Int. J. of GEOMATE, March, 2015, Vol. 8, No. 1 (Sl. No. 15), pp. 1117-1122
Geotech., Const. Mat. and Env., ISSN:2186-2982(P), 2186-2990(O), Japan

NUMERICAL ANALYSIS OF INFILTRATION INTO PERVIOUS CONCRETE-BASE SYSTEMS

Bertrand Teodosio[1], Jaehun Ahn[2] and Hyun-Suk Shin[3]

[1,2,3] Pusan National University, Korea

ABSTRACT: Decrease in pervious area due to urbanization and rainfall intensification because of climate change prompted to reconsider our philosophy in stormwater management. One of the innovative approaches for stormwater management is a concept called Low Impact Development (LID). Among other techniques of LID, construction of pervious pavement can utilize vast paved surfaces, traditionally impervious, allowing stormwater to infiltrate through its surface. In this study, the hydrologic performance of a particular pervious concrete system section was investigated using Finite Element Method (FEM) modelling. The influence of initial saturation and rainfall intensity to produce run-off were examined to imply possible design considerations. Further, rainfall data recorded from July 15, 2012 at Busan, South Korea were employed to investigate the effects of evaporation and underdrain in the hydrologic capacity and behavior of the pervious concrete system. The results and implications to hydrological design are discussed herein.

Keywords: Low Impact Development, Pervious concrete, Finite Element Method, Infiltration, Run-off

1. INTRODUCTION

Flooding is recurring in most urban areas which affects economic growth. According to Crichton [1], total gross domestic product (GDP) losses due to stormwater run-off accumulation are approximately 14% and 2% for poorer and richer countries, respectively.

Inundation does not only lead to economic damage, it also causes bereavement in different affected regions. Conferring to the United Nations [2], above 90% of recorded deaths from natural disasters are related to water from the year 1975 to 2001 in Asia.

Possible methodology to prevent severe flooding that could cause financial damage and life loss is through stormwater management. One of the innovative approaches for stormwater management is a concept called Low Impact Development (LID). LID is an emerging practice to lessen inundation and hazards due to lack of pervious surfaces in an urban region. Among the techniques of LID, construction of pervious pavement can allow stormwater to infiltrate through its surface preventing or attenuating run-off occurrence.

To quantify the feasibility of a pervious pavement, the hydrologic performance should be investigated by obtaining the infiltration capacity and run-off threshold of a system. Generally, infiltration capacity can be obtained using calculation methods such as Horton's Equation [3], Curve Numbers [4], and Green-Ampt Model [5, 6].

In this study, an FEM model, SVFlux [7], is initially verified with an analytical model, Green-Ampt [5, 6]. Then, the hydrologic performance of a particular pervious concrete system section is investigated using the FEM model.

2. INFILTRATION CALIBRATION

Infiltration is governed by the pull of gravity and capillary action. Soil characteristics including hydraulic conductivity, porosity, and ease of entry also affects the infiltration process.

In this section, Green-Ampt Model [5, 6] was compared to FEM model to verify the applicability of the FEM software used.

2.1 Green-Ampt Model

The Green-Ampt Model [5, 6] is a method to estimate infiltration which considers wetting front suction head, ψ, volumetric water content, θ, saturated hydraulic conductivity, k_s, and cumulative volume infiltrated, F. Eq. (1) shows the formula to be used for rainfall intensity, I, less than or equal to the saturated hydraulic conductivity of the medium to obtain the infiltration, f, at a specific time, t.

$$f = I \quad (I \leq k_s) \tag{1}$$

For rainfall intensity greater than the saturated hydraulic conductivity of the medium, the infiltration is estimated as following:

$$f = k_s\left(1 + \frac{\Delta\theta \cdot \psi}{F}\right) \quad (I > k_s) \tag{2}$$

where $\Delta\theta$ is the initial moisture deficit (θ_s-θ_i) and ψ

is the average suction at wetting front.

