Numerical Simulation of Flow within a storage area of HDPE modular pavement

IOP Conf. Series: Earth and Environmental Science **920** (2021) 012044 doi:10.1088/1755-1315/920/1/012044

Numerical Simulation of Flow within a storage area of HDPE modular pavement

A S N Amirah[1,2], F Y Boon[2], K A Nihla[1,2], Z M Salwa[1,2], A W Mahyun[1,2] and N Yaacof[3]

[1]Centof Excellence, Water Research and Environmental Sustainability Growth (WAREG), Universiti Malaysia Perlis (UniMAP), 02600 Arau, Perlis, Malaysia
[2] Faculty of Civil Engineering Technology, Universiti Malaysia Perlis, Kompleks Pusat Pengajian Jejawi 3, 02600 Arau, Perlis, Malaysia
[3] Faculty of Civil Engineering Technology, Universiti Malaysia Pahang (UMP), Lebuhraya Tun Razak 26300, Gambang, Kuantan, Pahang, Malaysia

E-mail: noramirah@unimap.edu.my

Abstract. The development of stromwater management usually promote to provide the safe passage of stromwater. However physical modelling need expensive laboratory experiments. Due to that this numerical study is performed to study the flow within storage area of HDPE modular pavement. This paper studied and compared the infiltration rate of diagonal modular and conventional pavement (control), determined the velocity magnitude and pressure of modular pavement at various rainfall intensities. FLOW-3D was used to run a simulation on a porous media flow model using the Navier-Stokes equation. Real rainfall data of Malaysia was used as the model inputs to get better analysis of pavement design. The present findings showed that storage area modular pavement has lower fraction of fluid than control, which means that it has greater holding capacity and capable to capture all the rainfall volume from 5mm/h to 85mm/h. Besides, rainfall intensity has a strong influence on velocity magnitude and pressure. The HDPE diagonal modular pavement strong enough to sustain with an increasing of velocity magnitude and pressure during extreme rainfall. Therefore, HDPE modular pavement indicates a better water interception capacity than conventional pavement. FLOW-3D helps the critical analysis of pavement design process and useful as supplementary tool.

1. Introduction

In recent year, increase of construction paved areas due to urbanization have significant changed on the hydrologic and hydraulic characteristics of the subsoil's catchment. Total impermeable area decreased infiltration and surface storage while increasing surface water runoff [1]. During rainfall, the conventional pavements produced high amount of runoff and incomplete stormwater infiltration would form ponds on the surface with different levels of the area. As result, conventional pavements in urban areas are becoming ineffective and unsustainable. Conventional impervious asphalt and concrete pavements are being replaced by permeable pavements as one of the stormwater management strategies. Therefore, municipalities in urban areas are being compelled or encourage to transition from impermeable to permeable paved surfaces, leading in a green and unsustainable urban surface evolution.

As the permeable pavement system is promoted by the stormwater management, a Green Stormwater Infrastructure (GSI) practices which consists of paving blocks to encourage the safe passage of stormwater by way of vertical infiltration. During rainfall events, stormwater will infiltrate through the interconnected void spaces in the pavement into a subsurface storage region. The captured water will infiltrate into the subgrade in areas where highly permeable soils are present [2]. In Malaysia, permeable pavement system was designed to capture particles and pollutants at the surface by filtering infiltrated stormwater. Interconnected void spaces in the pavement allow stormwater to filter through the soil below the paved surfaces, to minimize the environmental issues associated with surface runoff. Generally, the surface layer of the pavement is designed with permeable materials, while the base and sub-layers are impermeable. In this research, the infiltration rate, velocity magnitude, and pressure of modular pavement with various rainfall intensities of storage area modular pavement system were studied using FLOW-3D. FLOW-3D is a Computational Fluid Dynamics (CFD) software which used to analyse free-surface flows and provides significant insight into a wide range of physical flow patterns. The Volume of Fluid (VOF) and Fractional Area-Volume Obstacle Representation (FAVOR) methods is used to solves Navier-Stokes equations in order to determine the location of the frees surface and obstacles [3]. This is to helps minimize the depending on physical laboratory experiment and to help critical analysis of the flow pattern. The analysis of flow pattern in pavement system can improve the application, development and design of pavement. By using the volume of fluid (VOF) method developed, the FLOW-3D has the ability to allow the numerical model to create a sharp interface between the water and air without using the fine meshes required by other computational fluid dynamics (CFD) software. It is important to take the effect of air as the air filtration shorten the life of modular pavement than an impermeable pavement [4].

