most valuable infrastructure asset, valued at approximately £344 billion and as well as the roads, includes other infrastructure such as bridges, embankments and drainage systems (House of Commons, 2014). In 2012-2013 public spending on maintaining England's roads was £4 billion, divided between the UK Department of Transport, the Highways Agency (Highways England since 2015) and Local Authorities. The operation, maintenance and improvement of the SRN, which represents 2% of the total road network (7,080 km), is the responsibility of The Department of Transport through Highways England (House of Commons, 2014).

Road drainage systems are therefore a vital asset in transport infrastructure, contributing to the safety of road users by removing surface runoff, improving visibility and mitigating environmental problems to receiving waters. Hence, they are an important part of the maintenance programme developed by Highways England (Ellis and Rowlands, 2007; Coupe et al. 2015).

Filter Drains (FD), kerbs and gullies connected to pipes below ground and surface water channels along the pavement edge, are the main methods of dealing with surface runoff (DMRB-UK, 1997a). FD, also known as 'French Drains', are not only one of the most used drainage systems in the UK, but are also an historically important engineering technique across the world. FDs when used on highways are defined as Highway FD or HFD, terminology which will be used hereinafter. Approximately 50% of the SRN in England (in total about 7,000 km accounting for traffic flow in both directions) uses HFD as their main drainage technique (Coupe et al. 2015).

HFD are designed to cope with a wide range of storm events, to avoid flooding problems. Thus, the Design Manual for Roads and Bridges (DMRB-UK, 2004), Volume 4 Section 2 (Drainage), stipulates that highway drainage systems should be designed for high intensity events over a few minutes (short durations) with return periods of 1 year (with no surcharge of piped systems or road-edge channels) or 5 years with no flooding on the carriageway.

According to DMRB-UK, 1997b, UK HFDs should be a minimum of 0.6 m below the pavement sub-base in order to prevent groundwater entering the pavement structure. Including the full depth of the road structure, the typical depth for an HFD is up to 1 m with a width of approximately 1 m (Figure 1).

A perforated pipe is located at a depth of 850 mm in a full-sized HFD, details and recommendations such as its diameter, the type of aggregate used for the bedding layer and the main body of the HFD are all given in the Design Manual for Roads and Bridges (DMRB-UK, 2001) and the UK Highways Agency Manual of Contract Documents for Highway Works (MCDH) (2009).

After a long operational life, often 30 to 40 years of service, some HFD may need maintenance and in order to judge this, their performance is monitored using high-speed non-intrusive Ground Penetrating Radar (GPR) surveys, specifically SMARTscan both on verges and central reservations (Carnell, 2015). However, there is a lack of comprehensive understanding of the hydraulic processes that take place in HFDs and how resistant and resilient they are to flooding and clogging.

The impact of this research is wider than just the UK as HFD are used in other countries across the world such as the Republic of Ireland where a visual inspection carried by Bruen et al. (2006) on the Irish dual carriageways and motorways found that more than 40% of them had HFD as their main drainage system. Also in Ireland, issues around clogging have been commonly addressed by the use of a geotextile as a barrier to fine material ingress (Bruen et al. 2006; Desta et al. 2007) whilst still allowing water to flow through and into the drainage material and pipe. Other international drainage techniques similar to HFD also use geotextiles such as the so-called “edge drains” in the U.S.A (Kearns, 1992; Koerner et al., 1996) and Canada (Raymond et al. 2000); and also in Spain (Castro-Fresno et al. 2013; Andres-Valeri et al. 2014; Sañudo Fontaneda et al. 2016) where there are specifications including the use of geosynthetic products in drainage structures (AENOR, 2001; Bustos et al. 2007).

