Optimum coverage ratio of permeable pavement for rainwater infiltration of car park

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ABSTRACT

Permeable car park is a good place for rainwater infiltration and storage in the urban area. It can not only preserve rainwater but also reduce the heat island effect of city. To allow water infiltration to the ground, the car park is usually paved with grass blocks which can encourage water to drain through the soil pocket where vegetation grows. However, too much water infiltration may also reduce the bearing capacity of grass blocks against vehicular traffic and load. In addition, the area paved with grass blocks is no good for pedestrians to walk on either, especially for those with high heels. In the contrast, the impervious pavement or blocks are much more endurable to the vehicular traffic and load and also easier for the pedestrians to walk on. This study aims to find the optimal area ratio between pervious and impervious pavement of a paved parking lot, considering the rainwater infiltration and its effect on the changes of degree of saturation of soil. The PLAXIS 2D software was adopted for this study. It had been found that a 60% of pervious pavement coverage of a paved surface can yield 88% the same rainwater infiltration effect as those with 100% pervious area. This result can be useful for the car park designer to balance the needs of rainwater infiltration, vehicular traffic and pedestrian walk.

Keywords: pervious pavement, rainwater infiltration, degree of saturation, car park

1 INTRODUCTION

Due to the effect of global climate change, the short period and high intensity rainfall event has become more and more often to occur. The amount of rainfall is very likely to exceed the capacity of city drainage system and causes flooding problem in urban area. To mitigate the high intensity rainfall induced flooding problem, car park is a good space to keep the rainwater in the cities. The water infiltrates into the pervious car park can not only reduce the surface runoff but also moisten the vegetation and cool down local temperature. There are a large variety of pavement materials can be chosen from: interlocking blocks, grass blocks, cement slabs, asphalt concrete, etc. Figure 1 shows the schematic diagram of a permeable sidewalk which can keep water in the pores of pervious road base material. When heavy rain comes, the water can quickly infiltrate through the pervious surface pavement. But it should be born in mind that water infiltration takes time. The rainwater must be able to perch somewhere near the surface in order to slowly infiltrate to soil.

The pavement of car park must be able to sustain the vehicular traffic and load. But the load carry capacity of the pavement will be significantly reduced if its underlying base soil absorbs too much water. So it is not unusual to spot loosened pervious blocks in the car park. In order to solve this problem, it is better to separate pervious pavement from load carry pavement (Figure 3). The latter is usually impermeable. As shown in Figure 3, the parking lot with impermeable pavement on wheel loading area on two sides and the permeable pavement is in between. The purpose of this study is to find the optimal impermeable-permeable pavement ratio for the pervious car park.

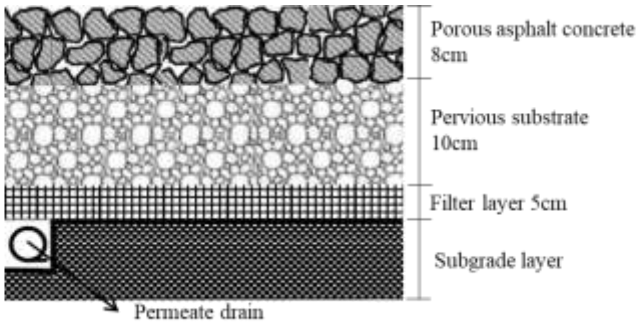

Fig. 1. Sidewalk drainage section (CPAMI, 2015)

2 MODEL SETTING

To simulate the rainwater infiltration through pervious pavement, the profile shown in Figure 2 is used as the pavement profile of a pervious car park. The numerical model setting of this study will be described as follows:

2.1 Geometric model

The "flow analysis" function of PLAXIS 2D was used here. The typical pervious pavement profile is shown in Figure 2. It consists of porous pavement (4 cm thick), base material (7 cm thick), subbase material (7 cm thick) and subgrade filter layer (10 cm thick). The total thickness of this porous pavement is 28cm. The width of each parking lot is 2.5 m. The impermeable pavement (i.e. concrete) is on both sides of each parking lot as shown in Figures 3 & 4. The depth to the bottom of the model is 2 m. To simplify flow analysis, this model only takes into account the water infiltrates from the previous pavement located at the center part of one parking lot.