2. Material and Methods

2.1. Design of Storage Area Modular Pavement

The model geometry of modular pavement was created using AutoCAD software and the design parameter followed Standard from Jabatan Kerja Raya [5]. The pavement model consisted of 3 layers which are surface layer with made up from High Density Polyethylene (HDPE) modular, base layer with gravel, and sub-base layer with sand. The storage area modular was made by a thin-walled diagonal HDPE columns. Previous design of diagonal pavement most is made with concrete, however because of the great difficulties in managing the non-biodegradable wastes, HDPE appears to be an effective replacement [6]. It was designed with the diameter of 80mm, thickness of 5mm. The modular pavement was filled by gravel which the dimension of 10 mm. Then, the storage area modular were interconnected with each other to form a layer with the size of 560 mm (L) x 560 mm (W) x 80 mm (H). The infiltration area need to limited to 560mm x 560mm to prevent boundary effects influencing the hydraulic flow [7]. Besides, the base layer which filled by gravel is designed with the thickness of 150mm. The sub-base layer which filled by sand with the dimension of 0.6 mm is designed with the thickness of 200mm [8]. Figure 1 illustrates the 3-dimensional view of storage area modular pavement.

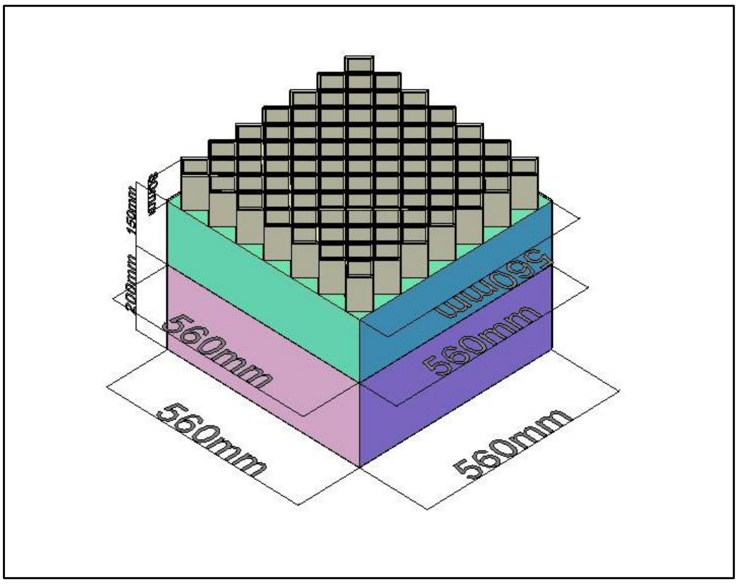


Figure 1. 3-dimensional view of storage area modular pavement

2.2. Numerical Model Setup

In order to run the FLOW-3D software, the designed geometry was converted to stereolithography (STL) file format. The meshing was done using non-conforming mesh blocks. Three mesh blocks are created, each block consisted total cell size of 100,000. Besides, the surface layer, base layer, and sub-base layer are divided into inflow and outflow values in the x, y, and z directions. Different levels of rainfall intensities which are light rain (5mm/h), and extreme rain (85mm/h) are inserted to the FLOW-3D software as volume flow rate for simulation [9]. Table 1 summarizes the boundary condition for each pavement layer. 2-dimenstional simulations for contour variable of fraction of fluid and velocity magnitude were conducted. Besides, 3-dimensional numerical simulation of pressure with complement of fluid was analysed.

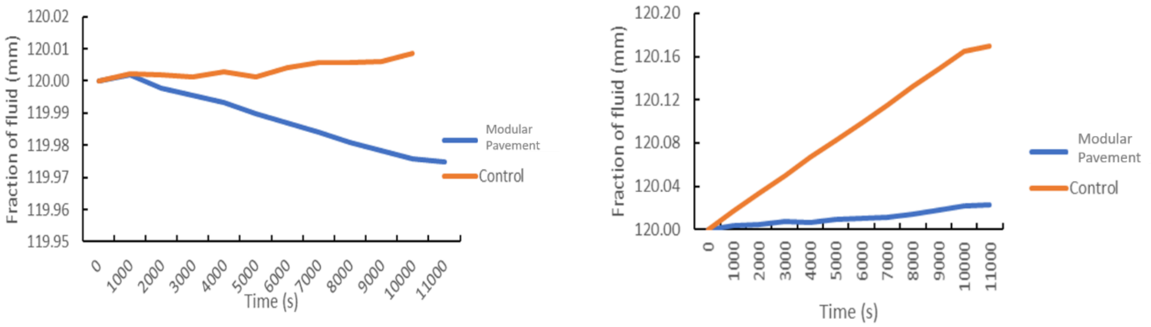
Table 1. Boundary condition for modular pavement

