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Modeling of the hydrological behaviour of pervious pavements, a physically based approach with FlexPDE

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Summary

The development of draining pavements within the laboratory of ESITC Caen had highlighted the need to quantify the contributions of the pervious surfaces to meet the expectations of local authorities and encourage the use of these techniques. This quantification work lends itself to the development of hydrological models to analyze the hydraulic behavior of pervious pavement structures, on which this article focusses, as well as their integration with urban planning. This study relies on a numerical model developed with FlexPDE and validated using both field and laboratory results. Results will show the hydrological behavior of pervious pavement structures for different contexts and designs.

Keywords

Hydrological behaviour, FlexPDE, Modeling, Permeable pavement, Pervious concrete

Introduction

Rainwater management is one of the key concerns to address to enable the development of sustainable cities. When a city expands itself onto green areas, a large number of Sustainable Urban Drainage Systems (SUDS) already exist and can be used, such as swales and ponds. However, to be fully sustainable, urban planning must avoid as much as possible to use these green areas but instead try to re-build the city itself. When an urban project is in a dense urban area, permeable pavements offer an alternative drainage system which presents both the advantage of being sustainable and the advantage of saving construction space. They do not require a specific space; they can be integrated to roads, car parks and public realm.

Permeable pavements are well studied all over the world by the scientific community (Tennis et al., 2004), (Illgen et al., 2007). However, these techniques are still not yet frequently used in urban projects. Research is still needed on issues such as clogging and evaporation, etc.

This work focused on the analysis of the hydrological processes within the pervious structures. The infiltration and retention of water inside permeable structures have already been well studied but only a few studies focus on the evaporation process. Inspired by various German studies (Göbel et al., 2013; Hollenbeck and Göbel, 2013) which have experimentally demonstrated the performance of permeable pavements for evaporation, this research aims to take evaporation into account.

Methods

Modelling approach

In order to quantify the impact of each parameter, a physics based modelling approach was chosen. A model was built using FlexPDE, which is a multi-physics finite element solution environment for partial differential equations. The model is based on the Richard equation (Equation 1) (Marsily (de), 1981), (Dakhlaoui, 1996).

$$\text{div} \left(K(h) \times \overrightarrow{\text{grad}}(h + z) \right) = \frac{\partial \theta}{\partial h} \times \frac{\partial h}{\partial t} \quad (1)$$

With:

- h , the hydraulic water head
- z , the altitude
- θ , the volumetric water content

The soil-water characteristic curve and the relation between the permeability and the water content are described for each material using the Van Genuchten laws (Equation 2 and 3).

$$\theta(h) = \theta_r + (\theta_s - \theta_r) \cdot \left(\frac{1}{1 + (\alpha \cdot h)^n} \right)^m \quad (2)$$

$$K(\theta) = K_s \cdot \left(\frac{\theta - \theta_r}{\theta_s - \theta_r} \right)^{1/2} \cdot \left[1 - \left(1 - \left(\frac{\theta - \theta_r}{\theta_s - \theta_r} \right)^{1/m} \right)^m \right]^2 \quad (3)$$

With:

- θ_s , the saturated volumetric water content
- θ_r , the critical volumetric water content
- K_s , the saturated coefficient of permeability
- α , n and m , the Van Genuchten coefficients

Boundary conditions are applied to simulate rainfall, evaporation, outflow and infiltration. Newman boundary conditions are used for each boundary. The drain outflow is modeled using the orifice equation (Equation 4) with a maximum value corresponding to the chosen limited outflow.

$$Q = C_d \times \sqrt{2 \cdot g \cdot h} \quad (4)$$

With: C_d , the orifice coefficient

The evaporation values used were recorded by the weather station Caen Carpiquet, distant to seven km from the site. The infiltration used to build the model corresponds to the infiltration rate measured on field at the ESITC Caen.

The model was built using proprieties of materials used for the construction of a field study of twelve parking lots made with pervious concrete blocks. Particular focus was made on parameter estimation. All parameters used in the model have been physically defined. For the Van Genuchten parameters the Modified Kovacs Model (Aubertin et al., 2003) has been used in order to estimate the value of “ a ” and “ n ” for each material.

