



Faculty of Engineering

**Potential of StormPav Green Pavement System  
Incorporating Stormwater Management**

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Potential of StormPav Green Pavement System  
Incorporating Stormwater Management

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## **DECLARATION**

I LOH SIEW LING, 16020128, FACULTY OF ENGINEERING hereby declare that the work entitled POTENTIAL OF STORMPAV GREEN PAVEMENT SYSTEM INCORPORATING STORMWATER MANAGEMENT is my original work. I have not copied from any other students' work or from any other sources except where due reference or acknowledgement is made explicitly in the text, nor has any part been written for me by another person. The thesis has not been accepted for any degree and is not concurrently submitted in candidature for any other degree.

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Loh Siew Ling (16020128)

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Date Submitted

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May the Almighty God richly bless all of you.

## **ABSTRACT**

This study is exploring the potential of transforming a conventional road intersection into a StormPav system, where multiple units of modular units are assembled together for traffic movement and road drainage. Incorporating with the urban stormwater management, a newly added function of the high strength concrete precast modules includes storing stormwater inside the internal module chambers during downpour. In order to remove standing water from road surface, service inlets are provided on the pavement to infiltrate the runoff at a controlled rate. This implication is tested in the laboratory and further verified through Computational Fluid Dynamics (CFD) simulations. As a result, both studies show that the surface running water is fully infiltrated through the service inlets that function like a multiple-orifice plate. The surface infiltration rate of the service inlet is found at a range of 5,000 – 20,000 mm/hr. Moreover, it is found that the range is of great advance compared to other products in the market. This work implies that multi-orifice road intersection is applicable for busy urban areas as it offers a solution to improve the existing road drainage during rainy season without disruption to traffic movement.

**Keywords:** Computational Fluid Dynamics (CFD), Industrialised Building System (IBS), SolidWorks, StormPav

**Potensi Persimpangan Jalan yang Berbilang Tujuan dengan  
Menggabungkan Pengurusan Air Larian**

**ABSTRAK**

*Kajian ini meneroka potensi mengubah persimpangan jalan konvensional kepada sistem StormPav, di mana pelbagai modular unit dipasangkan bersama untuk pergerakan lalu lintas dan saluran air atas jalan. Menggabungkan dengan pengurusan air ribut di bandar, Fungsi baru konkrit pratuang berkekuatan tinggi ditambah adalah termasuk menyimpan air ribut di dalam ruang modul dalaman semasa hujan lebat. Untuk menghilangkan air bertakung dari permukaan jalan, inlet servis disediakan untuk menyusup larian pada kadar terkawal. Implikasi ini diuji di makmal dan disahkan selanjutnya melalui simulasi Bendalir Dinamik (CFD). Hasilnya, kedua-dua kajian menunjukkan bahawa permukaan air yang mengalir sepenuhnya menyusup melalui saluran masuk yang berfungsi seperti “multiple-orifice plate”. Kadar penyusupan permukaan didapati pada kadar 5,000 - 20,000 mm / jam. Di samping itu, didapati bahawa kadar penyusupan ini adalah lebih besar berbanding dengan produk lain di pasaran. Hal ini menunjukkan bahawa persimpangan jalan pelbagai guna adalah sesuai digunakan di kawasan bandar yang sibuk kerana ia menawarkan penyelesaian untuk memperbaiki saluran jalan yang sedia ada semasa musim hujan tanpa gangguan kepada pergerakan lalu lintas.*

**Kata kunci:** Pengiraan dinamik bendalir, Sistem bangunan perindustrian, SolidWorks, StormPav

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## **LIST OF ABBREVIATIONS**

|     |                                       |
|-----|---------------------------------------|
| ARI | Average Rainfall Intensity            |
| CFD | Computational Fluid Dynamics          |
| DID | Department of Irrigation and Drainage |
| GI  | Green Infrastructure                  |
| IBS | Industrialized Building System        |
| ICP | Interlocking Concrete Pavement        |
| IDF | Intensity-Duration-Frequency          |
| MHO | Multi-Hole Orifice                    |
| OSD | On-site Stormwater Detention          |
| SHO | Single Hole Orifice                   |

# CHAPTER 1

## INTRODUCTION

### 1.1 Background

With the advancement of urban development, most of the landscape areas are paved with impervious pavement and concrete surfaces which disrupt the stormwater to penetrate into the soil for infiltration and to recharge groundwater. Over a timespan, the retaining water on the impervious surfaces might cause hydrological disaster such as flash flood, especially during intense storms (Hoedjes et al., 2014). Furthermore, surface runoff also brings inconveniences to the surrounding communities. As an illustration, water ponding on the tarred road can be dangerous when the road users are trying to avoid it by moving away from their own way, which potentially leads to the occurrence of accidents. Likewise, water is one of the destructing threats to asphalt pavement that causes severe impacts on the pavement, such as weakening the strength of pavement when water is penetrating and saturating the asphalt pavement layer through the surface cracks or voids (Dawson, 2009).