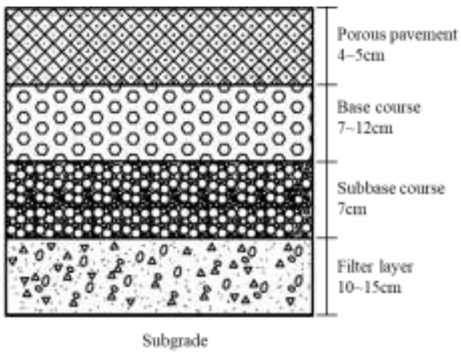

Fig. 2. Profile of pervious pavement in PLAXIS (Guo, 2016)

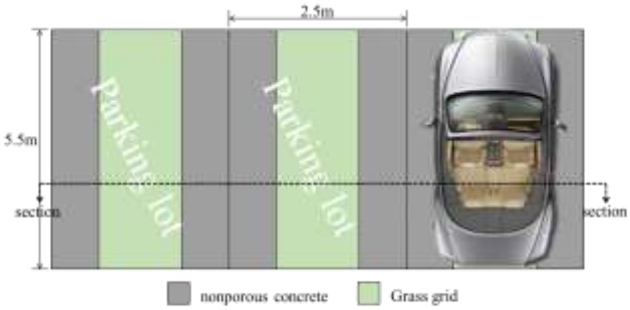

Fig. 3. Plane layout of the analysis model

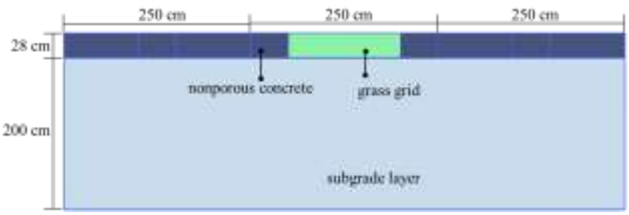

Fig. 4. Schematic cross section of the PLAXIS analysis model of single parking lot (pervious coverage ratio = 60%)

2.2 Soil parameter

As shown in Figure 4, there are 3 types of material used in the model: concrete, grass blocks and subgrade soil. Concrete is considered as impervious material; grass block is simulated by sand; subgrade soil is a clayey material. The basic material parameters used in this study are shown in Table 1.

Table 1. Three types of basic soil parameter

Property	Concrete	Sand	clay	Unit
γ_t	24	17	15	kN/m^3
γ_{sat}	Non-porous	20	18	kN/m^3
e_{int}	0.5	0.5	0.45	-
$k_{x,sat}$	Non-porous	1.16×10^{-4}	3.47×10^{-6}	m/s
$k_{y,sat}$	Non-porous	1.16×10^{-4}	1.13×10^{-7}	m/s

Figure 5 shows the typical soil-water characteristic curves (SWCC) of three Canadian soils (Vanapalli at al., 1999). It can be noticed that the SWCCs of sand and silt are concaved upward, while the curve for clay is concaved downward. The matric suction of clay drops rapidly when the degree of saturation increases to more than 90%. The SWCCs of clay used in this study are adopted from Wang at al. (2014) and shown in Figures 6 and 7.

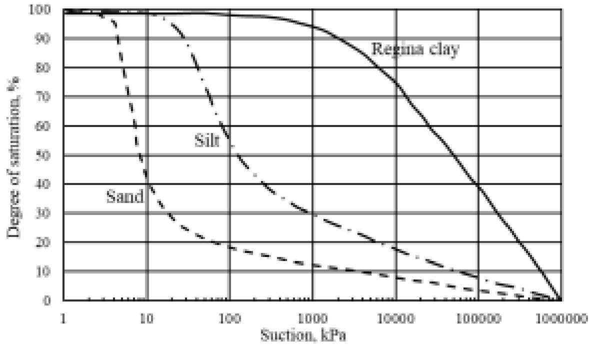

Fig. 5. Typical SWCC in Canadian (Vanapalli at al., 1999)