The cumulative volume of water infiltrated, F, can be estimated from the following equation:

$$k_s(t - t_s) = F - \Delta\theta \cdot \psi \cdot \ln(F + \Delta\theta \cdot \psi) - F_s + \Delta\theta \cdot \psi \cdot \ln(F_s + \Delta\theta \cdot \psi) \quad (3)$$

where t_s is the time to achieve surface saturation calculated by getting the ratio of the cumulative volume of infiltration at the moment of surface saturation, $F_s \left(= \frac{\Delta\theta \cdot \psi}{\frac{I}{k_s} - 1}\right)$, and rainfall intensity, I.

2.2 Finite Element Model (FEM)

The infiltration of a single layer crushed limestone was modelled in SVFlux [7] to compare with the Green-Ampt infiltration model. The Soil Water Characteristic Curve (SWCC) and saturated hydraulic conductivity, k_s, of the crushed limestone is presented in Table 1. The SWCC parameters of the crushed limestone was acquired from Ba et al. [8], and the saturated hydraulic conductivity, k_s, from Cote and Konrad [9].

Table 1 Crushed limestone material property

Layer	SWCC [8]					k_s
	θ_s	a	n	m	h	(cm/s)
Lime-stone	0.34	0.71	1.74	0.47	100	$1.1\text{x}10^{-4}$ [9]

Note: a, n, m, h are constants from Fredlund-Xing Fit [7].

The comparison of infiltration models is shown in Fig. 1 and Fig. 2 for constant rainfall intensity equivalent to 25 mm/ hr and 100 mm/hr, respectively.

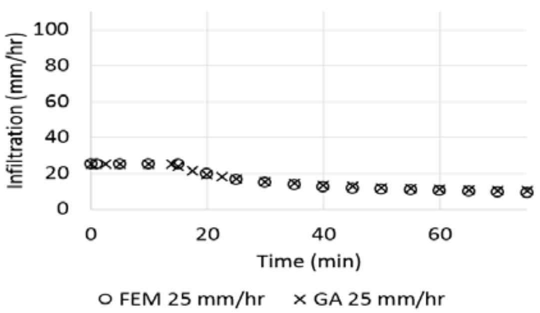

Fig. 1 FEM and GA models, I=25 mm/hr.

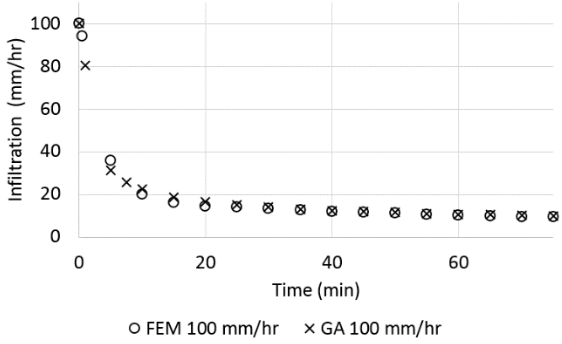

Fig. 2 FEM and GA models, I=100 mm/hr.

The Green-Ampt and FEM models for the infiltration of the single layer crushed limestone match very closely.

3. FEM SIMULATION

Three sets of simulations were conducted in this study. The first set investigated the influence of initial saturations of the pervious pavement system to the runoff threshold. The second set focused on the effect of rainfall intensity applied to the system to inspect the runoff buildup. The third set of simulation includes the application of the rainfall data collected from July 15, 2012 at Busan, South Korea. Rainfall data were used to investigate the run-off reduction by implementing underdrain and evaporation.

3.1 Initial Condition

For the following investigations, a pervious pavement system was modelled with two different layers. The top layer is a pervious concrete (PC) with a height of 0.15 m. The material property, SWCC and k_s, of the pervious concrete is listed in Table 2 based on experiments of Kim [10].

