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3D MODELLING OF STORMPAV GREEN PAVEMENT AT ROAD SHOULDER

Lui Zi Sheng

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3D MODELLING OF STORMPAV GREEN PAVEMENT AT ROAD SHOULDER

LUI ZI SHENG

A dissertation submitted in partial fulfilment
of the requirement for the degree of
Bachelor of Engineering with Honours
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Special thanks to my beloved parents, brothers, sisters and my fellow friends

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ABSTRACT

Rapid disposal of surface runoff to urban drains in conventional road drainage system makes it an ineffective measure to mitigate flood. Hence, On-Site stormwater Detention (OSD) is one of the common approaches to reduce the runoff volume in the dense developed areas. Normally, typical underground OSD facilities consist of tanks and pipe packages which increase the cost and complexity in construction. In this study, StormPav Green Pavement system is introduced as an alternative construction method to create the stormwater detention chamber. Dimension of a typical road shoulder in a housing estate is utilized as single unit of the stormwater detention system. Computational Fluid Dynamics (CFD) is applied on StormPav Green Pavement System as combined road shoulder and stormwater detention structure by utilizing SolidWorks Flow Simulation. Applicability of the system is tested by simulating flow through the multiple chambers within StormPav system via road curb-opening inlet and outlet. The CFD simulations demonstrate flow patterns resulted from 5-minute, 10-min and 15-min 10-year ARI design rainfall subjected to three design models with different locations of outlet (centerline, edge, between centerline and edge). The distance of inlet and outlet is found to play a major role in the flow pattern in the StormPav system. It is found that outlet located at edge is the ideal design for such a system. It has the most distributed flow and variations of velocity in the closed system. The further the outlet away from the inlet, the more the CFD simulations show flow trajectory plots that suggest a water mixing quality. This finding is interestingly point to a self-cleansing ability in the StormPav system that suggests the flow pattern is favorable to flush out sediments carried by stormwater from roads.

ABSTRAK

Sistem saliran konvensional jalan raya yang mempraktikkan pelupusan air larian hujan secara pantas ke dalam longkang tidak efektif dalam mengelakkan kejadian banjir. Oleh itu, On-*Site stormwater Detention (OSD)* iaitu infrastruktur saliran di tapak adalah salah satu pendekatan biasa untuk mengurangkan volume air larian di kawasan bandar yang padat. Struktur bawah tanah OSD bisanya mengandungi tangki dan pakej paip yang meningkatkan kos dan kerumitan dalam pembinaan insfrastruktur tersebut. Dalam projek ini, *StormPav Green Pavement System* dikenalkan sebagai kaedah pembinaan alternatif bagi membina ruang penahanan air hujan. Dimensi tipikal bahu jalan raya di kawasan perumahan digunakan sebagai dimensi seunit sistem penahanan air hujan. *Computational Fluid Dynamics (CFD)* iaitu kaedah dinamik bendalir berkomputeran diaplikasikan ke atas *StormPav Green Pavement System* sebagai kombinasi bahu jalan raya dan struktur penahanan air hujan dengan menggunakan *SolidWorks Flow Simulation.* Kebolehgunaan sistem tersebut dikaji dengan mensimulasikan pengaliran melalui ruang-ruang dalam sistem StormPav dari pembukaan berbendul jalan hingga ke outlet. Simulasi CFD mendemonstrasikan corak pengaliran apabila 5-minit, 10-minit dan 15-minit 10-tahun Selang Hujan Tahunan ditaklukkan ke tiga model reka bentuk yang mempunyai outlet di lokasi berbeza (tengah, hujung, antara tengah dan hujung). Jarak antara pembukaan masuk dan outlet didapati memainkan peranan utama dalam corak pengaliran dalam sistem StormPav. Outlet terletak di hujung model didapati sebagai reka bentuk ideal bagi sistem tersebut. Ia menunjukkan pengedaran pengaliran dan variasi halaju yang paling seimbang bagi sistem tertutup tersebut. Locasi outlet yang semakin jauh dari pembukaan masuk, semakin terangnya simulasi CFD menunjukkan plot trajektori pengaliran yang mencadangkan kualiti pencampuran air. Pencarian menarik ini mencadangkan bahawa corak pengaliran dalam sistem StormPav dapat mengusir sedimen yang dibawa masuk oleh air hujan dari jalan raya.