Despite the fact that geosynthetics have been included successfully in the structure of other SuDS such as Permeable Pavement Systems (PPS) in the UK (e.g. Pratt et al. 1999), their utilisation in association with HFDs is still viewed with scepticism by some engineers due to concerns over possible blockage of the aggregate layer and/or the pipe, leading to a reduction in infiltration capacity. In order to address these issues, there were 2 aims of this research:

1. To determine the effects on HFD hydraulic performance of the inclusion of geotextiles due to its water retention characteristic (WRC). This concept is described by Chinkulkijniwat et al. (2017), who also highlight the lack of knowledge of geotextile WRC.
2. To determine the influence of the geotextile on the potential for clogging for short return periods.

2. Materials and Methods

2.1. Experimental preparation and materials

Ten plate-glass rigs were set up: 4 replicates of the Standard HFD, and three replicates for each HFD model containing geotextiles at 2 different depths in the profile (50 mm and 500 mm respectively). The rigs had 5 mm thick walls and measured 215 mm x 215 mm x 650 mm, thus their volume was 0.030 m^3 and surface area was 0.046 m^2 (see Figure 2). No lower pipe was used, since the aim was to analyse the hydraulic and clogging performance of the aggregate and to isolate the influence of the geotextile layer on the general performance of the HFD, following the preparation method presented in Sañudo-Fontaneda et al. (2017). The outflow, used to build the hydrographs of performance for every HFD model, was measured using funnels placed at the bottom of each plate-glass rig to direct the outflow to a sample collector (see Figure 2).

The details of the materials used to replicate the three different HFD designs, as shown in Figure 2, are presented below:

1. Standard HFD. Made of Type B aggregate (see Figure 2).
2. HFD + Lower Geotextile. As in the Standard HFD plus a geotextile layer at 500 mm depth from the HFD surface and 50 mm from the base (see Figure 3).
3. HFD + Upper Geotextile. As in the Standard HFD above plus a geotextile layer at 50 mm depth from the surface (see Figure 3).

The aggregate utilised in this study was that normally used in UK HFD installations and was 20-40 mm, G_c 85/20, clean Granodiorite Type B. A type B aggregate Particle Size Distribution (PSD) is presented in Figure 2, complying with MCDH, 2009 and BS EN 13242 requirements (BSI, 2006).

The geotextile was a nonwoven fabric of virgin polypropylene fibres, with an approximate mass per unit area of 0.13 Kg/m^2. Nonwoven geotextiles have been widely used in roadworks and drainage due to their supporting ability and improvement to the internal drainage of the aggregate layers (Sañudo Fontaneda et al. 2016; Broda et al. 2017; Portelinha and Zornberg, 2017). This geotextile has been used previously in research for example the TRAMMEL drainage system (Clapham, 1981; Ingold, 1994). It is also one of the most widely used geosynthetics in Sustainable Drainage Systems (SuDS), especially PPS because of its well-known pollutant removal efficiency in providing a suitable surface for trapping oil and allowing microorganisms to grow (Newman et al. 2002; Coupe et al. 2003; Gomez-Ullate et al. 2010; Sañudo-Fontaneda et al. 2014b). The hydraulic properties of the geotextile are given in Table 1.

This geotextile was also selected for its mechanical properties in terms of structural performance as it was to be used at different depths in the HFD test rigs, and would therefore be subjected to different forces (Table 2). The pressure generated by the weight of the aggregates perpendicular to the surface of the geotextile would be 8.5 Pa in the case of a geotextile placed at 50 mm depth of the full scale HFD, and 85 Pa at 500 mm depth, with a bulk density of 1.7 t/m^3.

A rainfall/runoff simulator was specifically designed and built for the project (see Figure 3) and had the following characteristics:

- Intensity range for direct rainfall: 50-400 mm/h.
- Surface: 0.0441 m^2 (0.21 m x 0.21 m).
- Number of drippers: 9 (3 per row, total of 3 rows)
- Drop diameter: 3.5 mm.

Flow was controlled in real time with a flowmeter on the water delivery pipe (see Figure 3), which controlled rainfall intensity to between 50-400 mm/h as required.