For the bottom layer, the material properties of the crushed limestone presented in Table 1 were used. The height of the bottom layer was modelled to be 0.45 m. The width of the pervious pavement system was assumed to be 3 m.

Table 2 Pervious concrete material property

Layer	SWCC [10]					k_s
	θ_s	a	n	m	h	(cm/s)
Pervious Concrete	0.32	2.23	1.63	8.60	0.21	0.129 [10]

Note: a, n, m, h are constants from Fredlund-Xing Fit [7].

The boundary conditions of the system was assigned to be zero flux at the sides and at the bottom, which assumes a presence of a liner made up of a soil layer with very low permeability or a geomembrane resulting to no exfiltration. For the upper side of the PC layer, a direct rainfall was applied, hence, climate boundary condition in SVFlux [7] library was assigned. Refer to Fig. 3 for the boundary conditions designated to the pervious pavement system.

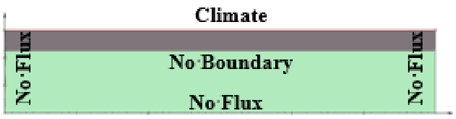

Fig. 3 Boundary conditions for FEM model.

To investigate the effect of antecedent moisture of the pervious concrete system, the initial degree of saturation was assigned to be 0%, 25% and 50%. The equivalent initial matric suction is listed in Table 3 for PC and limestone. Fig. 4 presents the mesh for PC and limestone layers. A constant rainfall intensity, 25 mm/hr, was applied for all three cases.

Table 3 Initial condition of the pavement system

Degree of Saturation	ψ_i (kPa) PC	ψ_i (kPa) Limestone
0%	-90	$-1x10^6$
25%	-1.4	-250
50%	-0.7	-3.7

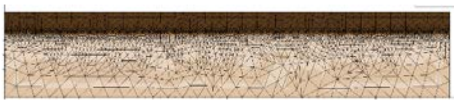

Fig. 4 FEM model.

The results are presented in Fig. 5. According to the figure, the initial saturation affects the run-off threshold due to the differences in water storage. The trends with varying initial saturation seem reasonable since the process of infiltration continues if there is water storage available to accommodate additional water in the system. The time when run-off initiates were 217, 183 and 94 minutes for initial condition equivalent to 0%, 25% and 50% saturation, respectively.

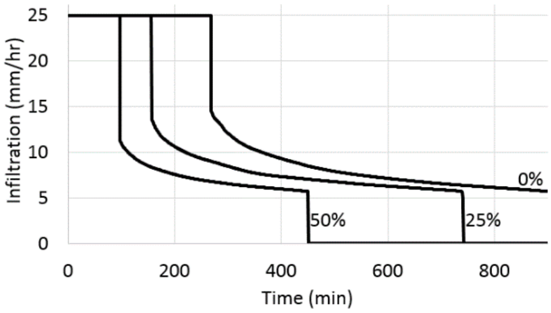

Fig. 5 Infiltration of pervious system having different initial saturations.

The total volume of voids, V_v, or water storage of the system is calculated to be 0.1994 m^3/m^2. Applying the constant rainfall intensity 25 mm/hr ($4.17x10^{-4}$ m/min), the time to fill the whole system is around 480 minutes for a dry initial condition. Or, due to the disparity of hydraulic conductivity of the two materials, run-off might occur after filling the PC layer. The total volume of voids, V_v, for the PC layer is 0.0483 m^3/m^2 and it may take about 120 minutes for the PC layer to be filled. Conferring to Fig. 5, the 0 % initial saturation system experienced a run-off at 217 minutes. The FEM value is between the computed time using V_v which has a range equivalent to 120 to 480 minutes, which is the case for other initial saturations.

The graphs for the cumulative run-off are displayed in Fig. 6. The cumulative run-off after 600 minutes for 0%, 25% and 50% are 0.33 m^3, 0.36 m^3 and 0.50m^3, accordingly.