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LIST OF ABBREVIATIONS

ARI	-	Average Recurrence Interval
CAD	-	Computer-Aided Design
CFD	-	Computational Fluid Dynamics
DID	-	Department of Irrigation and Drainage
IBS	-	Industrialized Building System
LIDs	-	Low-Impact Development System
MSMA	-	Manual Saliran Mesra Alam
OSD	-	On-Site Detention
SUDs	-	Sustainable Urban Drainage System
SWMM	-	Stormwater Management Model
USEPA	-	United State Environmental Protection Agency

Chapter 1

INTRODUCTION

1.1 Problem Statement

Conventional urban drainage system with road curb focused on removing surface runoff as quickly as possible and is deemed to be unfit in dense urban built environment todays. Current drainage system is increasingly challenged mainly due to increasing rain intensity and urbanization. Total rainfall amount and the frequency of wet days in Malaysia are observed to have an increasing trend for the past 30 years (Zawiah et al, 2010).

Addition of impervious road surfaces in urbanized areas leads to increase of runoff volume and decrease in the ability to deal with runoff load. During rainfall, runoff from the road surfaces is directly discharged into urban drain to cause the surface runoff volume to increase rapidly and hence, frequent flash flood. To overcome the dire situation, an idea is brought up to make use of road shoulder for On-Site Detention (OSD) system. OSD is one of the measures introduced in the Malaysian Urban Stormwater Management Manual (MSMA) to minimize impacts of urbanization towards urban water management.

This project is an extension of Ng (2016) in which the author suggested merging of road curb with hollow infiltration trench would be effective in reducing peak runoff against 15-minute 10-year Average Recurrence Interval (ARI) design rainfall. The investigations were carried out using the Storm Water Management Model (SWMM) in which a hollow infiltration trench has demonstrated to could reduce peak runoff (see Figure 1.1).

Chapter 2

LITERATURE REVIEW

2.1 Road Drainage System

Urban drainage is one of the most crucial elements to be carefully examined and considered in any development project. Effective drainage of paved surface is essential to the maintenance of road service levels and to traffic and public safety. Since the beginning of urbanization, drainage systems have existed as important city infrastructures to collect and convey stormwater away from urban areas (Chocat et al, 2007). However, conventional drainage systems generally have caused the increase in occurrence of flash flood (Zakaria et al, 2004). Among the causes, impacts due to urbanization and climate change have been widely acknowledged.

Developing countries in the humid tropics usually do not consider the impact of urbanization on drainage flow during development. Generally, the impervious area from urban development upstream leads to increase of flooding peak at downstream (Tucci, 2001). Physical developments increase impervious surface areas and thus the surface runoffs in town during rainfall events. In a natural forest, several processes take place which used up some of the rain water. The vegetation not only reduces amount of runoff that eventually ends up at downstream but also increases total lag time. Leaves and stems of plants slow runoff while pervious soil surface allows groundwater recharge as the water percolates through. Even during heavy rains when runoff flows over ground surface, the runoff is slowed and naturally filtered before it reaches river. In urban areas, permeable vegetated surfaces have been replaced with man-made surfaces such as concrete, cement or tar that are impervious to water. Under these urban conditions, most of rainfall contributes to surface runoff and directly discharged into rivers in a short duration. In Ruslan (1994), rapid disposal of water into constricted river channel results in flash flood when the river's discharge capacity is exceeded.

Climatic variability that includes increasing rainfall intensity also caused anticipated impacts on urban drainage system. In Willems et al. (2013), the expected increase in design intensities due to climate change can up to eighty percent, depending on the region. The average annual rainfall in Malaysia is recorded to be around 3000mm with the average rainfall of 3830mm in Sarawak (Alnaimi, Murugasen & Al-Qrimli, 2015). As a tropical country, increasing rainfall is expected to cause severe capacity problems in the urban drainage system.