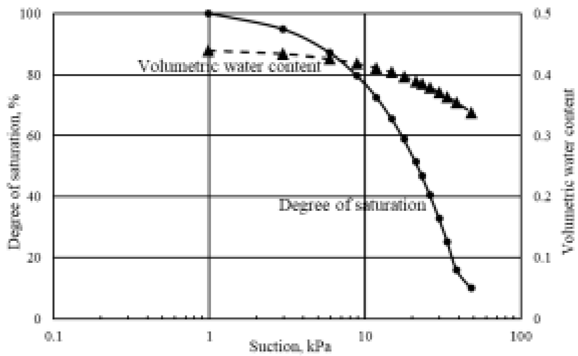

Fig. 6. SWCC of clay in this study (repaint from Wang at al., 2014)

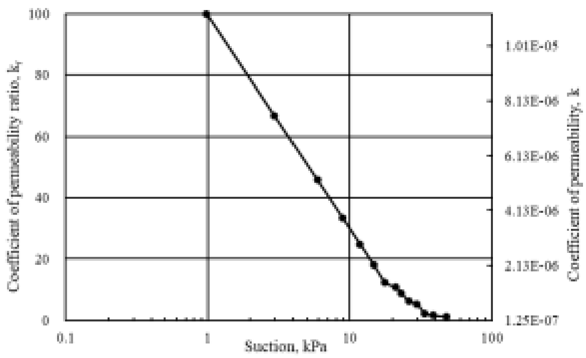

Fig. 7. Hydraulic conductivity in this study (repaint from Wang at al., 2014)

3 DESCRIPTION OF ANALYSIS PROCESS

3.1 Analysis process

After the geometric model is constructed, the soil parameters can be input. The ground water level is set at 3.5 m below ground surface and the corresponding degree of saturation of the subgrade soil to this groundwater level is 30% right under the pavement (Figure 8). Since the boundary of the model is far enough, the boundary at the lateral and bottom allowed no water to flow through. The initial degree of saturation of the model is shown in Figure 8.

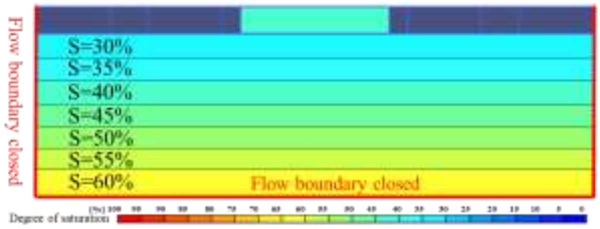

Fig. 8. Result of degree of saturation of initial condition

3.2 Description

To quantitatively interpret the advance of wetting front, the wetting front zone of rainwater infiltration is defined where the degree of saturation suddenly drops down in this study. For example, the wetting front zone is where the degree of saturation drops to 36.6% ~ 40.6% as shown in the figure on the left hand side of Figure 9. So the degree of saturation of 40% is used here as the indicator of the advancing wetting front (see Figure 9). The total width (B) of parking lot is 2.5 m, which is subdivided into impervious pavement (I/2 + I/2) and pervious pavement (P) as shown in Figure 9. The advance of wetting front in the vertical direction is measured from the bottom of pervious pavement to where the degree of saturation equal to 40%. Similarly, wetting front toward the lateral direction is measured from the edge of the pervious pavement to where the degree of saturation equal to 40% as shown in Figure 9.

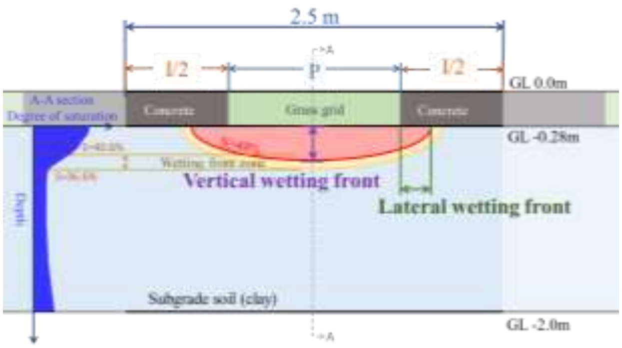

Fig. 9. Description of wetting front, vertical wetting front and lateral wetting front