Bedding Layer	**Surface layer**	**Base layer**	**Sub-base layer**
X_{in}	Symmetry	Symmetry	Symmetry
X_{out}	Symmetry	Symmetry	Symmetry
Y_{in}	Symmetry	Symmetry	Symmetry
Y_{out}	Symmetry	Symmetry	Symmetry
Z_{in}	Rainfall intensity	Symmetry	Symmetry
Z_{out}	Continuative	Continuative	Wall

3. Results and Discussion

3.1. Effect of Fraction of Fluid with various Rainfall Intensity

Figure 2 shows the fraction of fluid for modular and conventional pavement (control) with various rainfall intensities. Modular pavement has lower fraction of fluid compared to conventional pavement under same rainfall volume. It can be clearly found that modular pavement abled to capture all the rainfall volume and discharge to the subgrade instead of causing surface runoff on the surface of pavement. The higher fraction of fluid in control pavement indicated that the infiltration rate of pavement is lower than the rainfall intensity, hence, ponding will occur on the surface of soil and lead to surface runoff [5,6]. As shown in Figure 2, both modular and conventional pavement reached the highest results for fraction of fluid at rainfall intensity of 85 mm/h. These results go beyond previous research, showing that higher rainfall intensity required higher infiltration rate for the pavement to capture the stormwater [10]. When the rainfall intensity is greater than the infiltration rate of the pavement, the stormwater will remain on the surface and it required more time for the stormwater to infiltrate and fully discharge. Figure 2(b) shows that fraction of fluid for modular pavement slightly increased at 10,000s. When the infiltration capacity of modular pavement is lower than the rainfall intensity, excess stormwater will temporarily retain in surface depressions rather than producing surface runoff on the surface of pavement [11]. However, the results of conventional pavement showed that the fraction of fluid increased significantly along the rainfall event. The holding capacity of conventional pavement were decreasing when the rainfall duration increased. Hence, conventional pavement becomes saturated and less able to infiltrate the stormwater [12].