Conventional drainage systems in most country are mainly single-objective oriented design with its focus on collect and remove runoff from urbanized areas in shortest duration through drainage networks to closest receiving water bodies (Stahre, 2006). Road curb is one of the features of pavement carriageway which conveys surface runoff, including a portion or all the travel lane (DID, 2012). Road curbs are used to collect runoff and discharge it to downstream storm drainage system. The system focuses on water quantity control where water is treated as nuisance in the landscape and hence removed as soon as possible (Chocat et al, 2007). The system does not concern for water quality issues as well as long-term sustainability on the environments. In Stewart & Hytiris (2008), traditional drainage involves a significant amount of structural measures including concrete channels and pipes. In Huong and Pathirana (2013), rapid urbanization and global climate change could cause a substantial increase in the frequency and magnitude of urban flooding in many regions of the world. As the cost and time needed for restoration and installation of the system are tremendous, expanding conventional drainage as countermeasure for climate change and urbanization may not meet the criteria of sustainability (Hellstrom, Jeppsson & Karrman, 2000). Therefore, a sustainable engineering solution is needed to improve the control of stormwater in urban areas.

In this study, conventional system with road curb is merged with StormPav Green Pavement to solve the problem associated with degradation of ecosystem structure and function. Runoff velocities induced by road curbs can be reduced by modifying the road curbs, allowing the runoff to be spread over the porous materials within. Eliminating road curbs is generally not feasible for commercial and industrial roads. Consequently, the context of merging both road curbs and StormPav Green Pavement is gaining relevant.

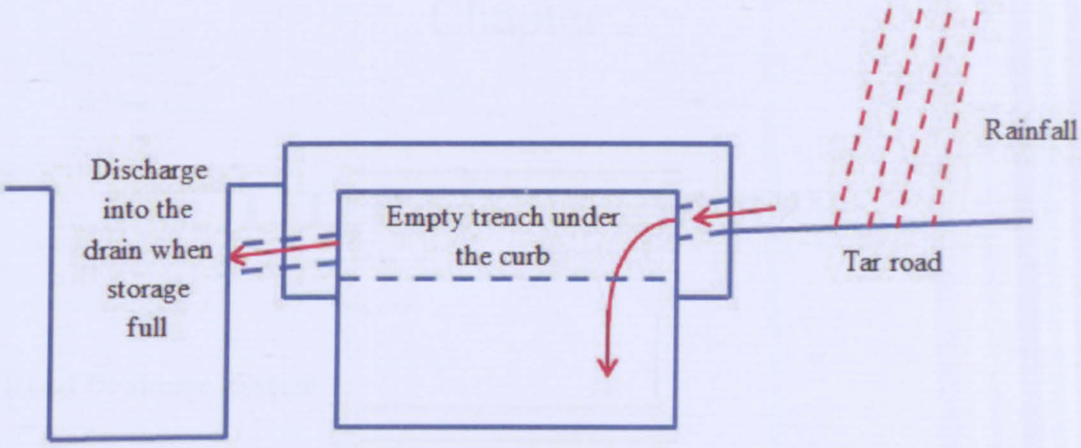

Figure 1.1: Hollow Infiltration Trench merged with Road Curb (Ng, 2016).

Continuing from the previous project, a form of Industrial Building System (IBS) precast-concrete pieces with hollow compartment is introduced here. It is named StormPav Green Pavement System. Construction wise, StormPav allows assembling of the pieces as the road shoulder and also incorporating a function of OSD to the road shoulder. Details of this system is presented in the literature review. Due to StormPav's compartmentalize nature, a 3D modelling using SolidWorks is utilized in this project.

1.2 Objectives

1. To develop a 3D model using SolidWorks of stormwater conveyance system by incorporating the StormPav as road shoulder; and
2. To determine the flow characteristics when StormPav is inserted as OSD at road shoulder.

2.2 StormPav Green Pavement

Conventional urban road drainage system with road curb and hard shoulder is analyzed in this study. The system practices rapid disposal of stormwater by directly discharge it into drainage downstream as shown in Figure 2.1. This system is no longer effective to mitigate flood especially during heavy rain. Therefore, StormPav Green Pavement system is introduced here for road shoulder as an alternative strategy to fight against urban flash flood.