Tab 1. Proprieties used for each material to describe the ESITC field study

| | Paver | Bedding | Filtration layer | Foundation | Soil | |
|------------|----------|----------|------------------|------------|----------|--|
| K_s | 1,00E-03 | 7,00E-04 | 3,00E-02 | 5,00E-02 | 5,00E-06 | Saturated coefficient of permeability |
| Θ_s | 23 % | 47 % | 10 % | 40 % | 43 % | Saturated volumetric water content |
| Θ_r | 2 % | 0,5 % | 1 % | 0,4 % | 10 % | Critical volumetric water content |
| α | 29,70 | 47,50 | 20,00 | 100,00 | 3,60 | Van Genuchten coefficient |
| n | 5,60 | 5,45 | 4,00 | 4,60 | 1,56 | Van Genuchten coefficient |
| m | 0,82 | 0,82 | 0,75 | 0,78 | 0,36 | Van Genuchten coefficient: $m = 1 - 1/n$ |

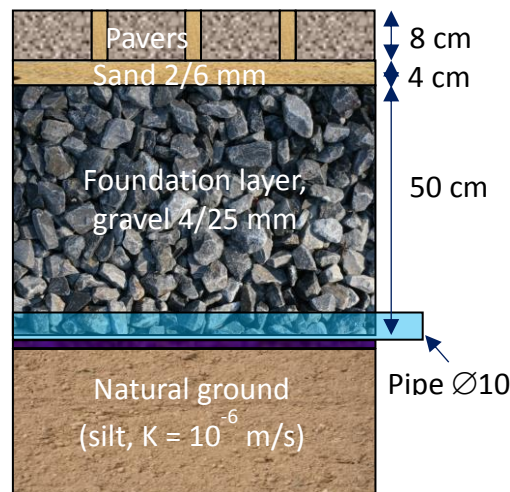


Fig 1. View of the structure built on site and modelling in FlexPDE

Field study and laboratory experiment

A research project named VECOPEXP is being conducted at ESITC laboratory. This project is following two pervious parking lot sites, in Epron and Caen, in Normandy. The pervious pavement structures were designed and built following different permeable pavement guides (Faleyeux, 2015), (Abdo, 2007). The originality of the structure is that their top layer is composed of pervious

concrete pavers made with crushed seashell as a substitute for natural aggregates, (Nguyen and Boutouil, 2013) .

The first site, at Epron, was used to build the model. This site is composed of twelve pervious parking spaces. Four of them are studied; they have impermeable lining on the sides and the bottom. The catchment is composed of 147m² of impervious parking area that discharges into the 50m² pervious pavements.

Weather condition, outflow and water pressure inside the structure are monitored in the field. Data collected from these sensors are used in order to build and validate the model.



Fig 2. Parking spaces made with pervious concrete pavers – ESITC Caen, Epron, France

In addition to the field study, a laboratory experiment was designed to reproduce the permeable pavement. This structure will allow for experimentation with different materials or designs as well as measuring the effects of clogging and pollutants filtration. Results from these tests will be used to improve the numerical model.

Results and Discussion

The model is still under sensitivity analysis stage. This sensitivity analysis is conducting with several parameters including structure and material parameters (permeability, clogging, structure dimensions, drain position, etc.) and site and weather parameters (soil permeability, permeable/impermeable ratio, potential evaporation, storm intensity, etc.).

The first parameters used are presented in the table 2, the rain event used for the simulation are presented in the figure 3. Runoff from impermeable catchment is coming from the left.

Tab 2. First parameters used for the sensitivity analysis

| Parameter | Symbol | Units | Reference value | Min value | Max value |
|--------------------------------|-----------|-------|-----------------|-------------|-------------|
| Structure width | Width | m | 5 | 1 | 10 |
| Structure slope | Slope | % | 0 | 5 | -5 |
| Drain vertical position/bottom | Drain_v | m | 0.1 | 0 | 0.25 |
| Drain horizontal position | Drain_h | m | middle | left | right |
| Soil (K _s =) | Soil | m/s | Silt (5E-6) | Clay (5E-9) | Sand (5E-4) |
| Depth of the water table | WT_depth | m | 2 | 1 | 5 |
| Impermeable catchment | Catchment | m | 5 | 0 | 25 |

