A 3-DIMENSIONAL NUMERICAL STUDY OF A FLOW WITHIN A PERMEABLE PAVEMENT

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Abstract: This numerical study has been performed to predict the flow patterns and characteristics within permeable pavement. Throughout the design and planning period for future construction are increasingly integrating computational fluid dynamics (CFD) into the process. As a result, engineers are interested in the reliability of CFD software to provide accurate flow data for a wide range of structures. CFD results have generally been in agreement with physical model experimental data.

A commercially known software, FLOW-3D, is applied to numerically solve the Navier-stokes equations for solution domains which are separated into three regions with overlapping boundaries to efficiently accommodate the grid resolutions, namely the honeycomb shaped modular, gravel and combined honeycomb shaped modular with gravel fill. The filtration of the fluid within the interstices of a permeable pavement, is evaluated by integrating the Reynolds Averaged Navier-Stokes equations (RANS) inside the voids rather than making use of the widespread "porous media" approach, such for example in Hsu et. al. (2002) and Lara et al (2006).

The calculated results such as pressure, velocities, flow rate, surface height are compared with the scale model data where available. The permeable pavement infiltration is in a good agreement with the measurement based on previous study by Yoo et al (2002).

In conclusion, the results from numerical simulation are generally well agreed with the existing data and flow information such as flow patterns at increased flow, discharge rate and pressure is obtained to be used for engineering design purpose. Overall, the potential for Flow-3D to model various geometries and configurations appears great. It should be noted that CFD should not be considered a complete replacement for physical modelling; however, it can definitely be used as a supplementary tool throughout the pavement design process.

***Keywords**:* Three-dimensional model, permeable pavement, infiltration, FLOW-3D.

INTRODUCTION

In the design process of any hydraulic structures, hydraulic model tests have usually been employed to verify the design concept with the aid of limited analysis tools as in previous study by Yoo et.al. (2002). In these days due to the advantage of the computer advancement, complicated engineering problems become a new computational approach using numerical methods, which complement the model test in a design process. The merit of numerical solution is that various probable flow phenomena can be simulated and calculated with minor input variations to obtain the data over the calculated domains. In this paper, numerical simulation using FLOW-3D is presented for the permeable pavement and their results are discussed.

Modelling Unsaturated Flow through Pavements

The unsaturated zone is located above the water table. Within this zone, the pore spaces are partially filled with water whereas the reminders of the voids are taken up by air. Therefore, the volumetric water content is lower than the soil porosity. Due to the fact that water in this zone is held in the soil pores under surface-tension forces, negative pressures or suction pressures are developed. In addition, in this zone both the volumetric water content and the hydraulic conductivity are function of this suction pressure. The soil volumetric water content is held between the soil grains under surface tension forces that are reflected in the radius of curvature of each meniscus. The hydraulic conductivity content increases with increasing the volumetric content (Freeze and Cherry, 1979).

In most cases, water in pavements is introduced to the pavement system through the process of infiltration into unsaturated pavement layers. Infiltration is a process in which water moves across the atmosphere-soil interface for example water seeps from the pavement ground surface and enters the base, subbase, and subgrade soils. The time rate at which water infiltrates across the atmosphere-soil interface is known as infiltration rate. The total volume of liquid crossing the interface over a given period of time is known as cumulative infiltration. Infiltration also signifies soil sorptivity. Under ponded conditions, infiltration into an initially dry soil profile has a high rate early in time, decreasing rapidly and then slowly settling down to nearly a constant rate (Tindall and James, 1999).

Water may infiltrate into the pavement from under a number of sources, some of the most common being surface water entering the pavement-shoulder joints, longitudinal as well as transverse construction joints and pavement cracks. Similarly, seasonal increase in ground water table elevation, along with a rise in the associated capillary fringe may allow near saturation of pavement components at various times.

Soil characteristics play an important role in the infiltration rate. Total infiltration of any layer depends upon its porosity, thickness and quantity of water or other liquid present. Soil texture, structure, organic matter, root activity, and other physical properties determine the magnitude of the porosity of a given soil (Tindall and James, 1999).