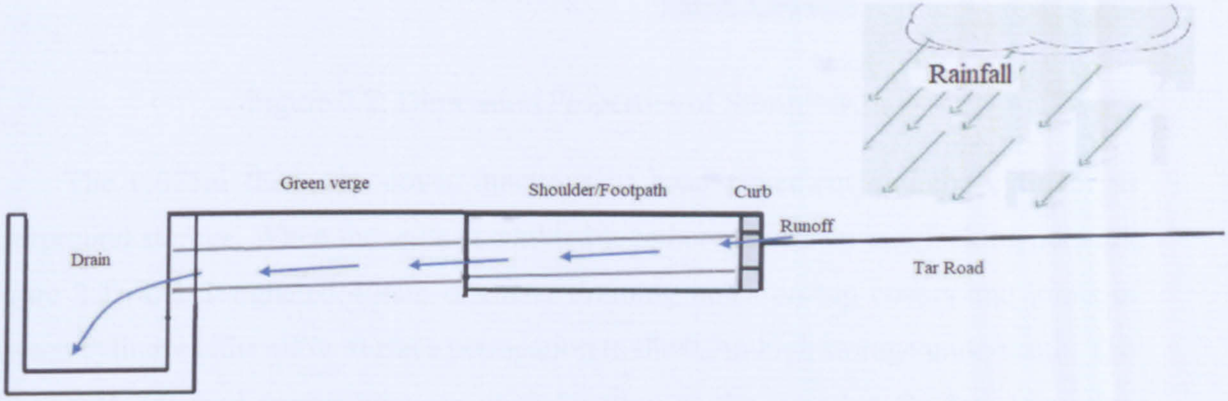

Figure 2.1: Direct Discharge of Stormwater in Conventional Drainage System.

StormPav is designed to be a combination of road pavement and underground stormwater detention system (Mah, 2016). A single modular unit consists of three precast concrete pieces, namely a top cover, a bottom plate and a hollow cylinder is showed in Figure 2.2. The IBS modular unit is casted with specially designed Grade 50 concrete mix which could withstand a crushing load of 100kN/unit (Mah, et al., 2018a).

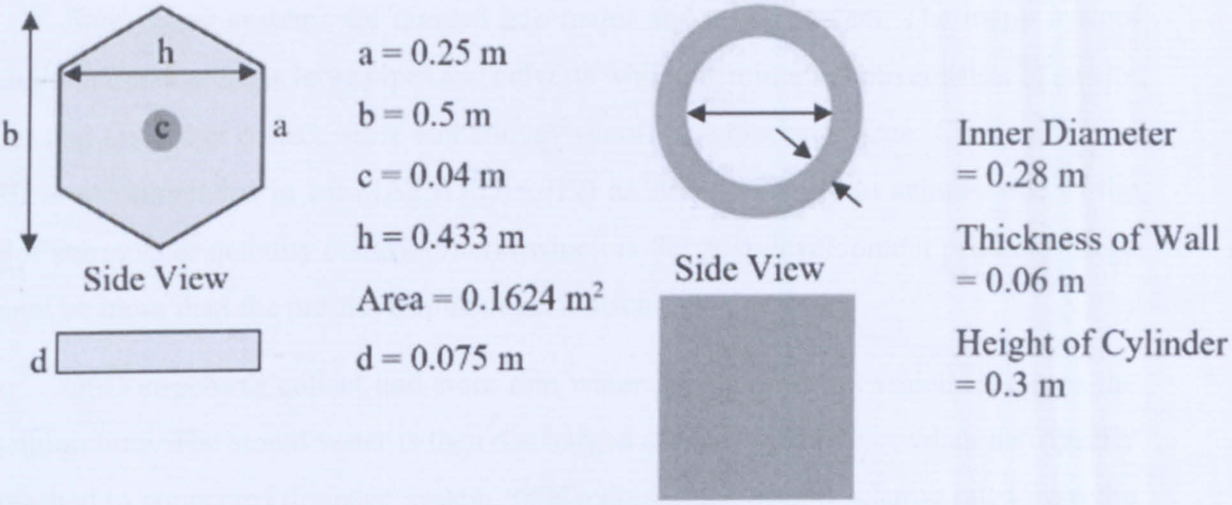

Figure 2.2: Dimension Properties of StormPav.