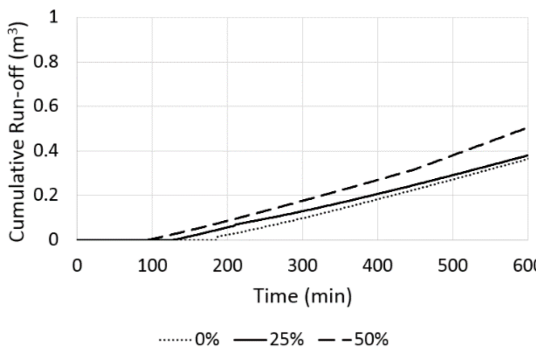

Fig. 6 Cumulative runoff of pervious system with varying initial saturation.

3.2 Rainfall Intensity

A range of constant rainfall intensity was assigned to be a variable with all the remaining parameters left constant. The constant initial condition chosen was 25% saturation. The rainfall intensities applied were 25, 50, 75, and 100 mm/hr. The results of infiltration are presented in Fig. 7. Run-offs were experienced at time equal to 183, 62, 27, and 23 minutes for rainfall intensities of 25, 50, 75, and 100 mm/hr, respectively.

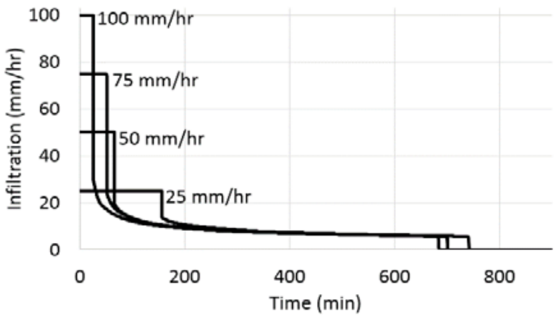

Fig. 7 Infiltration of pervious system having different rainfall intensities applied.

The cumulative run-off are 2.62 m^3, 1.89 m^3, 1.11 m^3, and 0.36 m^3 for 100 mm/hr, 75 mm/hr, 50 mm/hr, and 25 mm/hr, respectively, for the rainfall intensity test simulation within 600 minutes. Refer to Fig. 8 for the cumulative run-off graphs of pervious pavement system with different rainfall intensities applied.

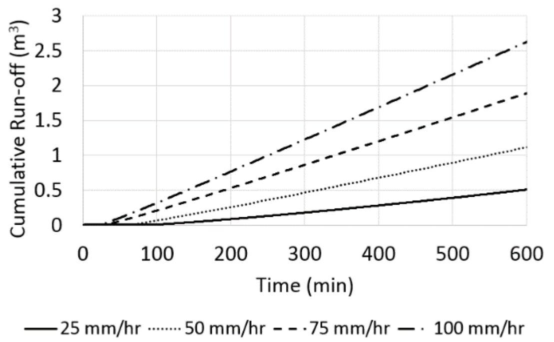

Fig. 8 Cumulative runoff of pervious system with varying rainfall intensities applied.

3.3 Actual Rainfall Data

The historical weather from WeatherSpark [11] is listed in Table 5 which was used for the implementation of evaporation effect in the SVFlux [7]. A rainfall data were collected from July 15, 2012 in Busan, South Korea. The potential evaporation method used was Wilson Limiting Equation [7]. The time history of the rainfall is also presented in Fig. 9.

Table 5 Historical weather in Busan, Korea [11]

	T (°C)	H (%)	W (mph)
Max	29.4	94	21
Min	22.8	68	17
Ave	26.1	81	19

Note: T=temperature; H=humidity; W=wind speed.