FLOW-3D background

FLOW-3D has the ability to ignore the air surrounding the flowing water by using the volume of fluid (VOF) method developed by Hirt and Nicholas (1981). This method also allows 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. Another method, developed by Hirt and Sicilian (1985), known as fractional area volume obstacle representation (FAVOR) method, is also a trademark of FLOW-3D. It allows the program to use fully structured grids that are very easy to generate throughout the entire flow domain. FLOW-3D utilizes a finite difference solution scheme and also has the ability to calculate solutions using various implicit and explicit solver options. The ability of using multiple and nested meshes as well as the re-run capability available in FLOW-3D are other options that make the numerical model suitable for permeable pavement modelling.

Numerical solutions to the problems based on the full Reynolds Averaged Navier-Stokes equations (RANS) with the Volume of Fluid surface tracking method (RANS/VOF) have indeed been thoroughly tested, and have found their way into engineering practice. Interesting examples of how these issues have been addressed both physically and numerically are, for instance reported in Karim et al (2009), Greben et al (2008), Hsu et al (2008), Lara et al (2008), Lin et al (2002), Lara et al (2006), Garcia et al (2004), Ting et al (2004), Hur et al (2003), Huang et al (2003), Hsu et al (2002), Requejo et al (2002), Tirindelli et al (2000), Lin et al (1998), can Gent (1995).

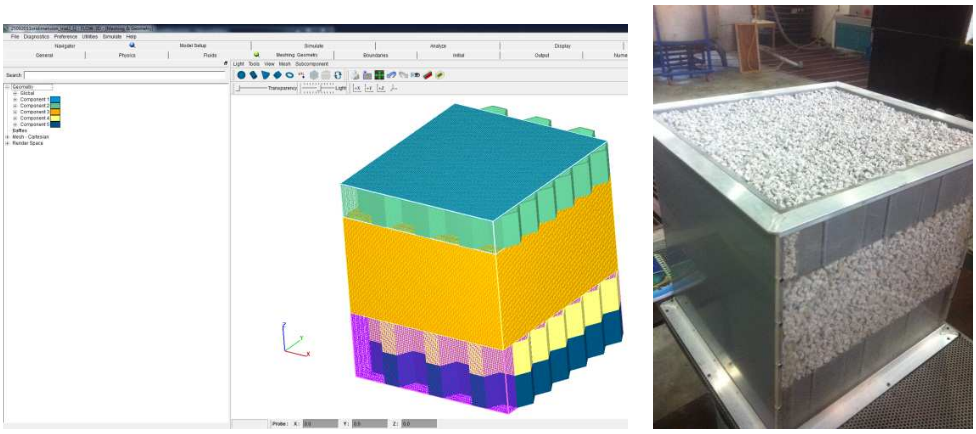
Modelling approach

The physical model of the permeable pavement was placed in a rectangular flume as shown in Figure 1. In this permeable pavement, it has three different layers consists of surface layer, gravel base and sub-base. In this paper, numerical simulation using FLOW-3D is presented for the permeable pavement as shown in Figure 2(a) based on physical model specifically in Figure 2(b) and their discussed compared with existing data where available.

Models of Permeable Pavement

For the present study a full scale model of the permeable pavement was made in FLOW-3D, 3-dimensionl surfaces in a stereolithographic (STL) CAD format were generated as shown in Figure 3, and subsequently 3-dimensional solid models were constructed using a CAD tool for each region. Table 1 shows the sizes and numbers of meshes for each domain.

Figure 1: Physical model of the permeable pavement in laboratory

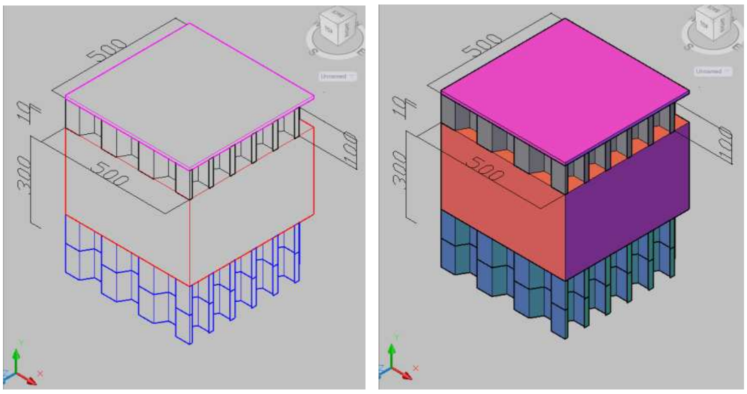


(a) (b)