2.2. Experimental methodology

There were 2 main stages:

Stage 1. Hydraulic characterization of HFD performance was carried out by simulating flow produced by three rainfall intensities (2.5, 5 and 10 mm/h) raining over a draining area consisting of 2 carriageways and a hard-shoulder (Table 3) and three storm durations (5, 10 and 15 minutes), resulting in 9 different storm scenarios. The 1 in 1 year storm required for design of HFD by the DRMB (2004) was the highest rainfall event simulated at this stage 1 (10 mm/h) and the longest storm duration (15 minutes). A total of 90 tests were carried out, 10 runs of each storm scenario, producing a total of 2,026 infiltration rate data points (outflow measured per minute on each rig and each test). The Rational Method is suggested for SuDS (Woods Ballard et al. 2015), therefore calculations were undertaken to determine the relationship between rainfall intensities and the flow entering the models as a result of the surface runoff produced by these storm events. Two and 3 carriageways are the most common number of lanes used on UK roads; this was the justification for their use in calculating runoff flows (DMRB-UK, 1999).

Basing the calculations on the Rational Method, laboratory rainfall events of 100, 200 and 400 mm/h (intensity values which will be used hereinafter for the analysis of the laboratory results) controlled by the flowmeter connected to the rainfall/runoff simulator (see Figure 3) were generated over the surface of the laboratory models (0.046 m^2 surface area) in order to accomplish the rainfall scenarios and runoff flows represented on Table 3.

Stage 2. Pollutants were periodically added to the rigs once Stage 1 was completed in order to simulate 2 years in-use of the HFD models, each rig was therefore subjected to the following conditions in terms of pollutant addition:

- Amount of sediment: 30 g/rig/test (i.e. 360 g added to each rig in total over the course of the experiments) just before the addition of oil, representing sediment deposited on West Midland, UK highways of approximately 1,000 kg/m/year (Carnell Group Ltd., *pers comm*). The sediment was obtained from arisings collected from gully pots connected to HFD pipes from a highway in the West Midlands, UK. For each rig, 12 rainfall events of 10 mm/h raining over a drainage area consisting of 2 carriageways and a hard-shoulder of 15 minutes' duration (replicating the worst case scenario); a total of 120 tests were carried out, producing a total of 2,739 infiltration measurements (outflow measured per minute for each test). The intensity and storm duration used represented a 1 in 1-year storm event in the West Midlands (UK) (Sañudo-Fontaneda et al. 2016), as required to avoid surcharge in the pipe by the DMRB-UK 2004. The West Midlands was used as the reference for calculations, both from the amount of sediments and the rainfall volumes, due to the fact that there will be field studies undertaken in the future which will use the laboratory studies as comparators. The reason for using 2 years' worth of sediments was based on previous studies carried out by Mitchell (2015) in Scotland which indicated 2 years until the start of clogging issues, both in the surface layer and the pipe at the bottom of the HFD.

  - Amount of oil: 6.121 g/rig/test (74.58 g of oil was added to each rig in total over the course of the experiments) was based on Gomez-Ullate et al. (2010), Sañudo-Fontaneda et al. (2014b) and Bayon et al. (2015) who multiplied the suggested 9.27 g/year/m^2 by Pratt et al. (1999) by 100 to represent a worst-case scenario such as a catastrophic oil spill from a car sump. The oil was a used part synthetic lubricating oil, mainly composed of high molecular weight fractions, with C21-C40 making up 99.03% of total petroleum hydrocarbons (TPH).

2.3. Experimental analyses

The effect of the inclusion of a geotextile layer on HFD performance was investigated using 2 main approaches:

- Hydraulic performance of the HFD designs
  - Hydrographs of performance. The hydrographs were plotted at minute intervals using the volume of outflow measured in the sample collectors (Figure 3) from each rig under the different rainfall scenarios and then comparing the influence of the addition or not of geotextiles and pollutants. The outflow represented the infiltration rate for the whole HFD system simulated in the laboratory.
- Attenuation performance. Attenuation is considered to be the retention of rainfall in the HFD structure before production of the first outflow discharge during a storm event since the beginning of the rainfall event simulated. This could be affected by the presence or absence of a geotextile and hence was used to provide an indication of HFD performance. This time represented the capacity of each HFD design to delay commencement of discharge flow, and also the time to reach peak-flow.
- Geotextile effect on the hydraulic and clogging performance of HFD. Once the hydraulic performance of HFD was analysed, the effect of the inclusion of a geotextile in the HFD structure was analysed in isolation, including the study of potential clogging scenarios derived from the presence of the geotextile, as it is shown below:

- Geotextile effect on the hydraulic performance of HFD. Statistical analyses were carried out in order to assess the influence of the geotextile on the attenuation levels used to measure the hydraulic performance in the HFD designs.
- Geotextile effect on the potential for clogging on HFD. The accumulation of pollutants at different levels within the HFD structure measured from the surface was analysed in order to determine where the sediments preferentially deposited within the HFD structure. Once all the hydraulic experiments were finished, the sediments were carefully recovered from the laboratory models and weighed. The trapping efficiency of each HFD design was measured by weighing the sediments accumulated in the whole model profile at the end of all experiments and comparing them with the amount of sediments added to the rigs.

3. Results and Discussions

3.1. Hydraulic performance of the HFD designs (hydrographs and attenuation levels)

3.1.1. Stage 1: Hydraulic performance of the HFD test rigs

Hydrographs of performance were produced for all storm durations (5, 10 and 15 minutes), including all HFD designs (no geotextile, lower geotextile and upper geotextile) and laboratory rainfall intensities (100, 200 and 400 mm/h). Figures 4, 5 and 6 show hydrographs for the 5-minute storm duration only as the trends for 10 and 15 minutes were similar.

Figures 5 and 6 show that, at the higher rainfall intensities (200 and 400 mm/h) the test rigs behaved in a similar manner. However, at 100 mm/h (Figure 4) there was more of a discrepancy between the rigs; those with an upper geotextile in particular exhibiting lower rates than the others, as well as longer delays in both the rising and falling limbs. Effluent took approximately 60 secs to be recorded after rainfall for the higher rainfall intensities, but did not appear until 102 seconds in the rigs rained on at 100 mm/h. As intensity increased, the time to base flow reduced, and again at 100 mm/h those rigs with the upper geotextile took longer than any of the other rigs regardless of structure or rainfall intensity.

Regardless of rig structure, Figure 7 shows that at the lower rainfall intensities peak flow was achieved at the same time, approximately 300 seconds. However, for the higher rainfall intensities, the structures behaved slightly differently, with all 3 taking less time to peak than at lower intensities. Those with no geotextile reached the peak more quickly than those with a lower geotextile which were quicker than rigs with an upper geotextile.

In order to assess the statistical significance of geotextile location, duration of the simulated rainfall and its intensity, statistical testing was undertaken. A Kolmogorov-Smirnov test was carried out in order to check whether the data were normally distributed. The potential influence of the presence of a geotextile on hydraulic performance was analysed using ANOVA for parametric variables (normally distributed) with k-samples (3 for geotextile location: no geotextile, lower geotextile and upper geotextile). ANOVA was also used to check the statistical significance of storm duration on attenuation, and the influence of rainfall intensity on attenuation performance was tested using Kruskal Wallis. Table 4 summarises the results of these statistical tests, showing that geotextile location had a significant influence on attenuation, as did rainfall intensity, both at the 95% confidence level. However, storm duration was found not to significantly affect attenuation performance.

Table 5 shows the impact of rig structure and rainfall intensity on attenuation performance through the use of equations of performance (trends). The values of R^2 for the rigs without a geotextile and those including a lower geotextile were >0.70, whilst that for the rigs with an upper geotextile was >0.5.

3.1.2. Stage 2: the effect of pollutant addition on HFD performance

That the addition of pollutants did influence hydraulic performance is illustrated in Figure 8 which shows that the capacity of the system was reduced in terms of its ability to attenuate the storm peak. Sediments also introduced higher variability as it can be seen in the number of outlayers within the experiments. This particular behaviour from the sediments was highlighted by Sañudo-Fontaneda et al. (2013) when studying the reduction of the infiltration capacity of PPS under different clogging scenarios.