The 0.075m thick top cover functions as road pavement and the cylinder as underground storage. When the units assembled together to form an interlocking network (Figure 2.3), the designated 40mm diameter draining holes on top covers and joints in between cylinder units allow surface permeation to the 0.3m high storage underneath. The hollow cylinders and spaces between units function as the intended On-Site Detention (OSD) storage in the pavement system with a capacity of $0.19 m^3/m^2$ of pavement area. Similar to the top cover, bottom plate that rests on subgrade is designed with opening, which allows infiltration to take place to the surrounding soil.

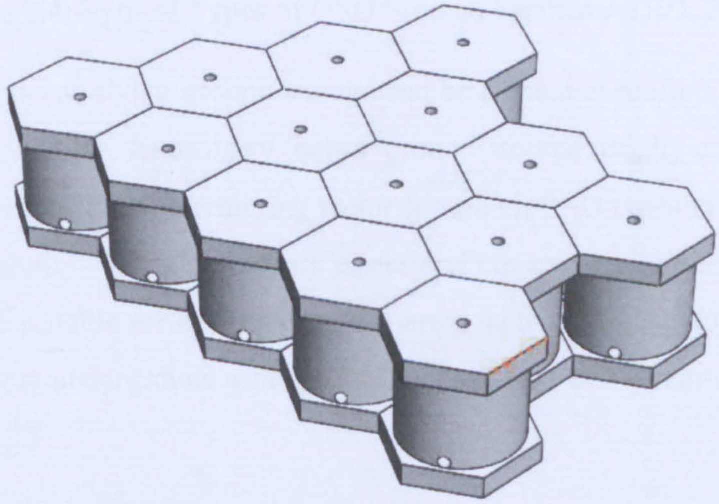

Figure 2.3: Interlocking StormPav Units.

Stormwater systems are divided into major and minor system. The major system includes natural streams, large pipes and culverts while the minor system consists of swales, pipes and OSD that collect, store and convey runoff to a discharge area. Construction of OSD is recommended in MSMA2 (DID, 2012) as storage facility to achieve one of the major stormwater quantity control criteria which is the post-development peak discharge cannot be more than the pre-development peak discharge.

OSD structures collect and store rain water during an event which increases the detention time. The stored water is then discharged at controlled rate or when its capacity is reached to connected drainage system, thus reducing the peak discharge rates from the site. In DID (2012), construction of such storage facilities can be above-ground, below-ground or combination of both as displayed in Figure 2.4.