Figure 2(a): Permeable pavement 3-dimensional model in FLOW-3D
Figure 2(b): Permeable pavement physical model

Table 1: Domain sizes and meshes for each domain

Direction	Mesh 1	Mesh 2	Mesh 3
X distance	525mm	525mm	525mm
Mesh No.	105	88	105
Y distance	563mm	563mm	563mm
Mesh No.	113	94	113
Z distance	10mm	300mm	200mm
Mesh No.	21	50	40
Total Mesh No.	249165	413600	474600



(a) (b)

Figure 3: (a) Model permeable pavement in (STL) CAD format
(b) A 3-dimensional model generated from STL

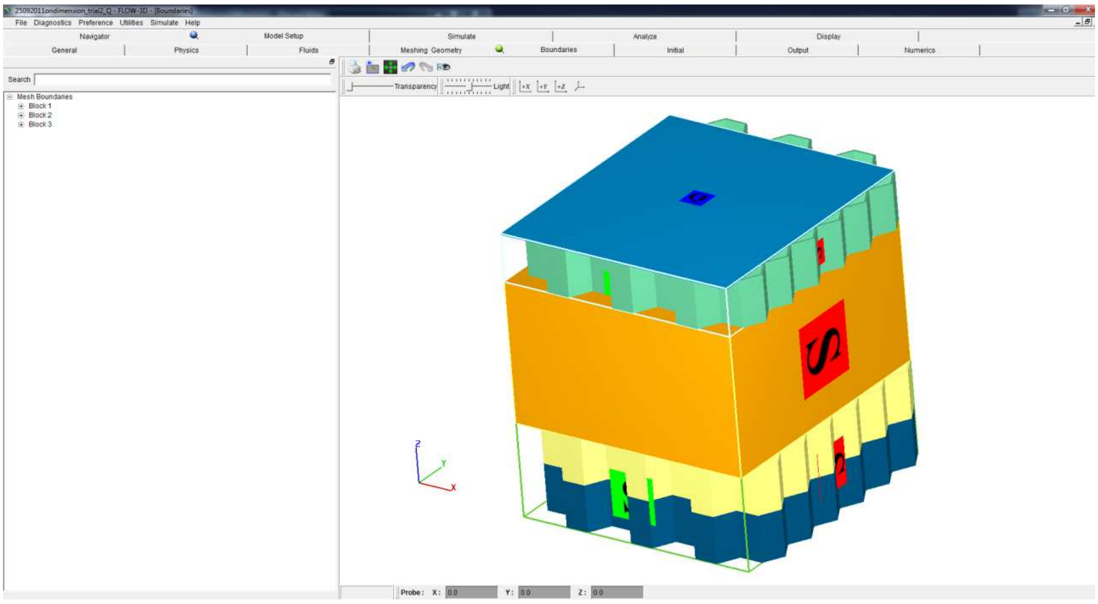


Figure 4: Boundary condition of permeable pavement model in FLOW-3D

Table2: Summary of boundary conditions for each domain

	Mesh 1	Mesh 2	Mesh 3
XMIN	Symmetry	Symmetry	Symmetry
XMAX	Symmetry	Symmetry	Symmetry
YMIN	Symmetry	Symmetry	Symmetry
YMAX	Symmetry	Symmetry	Symmetry
ZMIN	Continuative	Continuative	Wall
ZMAX	Volume flow rate	Symmetry	Symmetry