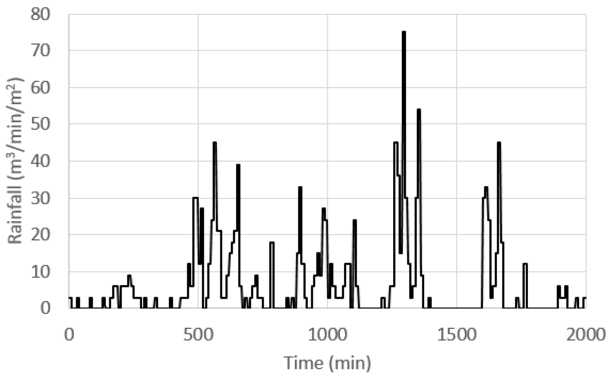

Fig. 9 Rainfall data (July 15, 2012)

To investigate the effect of an underdrain, an opening that has the ability to drain substantial water flow, was modelled at the midpoint of the width on the bottom surface of the basalt layer. The boundary condition for the underdrain is an excess pore pressure constant equal to zero (u=0). The opening is 100 mm in diameter. Fig. 10 illustrates the section with drain installed.

Fig. 10 Pervious pavement system section with pipe installed.

There are four cases for the application of the collected rainfall data. Table 6 presents the cases for examining the effect of pipe and evaporation in the hydrologic performance of the pervious concrete and limestone.

Table 6 FEM cases for run-off analysis concerning drain and evaporation

Case	Pipe	Evaporation
1	None	None
2	None	Implemented
3	Implemented	None
4	Implemented	Implemented

The results of run-off histories for four cases are shown in Fig. 11. Case 1 shows run-off without drain installed and without evaporation implemented. It is evident from the graph that for a no exfiltration pervious pavement system and no evaporation implemented, notable volume of run-off should be experienced. Conferring to the plot of Case 2, there is a small amount of reduction in the run-off due to the evaporation implementation which serves as an outlet at the top surface of the system. When the drain was installed, the run-off plummeted which is evident in both Case 3 and Case 4.

The cumulative run-off volumes are plotted in Fig. 12. The maximum run-off volume collected for Case 1 is 0.36 m^3. By implementing evaporation in Case 2, the cumulative run-off volume decreased to 0.28 m^3. Case 3 and Case 4 collected 0.13 m^3. However, Case 4 experienced the run-off at a later time.

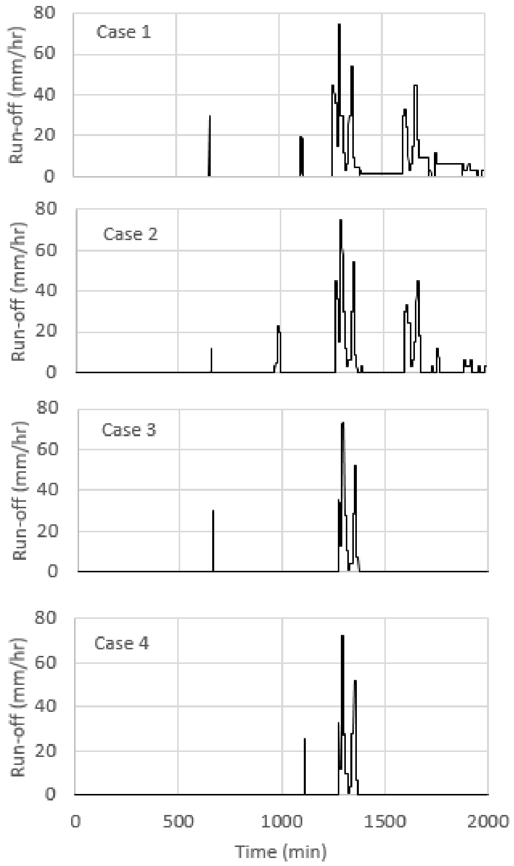

Fig. 11 Run-off histories for rainfall data applied to pervious pavement system.