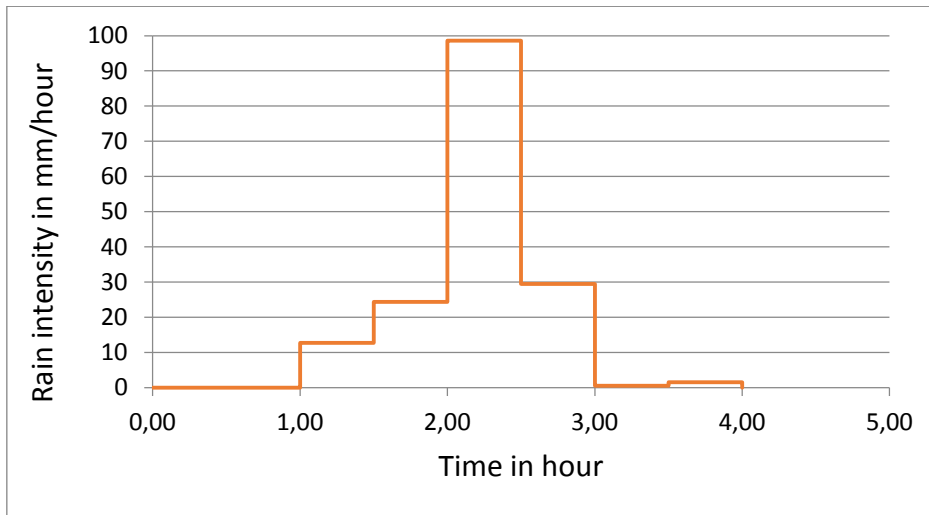


Fig 3. Storm event used for the sensitivity analysis

This event corresponds to a real storm that occurs in Caen (France) in July 2013 with a total of 83.5 mm of rain in 2.5 hours. After the storm, the simulation runs for twelve hours with a potential evaporation that corresponds to 4 mm per day.

First results are presented in figure 4; they show in percentage the water balance twelve hour after the end of the rainfall event. Simulations are classed according to the % of infiltration. The last simulation corresponds to a different rainfall event; 5.8 mm in 1.5 hour.

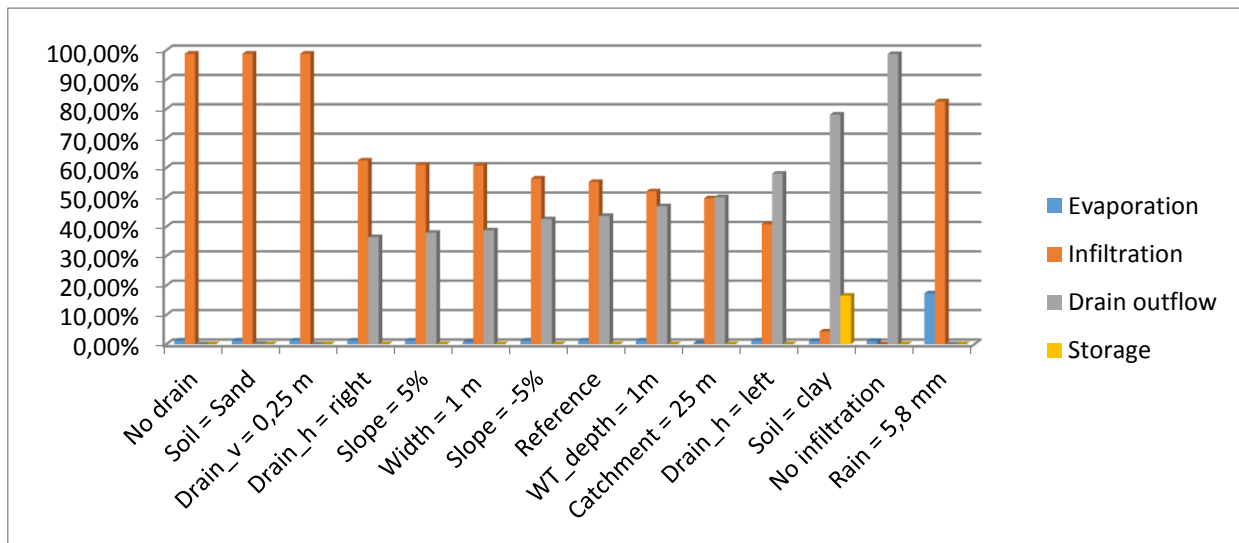


Fig 4. First results of the sensitivity analysis – work still in progress

These first results showed the importance of structural and environmental parameters for the hydrological performances of permeable pavements. As expected, evaporation is negligible for an extreme storm event but raise up to 17% for non-extreme event. Regarding the structural parameters, vertical and horizontal drain position have an important influence. Knowing this could be interesting to reduce drain outflow and maximise infiltration with a better design.

In the future different scenarios will be built, based on the most influent parameters, in order to quantify the different hydrological processes within the pervious structure. A better comprehension of hydrological processes is expected. The results will be used as input for the modelling of pervious pavement impacts at the urban catchment scale.

Conclusions

Pervious pavers are one of the solutions that contribute to finding an innovative and sustainable answer to effective rain water management in urban area. A better understanding of hydrological processes within the pervious structure is needed as a first step to quantify their benefits. In order to achieve this, a numerical model of the different hydrological processes inside a permeable structure was built using FlexPDE software, including evaporation. Results will give understanding for the use of this technique in different environmental situation to help maximise their benefits.

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