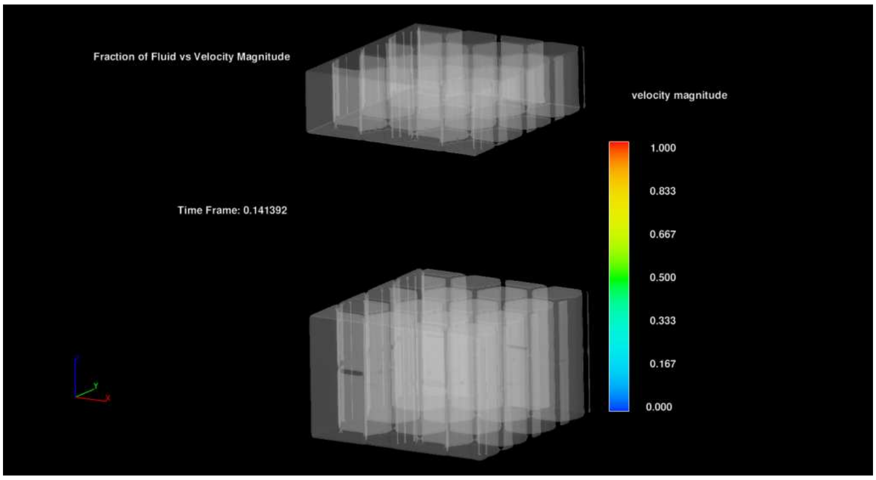


Figure 5: Velocity magnitude at time frame 0 seconds

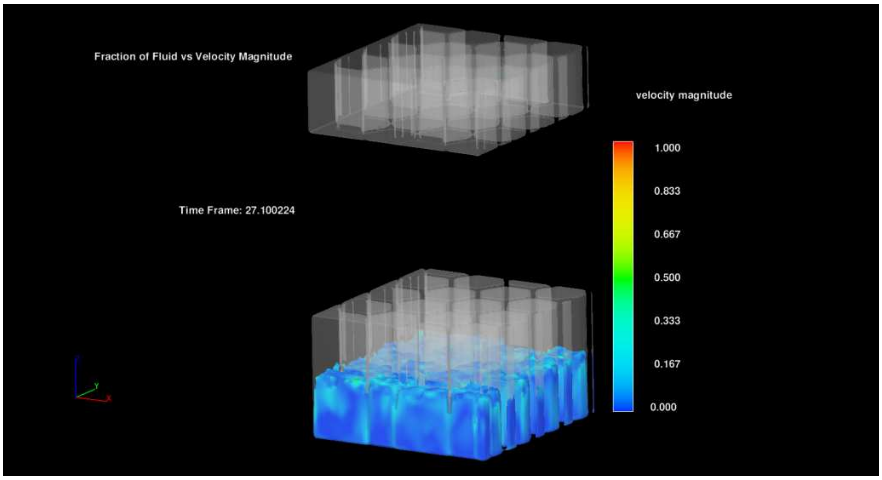


Figure 6: Velocity magnitude at runtime 27 seconds

Boundary Conditions

Currently, the calculation domains are divided into three sequential zones with overlapping boundaries, which enable the calculations to efficiently make use of meshes as well as to avoid the time step limitations due to high infiltration at the module. Inlet conditions of the permeable pavement are set as volume flow rate of 0.00032 m^3/s to visualise 64 mm/hr rainfall intensity. Whereas the bottom of boundary block 1 set as continuative. Boundary conditions for both inlet and outlet of block 2 have set as continuative because to allow water infiltrate. Block 3 has different inlet outlet as block 1 where the inlet is a continuative while the bottom is wall to visual no infiltration. Velocity and discharge with respect to time while downstream boundary conditions of the permeable pavement can be described using an outflow for unsaturated and wall for saturated. For the permeable pavement simulation, calculated inflow discharge and velocity are used to derive the inflow boundary conditions, while for the downstream, continuation conditions are used. As for each sides of boundary, symmetry condition selected as to visualise experiment model. For other conditions, no slip conditions are applied for the walls and boundaries present, and atmospheric pressure conditions for the top as shown in Figure 4. The table 2 shows the summary of the boundary conditions applied for each domain.

INITIAL RESULTS AND DISCUSSION

While laboratory scale permeable pavement columns are helpful in understanding the processes that occur within a permeable pavement, Chanel and Doering (2007) found they are not necessarily completely representative of a field infiltration system. Quantity and delivery of flows through the laboratory rig are different from those encountered in the field, maintaining a constant level, for example, is not reflective of field conditions. However, these infiltration help us to understand the processes responsible for hydraulic and water quantity behaviour, in a way that cannot be done by using field monitoring.

The flow pattern within permeable pavement can be monitored in 3-dimensional as shown in Figure 5. From this observation, the surface velocity distribution for permeable pavement varies with different porosity for each layer. Initial velocity was zero as shown in Figure 6, input data for Z max boundary condition was 2.04m/s due to terminal velocity of rainfall of moderate rainfall simulation. Water level and velocity magnitude simulated were at the same level to observation data of model during run time 27 sec total runtime as shown in Figure 6. In general, a good agreement is found between the physical experiment and numerical simulation in terms of water surface variation in time and space as studied in Karim et.al. (2009) in their study about modelling and simulation of wave transformation in porous structures using VOF based two-phase flow model. These results verify the model accuracy and stability.