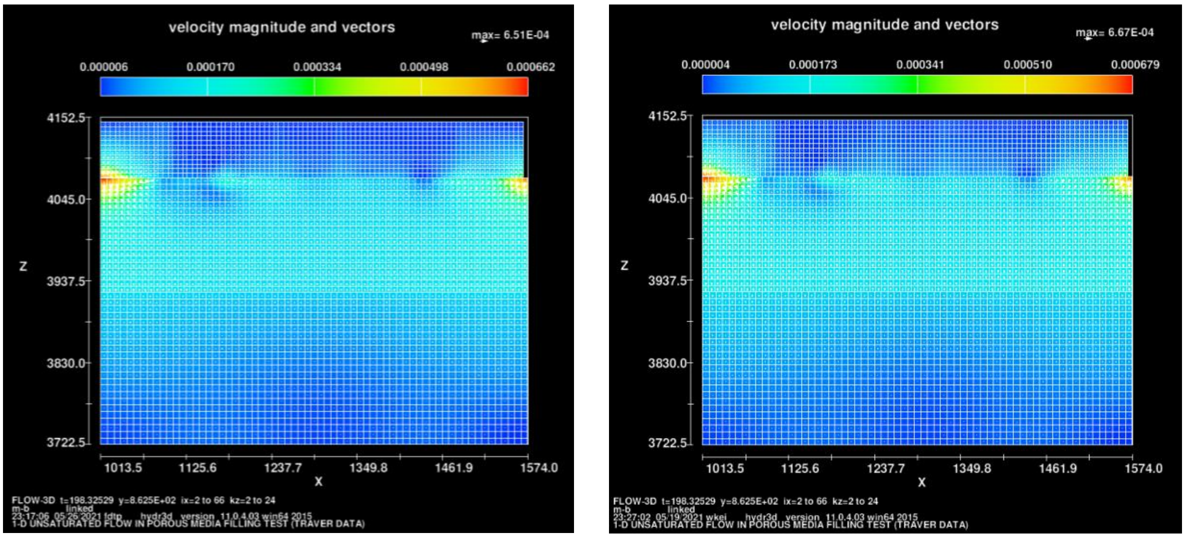


(a) 5mm/h (b) 85mm/h

Figure 2. Fraction of fluid under various rainfall intensities

3.2. Effect of Velocity magnitude with various Rainfall Intensity

Figure 3 illustrates simulation result of velocity magnitude for modular pavement under rainfall intensity of 5 mm/h and 85 mm/h at 200s. The vectors are coloured according to flow property such as velocity which red for high velocity while blue indicated low velocity. According to Fig. 3, various porosity for each pavement layer has different surface velocity distribution. The maximum velocity magnitudes of modular pavement are 223.92 cm/h and 244.44 cm/h when rainfall intensities increased from 5 mm/h to 85 mm/h. The effect of velocity magnitude is proportional to rainfall intensity. The simulation results of velocity magnitudes for modular pavement were positive which indicated there is no reverse flow in the pavement. These results tied well with previous studies which high flow velocity (244.44 cm/h) during rainfall intensity of 85 mm/h, will cause surface runoff, reduce of hydraulic gradient and decrease the infiltration of water during rainfall event [13]. Moreover, lower flow velocity (223.93 cm/h) during rainfall intensity of 5 mm/h could enhance absorption of water in the pavement, hence, higher water infiltration occurred compared to higher flow velocity [14]. Velocity magnitude was influenced by rainfall intensity because increasing of rainfall volume will supply more energy to disturb the runoff flow, hence increase the velocity magnitude in the pavements [12].

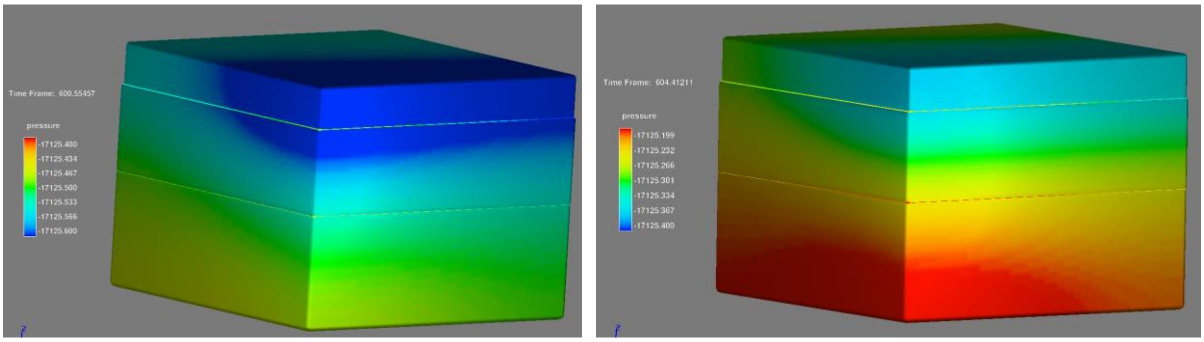


(a) 5 mm/h (b) 85 mm/h

Figure 3. Velocity magnitude for modular pavement under various rainfall intensities

3.3. Effect of Pressure with various of Rainfall Intensity

Figure 4 illustrates the simulation results of pressure for modular pavement at rainfall intensities of 5 mm/h and 85 mm/h. The maximum pore water pressure of modular pavement increased from -17125.4 Pa to -17125.2 Pa (the negative value indicated as the direction of water flow vertically downward or follow gravity) with the increased of rainfall intensity from 5 mm/h to 85 mm/h. Pore water pressure was influenced by rainfall intensity. Generally, stormwater that infiltrated into the pavement will formed a pressure on stormwater further down in the pavement profile, which created a sub-surface flow which increase the soil moisture and pore water pressure. At rainfall intensity of 85 mm/h, stormwater will infiltrate into the pavement which increasing the soil moisture. Hence, the soil moisture will be the highest, as well as highest pore water pressure [15]. However, increasing of pore pressure will increase the permeability of water and reduce the soil shear strength which induce infiltration of rainfall which prevent soil erosion [16]. Furthermore, the pressure was increased when stormwater flow through surface layer to sub-base layer at rainfall intensity of 5 mm/h and 85 mm/h due to the increasing of depth. In general, pressure increase when depth increase. The sub-base layer, which is the deepest in the modular pavement, has the highest pressure compared to surface and base layers.