It was also found that geotextile position influenced hydraulic performance (Figure 9) since the time to peak for all models was increased from no geotextile structures to an upper geotextile. This finding suggests that designers and practitioners looking for an increase in the time to peak should include the geotextile closer to the surface of the HFD.

3.2 Geotextile effect on the hydraulic and clogging performance of HFD

3.2.1 Geotextile effect on the hydraulic performance of HFD

Initial bivariate correlation analyses shown in Table 6 highlighted significant linear relationships between attenuation performance and the addition of sediments at a 95% confidence level as well as high correlation between attenuation, rainfall intensity, storm duration and geotextile location.

In order to confirm these preliminary findings, a Kruskal Wallis test was carried out to compare the influence of the inclusion of a geotextile on hydraulic performance using attenuation levels, whilst a Mann-Whitney test was performed to validate the influence of sediment addition on hydraulic performance. The results are shown in Table 7 which confirmed that the addition of sediments and the presence of a geotextile had a statistically significant effect on hydraulic performance.

3.2.2 The presence of a geotextile and its effect on the potential for clogging

No clogging issues were observed during storm events that simulated 2-years' worth of pollutant addition (sediments and oil) over the laboratory models although the hydraulic behaviour was found to be different. Eventually, however, a crust of oil and sediment developed on the rig surface and began to create an impermeable layer preventing the downprofile migration of the sediment as found in other studies such as Mitchell (2015).

It was found that the pollutants preferentially accumulated in the top 50 mm of the HFD profile despite the presence of geotextile as can be seen in Table 8. More than 70% of the total amount of pollutants added to the models were found in the top of the profile for rigs either without a geotextile, or with one located lower in the profile. However, 98.2% of the pollutants were found at the top of the profile for rigs with an upper geotextile. Whilst complete clogging of the system was not an issue over the course of the experiments, nonetheless the likelihood would be that the rigs with an upper geotextile would eventually clog, and more quickly than the other structures being tested. In fact, Zhao et al. (2016) found that nonwoven geotextiles are beneficial in providing a groundwater drainage layer. However, there are other possible variables influencing the loss of hydraulic capacity in the field such as chemical clogging (Veylon et al. 2016).

Based on this study, the hydraulic deterioration of geosynthetics should be addressed in long-term field studies in order to quantify the potential for clogging when used in an HFD. Furthermore, Yoo (2016) pointed out the need to understand the hydraulic deterioration of geosynthetic filter drainage systems for their use in other civil engineering structures such as tunnels.

4. Conclusions

This research has shown that using a geotextile in an HFD can contribute positively to improve the safety of highways since peak flow is delayed as is time to peak due to the geotextile's ability to become wet whilst maintaining a head of water before allowing it to pass through (WRC).

Increasing rainfall intensity influenced the hydraulic performance of HFD rigs by decreasing time to peak in all designs. However, storm duration did not influence peak attenuation in any of the HFD designs, although it did affect the volume of runoff infiltrated. In addition, the presence of a geotextile influenced hydraulic performance by increasing peak attenuation, hence delaying the time to peak in comparison with rigs without a geotextile. Moreover, the position of the geotextile layer influenced hydraulic performance (p-value = 0.05), with the higher geotextile exhibiting longer times to peak, followed by the lower geotextile; rigs without a geotextile had the shortest time to peak.

The addition of pollutants (sediments and oil) significantly influenced hydraulic performance of all designs, reducing the capacity for infiltration with the eventual formation of an impermeable crust at the surface of the rigs. The majority of applied pollutants preferentially accumulated higher in the HFD profile in the top 50 mm, confirming the findings of previous studies such as Mitchell (2015) and Coupe et al. (2015). Furthermore, the presence of an upper geotextile trapped more than 95% of the applied pollutants in the top 50 mm of the profile in comparison with the lower geotextile (75.9%) and no geotextile (72.4%). Finally, no clogging was observed as a result of the addition of 2 years' worth of sediment.

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