SUMMARY AND CONCLUSIONS

The simulation predicted the velocity fields quite well. The flow features at each layer of permeable pavement showed the very strong velocity magnitude. With this investigation, it is considered that FLOW-3D can reasonably predict the real flow within permeable pavement. In conclusion, it is suggested that numerical data and the scale model test should serve the design purpose complementing each other.

REFERENCES

[1] Chanel, P.G., and Doering, J.C., (2007). An evaluation of computational fluid dynamics for spillway modelling. In Proceedings of the 16th Australasian Fluid Mechanics Conference (AFMC), Gold Coast, Queensland, Australia, 3-7 December 2007. pp. 1201-1206.

[2] Gracia, N., Lara, J.L., Losada, I.J., (2004). 2-D numerical analysis of near-field flow at low-crested breakwaters. Coastal Engineering 51 (10), 991-1020.

[3] Greben, J.M., Cooper A.K., Gledhill I., de Villiers R. (2008). Numerical modelling of structures of dolosse and their interaction with waves.

[4] Hirt, C.W., and Nichols, B.D., (1981). Volume of Fluid (VOF) method for the dynamics of free boundaries. Journal of Computational Physics, 39(1): 201-205. doi: 10.1016/0021-9991(81)90145-5.

[5] Hirt, C.W., and Sicilian, J.M., (1985). A porosity technique for the definition of obstacles in rectangular cell meshes. In Proceedings of the 4th International Conference on Ship Hydro-dynamics, Washington, D.C., 24-27 September 1985. National Academy of Sciences, Washington, D.C.

[6] Hsu T.J., Sakakiyama, T., Liu P.L.F., (2002). A numerical model for wave motions and turbulence flows in front of a composite breakwater. Coastal Engineering 46, 25-50.

[7] Hsu T.W., Chang J.Y., Lan Y.J., Lai J.W., Ou S.H., (2008). A parabolic equation for wave propagation over porous structures. Coastal Engineering 55, 1148-1158.

[8] Huang C.J., Chang H.H., Hwung H.H., (2003). Structure permeability effects on the interaction of a solitary wave and a submerged breakwater. Costal Engineering 49, 1-24.

[9] Hur D.S., Mizutani N., (2003). Numerical estimation of the wave forces acting on a three dimensional body on submerged breakwater. Coastal Engineering 47, 329-345.

[10] Karim M.F., Tanimoto K., Hieu P.D., (2009). Modelling and simulation of wave transformation in porous structures using VOF based two-phase flow model. Applied Mathematical Modeling 33, 343-360.

[11] Lara J.L., Garcia N., Losada I.J. (2006) - RANS modelling applied to random wave interaction with submerged permeable structures. Coastal Engineering 53, 395–417.

[12] Lara J.L., Losada I.J., Guanche R. (2008) - Wave interaction with low-mound breakwaters using a RANS model. Ocean Engineering 35, 1388–1400.

[13] Lin P., Karunarathna S.A.S.A. (2007) - Numerical study of solitary wave interaction with porous breakwaters. Journal of waterway, port, coastal and ocean engineering Sep/Oct2007, 352-363.

[14] Lin, P., Liu, P.L.-F., (1998) - A numerical study of breaking waves in the surf zone. Journal of Fluid Mechanics 359,239-264

[15] Requejo, S., Vidal, C., Losada, I.J., (2002) - Modelling of wave loads and hydraulic performance of vertical permeable structures. Coastal Engineering 46, 249–276.

[16] Ting C.L., Lin M.C., Cheng C.Y. (2004) - Porosity effects on non-breaking surface waves over permeable submerged breakwaters. Coastal Engineering 50, 213–224.

[17] Tirindelli M., Lamberti A., Paphitis D., Vidal C., Hawkins S., Morchella P., Sanchez-Arcilla A. (2000) – Wave action on rubble mound breakwaters: the problem of scale effect. DELOS EVK3-CT-2000-00041

[18] van Gent M.R.A. (1995) - Porous flow through rubble-mound material. Journal of Waterway Port Coastal and Ocean Engineering. May/June 1995, 176-181.

[19] Yoo S., Hong K., and Hwang M., (2002). A 3-dimensional numerical study of a flow patterns around a multipurpose dam. In Proceedings of the 5th International Conference on Hydroinformatics, Cardiff, UK, 353-357.