(a) 5 mm/h (b) 85 mm/h

Figure 4. Pressure of modular pavement under various rainfall intensity

4. Conclusions

The presented finding showed that storage area modular pavement has lower fraction of fluid which means that it has greater holding capacity which able to capture all the rainfall at extreme flow. By comparing the simulation results of fraction of fluid for modular and conventional pavements (control), modular pavement indicates a better water interception capacity as compared to conventional pavement at rainfall intensities of 5 mm/h to 85 mm/h. This indicated that with the same volume of area, the capability of hold is differ between conventional and modular pavement. As the conventional pavement was made with impermeable substance and created more runoff than infiltrated into ground. The modular pavement was unbound and makes the water east to penetrate. The design also capable with the intensity of rainfall in Malaysia. In addition, modular pavement has strong influence on velocity magnitude and pressure. Both velocity magnitude and pressure increased when the rainfall intensity increased. In conclusion, these findings indicate that adding a storage area HDPE diagonal modular layer can improve the effectiveness of infiltration rate and reduce surface runoff for conventional pavement. The numerical simulation by FLOW-3D helps the pavement design process to model various geometries and configuration and great supplementary tool. With using FlOW-3D simulation helps the design of modular pavement is design well. The FLOW-3D help to understand the infiltration rate, velocities and pressure behaviour in modular pavement visually. So that the analysis of the modular pavement can be more critically analysis.

5. References

[1] O'Driscoll et al. 2010 Urbanization Effects on Watershed Hydrology and In-Stream Processes in the Southern United States *Water* 2 (3) 605–648

[2] Abustan et al. 2012 Review of Permeable Pavement Systems in Malaysia Conditions *OIDA International Journal of Sustainable Development* 4 (2) 27-36

[3] Abdurrasheed et al. 2019 Modelling of Flow Parameters through Subsurface Drainage Modules for Application in BIOECODS *Water* 11 (9) 1–15

[4] Mallick *et al*. 2003 An Evaluation of Factors Affecting Permeability of Superpave Designed Pavements. *AL, USA: NCAT Report 03-02* (National Centre for Asphalt Technology, Auburn University)

[5] Jabatan Kerja Raya. 2013 *Manual Pavement Design* 1–29.

[6] Tahmoorian F, Samali B, and Yeaman J. 2017 Evaluation of Structural and Thermal Properties of Rubber and HDPS for Utilasition as Binder Modifier *Modified Asphalt* (IntechOpen)

[7] Rashid M A, Abustan I, and Hamzah M O. 2013 Numerical Simulation of a 3-D Flow within a Storage Area Hexagonal Modular Pavement Systems *IOP Conference Series: Earth and environmental science* (Putrajaya, Malaysia)

[8] Pokharel S K, Martin I, and Breault M. 2013 Causeway Design with Neoweb Geocells *Proc. of Design and Practice of Geosynthetic-Reinforced Soil Structures* (Bologna, Italy) 351-358.

[9] Omotosho *et al. 2017* Earth-Space Rain Attenuation Prediction: It's Impact at Ku, Ka and V-Band over some Equatorial Stations *Proceeding of International conference on science and Sustainable Development (ICSSD): The role of science in novel research and advances in technology* (Center of research, innovating and discovery, Covenant University, Nigeria)

[10] Bean *et al.* 2004 Study on the Surface Infiltration Rate Permeable Pavements *1st water and environment specialty conference of the Canadian Society for Civil Engineering* (Saskatchewan, Canada)

[11] Zhao *et al.* 2018 Effect of Soil Surface Roughness on Infiltration Water, Ponding and Runoff on Tilled Soils under Rainfall Simulation Experiments *Soil and Tillage Research* 179 47–53

[12] Holden J 2005 Infiltration and Soil Water Process *Water Encyclopedia* 1-5-5 (14.5)

[13] Mineo *et al.* 2019 Assessment of Rainfall Kinetic-Energy-Intensity Relationship *Water* 11(1994) 1-23

[14] Khan *et al.* 2016 Effect of Slope, Rainfall Intensity and Mulch on Erosion and Infiltration

Under Simulated Rain on Purple Soil of South-Western Sichuan Province, China *Water* 8 (11) 1–18
[15] Fritzson H. 2017 *Effect of Environmental Factors on Pore Water Pressure in River Bank Sediments* (Solleftea: Sweden)
[16] Liu C W W, Ng H W and Feng S. 2015 Analytical Solutions for Calculating Pore-Water Pressure In an Infinite Unsaturated Slope with Different Root Architectures *Canada Geotech* 52 (12) 1981–1992