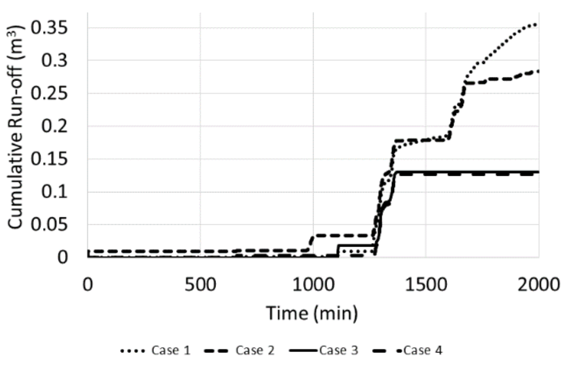

Fig. 12 Cumulative run-offs for rainfall data applied to pervious pavement system.

4. CONCLUSION

In this study, three sets of numerical simulations were conducted. The first set was conducted to investigate the influence of initial saturation condition of the pervious pavement system on the run-off buildup. A constant rainfall intensity of 25 mm/hr was applied. The run-off occurred at the times between when the PC layer is filled and when the whole system is.

The second set of investigations focused on the effect of rainfall intensity applied to the system. The curves observed were reasonable. There is an inverse proportionality between the rainfall intensity applied and run-off threshold. As the rainfall intensity applied was increased, the time for run-off to occur decreased.

The third set of simulation includes the application of the rainfall data collected from July 15, 2012 at Busan, South Korea. Rainfall data were used to investigate the run-off reduction by implementing underdrain and considering evaporation. The evaporation may have little significance when the underdrain was implemented to the system.

It is noted that the results discussed here are based on specific analysis conditions, and more analyses and experiments should be conducted to generalize the findings.

5. ACKNOWLEDGEMENTS

This research was supported by a grant from Advanced Water Research Program funded by Ministry of Land, Infrastructure and Transport of Korea government.

6. REFERENCES

[1] Crichton D, International historical, political, economic, social, and engineering responses to flood risk. Florida: CRC Press, 2011.
[2] United Nations, “Guidelines for reducing flood losses”. Geneva: United Nations International Strategy for Disaster Reduction (UNISDR), 2004.
[3] Chahinian N, Moussa R, Andrieux P and Voltz M, “Comparison of infiltration models to simulate flood events at the field scale”, J. of Hydrology, Vol. 306, 2005, pp. 191-214.
[4] Ponce V and Hawkins R, “Runoff curve number: has it reached maturity?”, J. of Hydrologic Engineering, Jan. 1996, pp. 11-19.
[5] Mein RG and Larson CL, “Modeling infiltration during a steady rain”, J. of Water Resources Research, Vol 9, No. 2, Apr. 1973, pp 384-395.
[6] Zhang J, “A laboratory scale study of

infiltration from pervious pavements". Australia: RMIT University, 2006, ch. 4.

[7] Thode R and Fredlund M, "SVFlux Tutorial Manual". Saskatchewan, Canada: SoilVision Systems Ltd., 2013, ch. 2.

[8] Ba M, Nokkaew K, Fall M and Tinjum J, "Effect of matric suction on resilient modulus of compacted aggregate base courses", J. of Geotechnical and Geological Engineering, Vol 31, Issue 5, Oct. 2013, pp 1497-1510.

[9] Cote J and Konrad JM, "Assessment of hydraulic characteristics of unsaturated base-course materials: a practical method for pavement engineers", Canadian Geotechnical Journal, Vol 40, 2003, pp 121-136

[10] Kim S, "Infiltration characteristics of pervious concrete-base system", South Korea: Pusan National University, in progress.

[11] WeatherSpark, "Historical weather for 2012 in Pusan",https://weatherspark.com/history/33275/2012/Pusan-Kyongsang-Namdo-South-Korea.

Int. J. of GEOMATE, March, 2015, Vol. 8, No. 1 (Sl. No. 15), pp. 1117-1122.
MS No. 4234 received on June 16, 2014 and reviewed under GEOMATE publication policies.

Pertinent discussion including authors' closure, if any, will be published in March 2016 if the discussion is received by Sept. 2015.

Corresponding Author: Jaehun Ahn