4 ANALYSIS RESULTS

The scenario of the rainwater infiltration adopted here is: rainfall duration = 1 hour and rainfall intensity = 1 cm/hour. Enough water is perched in the grass blocks; the time for rainwater infiltration is 1 day. Under these conditions, the degrees of saturation inside the subgrade soil are shown in Figure 10 and discussed as follows:

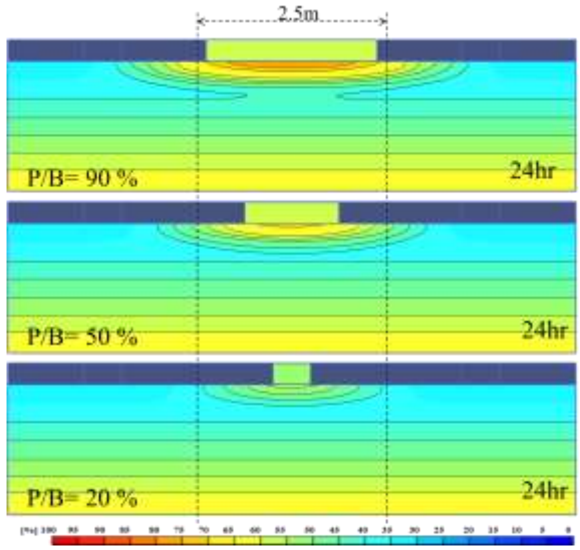

Fig. 10. One day after rain, the result of degree of saturation

4.1 Vertical wetting front

The development of vertical wetting front with time is shown in Figure 11. When the time for rainwater infiltration is short, say less than 2 hours, changing the coverage ratio of the permeable pavement (P/B) has little effect on the vertical wetting front simply because time is not enough. However, if the infiltration time extends to more than 4 hours, the vertical wetting front begins to increase with increasing P/B ratio. The larger the P/B ratio, the further the vertical wetting front infiltrates. For example, the vertical wetting front after 20 hours infiltration increases from 0.38 m (P/B=60%) to 0.43 m (P/B=100%). In other words, having vertical wetting front of P/B = 60%, the vertical wetting front can infiltrate 88% of the distance as that P/B = 100% can do after 20 hours of infiltration. Lastly, it should be pointed out that the curve for 24 hours infiltration is not complete. No data are shown when P/B > 60%. This is simply because the vertical wetting front (S = 40%) is mixing with the in-situ soil layer of 40% initial degree of saturation (Fig. 8). So it becomes unable to clearly identify the advance of vertical wetting front.

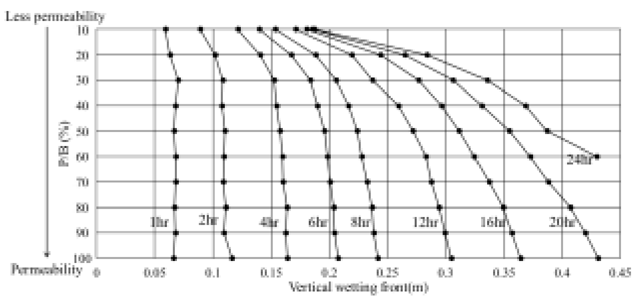

Fig. 11. Result of vertical wetting front

4.2 Lateral wetting front

The development of lateral wetting front with time is shown in Figure 12. Since the soil permeability in the vertical direction is smaller than that in lateral direction (1.13×10^{-7} m/s < 3.47×10^{-6} m/s, Table 1), the infiltration distance of lateral wetting front is larger than that of vertical front. However, the advance of lateral wetting front is not much influenced by the P/B ratio over a wide range of infiltration time if P/B > 60%. In other words, if P/B > 60%, any more increase in pervious pavement coverage has little effect on the advance of lateral wetting front. But the infiltration distance of lateral wetting front will increase with infiltration time. After 24 hours, the infiltration distance of lateral wetting front can reach 120 cm which is larger than that of vertical wetting front.