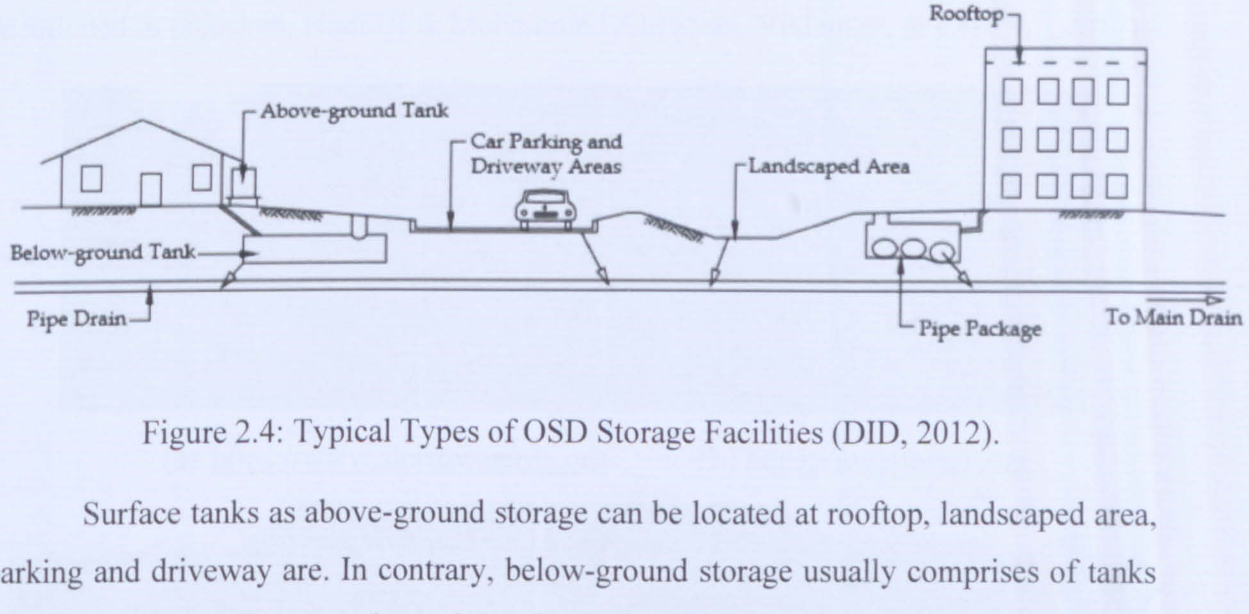

Figure 2.4: Typical Types of OSD Storage Facilities (DID, 2012).

Surface tanks as above-ground storage can be located at rooftop, landscaped area, parking and driveway are. In contrary, below-ground storage usually comprises of tanks and pipe packages. The core determining factor for which OSD types to be constructed is on the land availability. Surface tanks are easier and cheaper while underground storage facilities are more suitable for developed urban areas as they take up no valuable surface land area. A typical underground storage tank constructed using reinforced concrete is showed in Figure 2.5.

Figure 2.5: Typical Underground Water Tank (www.precast.org).

Installation of water tanks usually requires site preparation in order to fit in large size of such tanks. Custom design is needed when it comes to specific site conditions such as providing storage for developed areas with limited space. Some other examples of OSD are infiltration trench, pervious road pavement, vegetative swale and rain garden that are adjacent to roads (see Figure 2.6). These are hence the control-at-source approaches mentioned in (Blecken, Hunt III & Mohammed Al-rubaei, Viklander, & Lord W., 2017)

(a) https://www.stormwaterpa.org (b) https://ascelibrary.org

(c) https://prj.geosyntec.com (d) https://phys.org

Figure 2.6 OSD for urban road drainage, (a) Infiltration trench, (b) Pervious road pavement, (c) Vegetative swale and (d) Rain garden.

StormPav comes with small precast concrete pieces that provide the needed flexibility in term of installation in developed urban area. StormPav occupies less underground area and can be implemented in most urban areas. In this case, StormPav is implemented as the pavement of road shoulder, providing a stormwater detention storage underneath that could capture surface runoff at the same time. This could overcome the limitations of road curb system while benefits of road curb in road access control and stormwater conveyance are maintained. The small concrete pieces allow easy assembly, making StormPav suitable to merge into urban drainage system as road shoulder. While incorporating function of OSD in the system, the benefits of infiltration is also provided. The implementation of StormPav in drainage system can be used to mitigate the impacts of urbanization as groundwater recharge is allowed through the designed openings at bottom plates of StormPav units.

2.3 Modelling of Urban Drainage System

2.3.1 Storm Water Management Model (SWMM)

The practice of using modelling techniques to evaluate field data that are difficult or impossible to measure, has now become well-known for a range of flow analysis (Rinaldi & Darby, 2008). SWMM is utilized in this study to compute peak runoff of selected catchment area. SWMM is a distributed, dynamic rainfall-runoff simulation model used for single rainfall event or long-term (continuous) simulation of runoff quantity and quality from primarily urban areas (Rossman, 2010).

SWMM is first developed and distributed in 1971 under the sponsorship of the United States Environmental Protection Agency (USEPA). The model has undergone several upgrades and the latest version of this simulation model is SWMM 5. SWMM 5 provides an integrated environment for editing study area input data, running hydrologic, hydraulic and water quality simulations, while results can be displayed in different formats. It becomes increasingly popular to be used in drainage and stormwater studies.