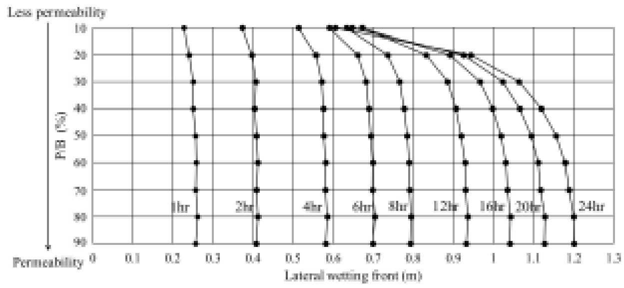

Fig. 12. Result of lateral wetting front

4.3 Influence between adjacent parking lots

The development of wetting front of an individual parking lot space with different coverage ratios of pervious pavement (P/B) has been discussed above. This section will demonstrate the mutual influence between two adjacent parking lots in terms of infiltration distance of wetting front. Figure 13 shows the mutual influence between adjacent parking lots under different P/B ratios after one day of rainwater infiltration. As the pervious pavement ratio P/B increases, the wetting front contours of two adjacent parking lots begin to touch each other after 24 hours when P/B = 30%. As P/B ratio gets beyond 30%, the wetting front begins to overlap with each other. Therefore, for a permeable car park, it is suggested that the coverage ratio of pervious pavement P/B must be kept at least 30% for the rainwater infiltration in the permeable car parks.

To further study the effect of rainwater infiltration, the change of degree of soil saturation is studied as follows. Figure 14 shows the contours of degree of soil saturation resulted by two adjacent parking lots at P/B = 60%. Because of the contours of S = 40% has mixed with that of the initial degree of saturation of the ground. The wetting front of S=40% cannot be clearly found. Instead, wetting front with S = 42% is used to replace the one with S=40%. Such a minor change only has a very little effect on the results of this study here. As shown in Figure 14, the maximum vertical wetting fronts resulted by two adjacent parking lots are equal to 0.435 m (P/B = 60%) and 0.497 m (P/B=100%). In other words, when P/B = 60%, its vertical wetting front can infiltrate to a distance which is equal to 88% of the wetting front infiltration distance of P/B = 100%. So, P/B = 60% is recommended here for a pervious pavement coverage ratio considering the rainwater infiltration, the esthetical aspect, and also the need of vehicular traffic load and pedestrians walk.

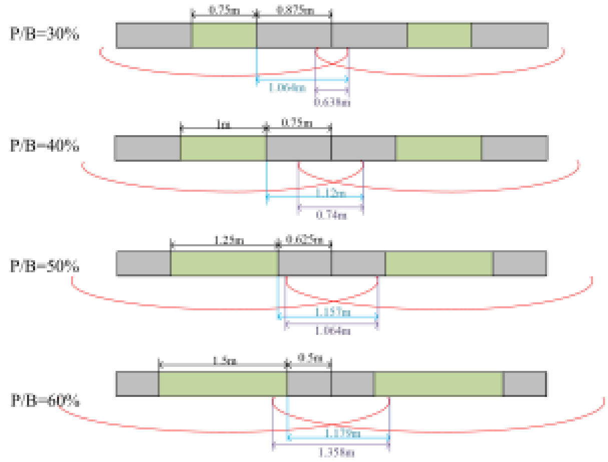

Fig. 13. Infiltration status of wetting front one day after rain

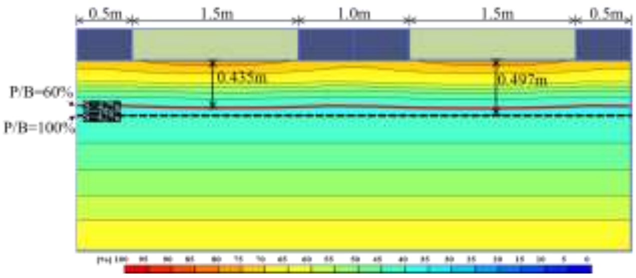

Fig. 14. Infiltration status of wetting front at P/B=60%

5 CONCULETION

Permeable car park is a good place for rainwater infiltration and storage in the urban area. Using PLAXIS 2D software, this study has evaluated the change of soil degree of saturation under the effect of rainwater infiltration from car park pavements. It had been found that a 60% of pervious pavement coverage of the paved car park can yield 88% the same rainwater infiltration effect as those with 100% pervious area in terms of water front advance in the subsoil. This result can be useful for the car park designer to balance the needs of rainwater infiltration, vehicular traffic and pedestrian walk.

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