To ameliorate the hydrological impacts of urban development, On-Site Detention (OSD) storage is an effective functioning system to resolve the drainage problems by retarding the peak runoff and enlarging the storage capacity within a limited space (O'Loughlin et al., 1995; Coombes et al., 2001). Adhering to this concept, StormPav<sup>1</sup> – a precast concrete modular unit is invented as a mini detention storage to be installed underground for stormwater management purposes (Mannan et al., 2016). As demonstrated in Figure 1.1, each StormPav modular unit is composed of two hexagonal plates which act as a top cover and bottom plate, meanwhile a hollow cylinder is placed at the intermediate layer for stormwater detention. Furthermore, a service inlet in the form of an orifice is

provided for each hexagonal plate to drain off the storm runoff from road surface to underground storage and subsurface. Moreover, these multiple units of StormPav also perform as a pavement structure with high structural strength to support traffic loadings. Further information about StormPav detention system is discussed in Section 2.4.

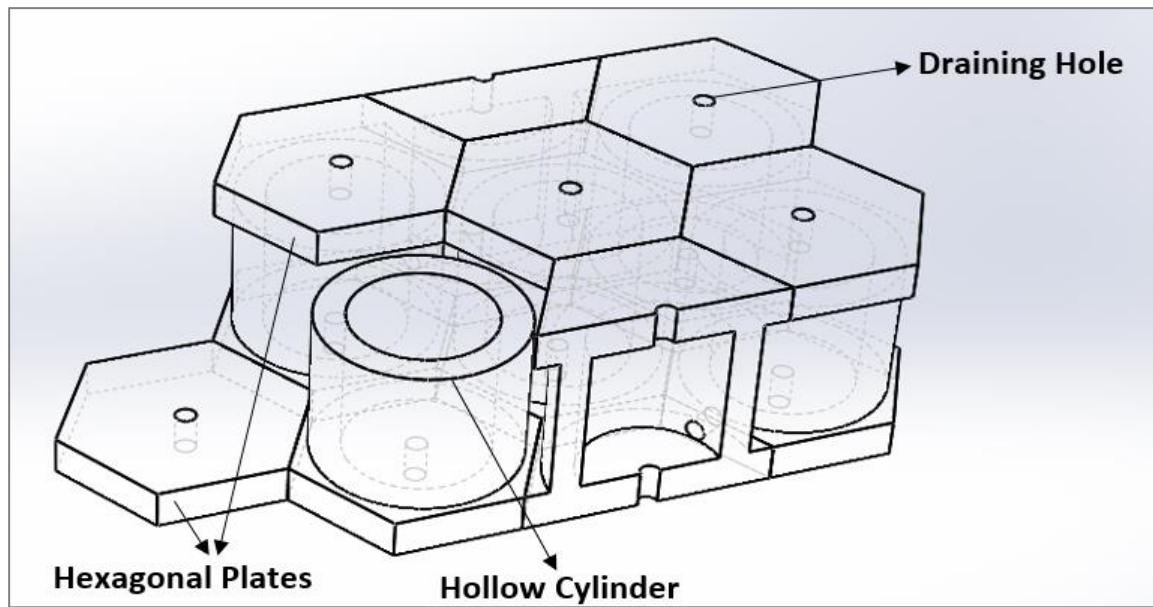


**Figure 1.1:** Illustration of StormPav System

## 1.2 Motivation

Road pavement could be unsatisfactory due to a number of reasons. Sarawak, for example, has poor soil conditions for road construction and water draining. In addition to poor road drainage system, water ponding and potholes are two common phenomenon commonly observed on the local streets (refer to Figure 1.2). Along with the traffic loadings, tarred road performs badly with more cracks due to weakening of asphalt pavement layers when subjected

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<sup>1</sup> StormPav is a product of protected patent technology, developed by M. A. Mannan and team, and registered under MyIPO PI2016704420 in November 2016.

to high rainfall rate. Obviously, the formation of cracks cause the stormwater to penetrate the asphalt caps and lead to the damaging of road sub-base. Once this happens, road deterioration would be more often and poses a risk to lives and properties, such as accident, traffic delays and washout of structure.

According to Public Works Department of Sarawak (also known as JKR Sarawak), tarred road surface at intersections like roundabout and road junction suffer more damages than the carriageway (Mah et al., 2017). At a junction for example, vehicles tend to brake instantly or to pick up speed when the traffic light changes its cycle to red or green. This has exerted extra forces on the asphalt pavement and its subbase to be worn out rapidly. Through discussions with JKR Sarawak Research Centre, this issue of frequent damaging of road intersections in Sarawak had been highlighted by their officers from the Road Branch. In order to ease the traffic movement, JKR Sarawak spent a huge amount of budget for road repairing in the past. Unfortunately, the performance of the conventional asphalt pavement remains disappointing. Therefore, this project is carried out as a way to overcome the problem stated above by introducing a multi-purpose road intersection. This could be done by installing StormPav modular units at road intersections which are envision to function as road pavement and stormwater management strategy for road drainage.



**Figure 1.2:** Poned Water and the Formation of Pothole

### **1.3 Problem Statement**

The service inlet of StormPav cover plays a significant role to remove the ponding water from road surfaces. On the other perspective, the inlet also behaves as a flow regulator that permits the storm runoff to be drained off from road surfaces in a controlled rate. Since each cover plate is provided with a single orifice, the number of orifice increases if more plates are grouped together. Just like any interlocking system, the top layer of this green pavement structure would perform as a multi-hole orifice plate which poses a higher discharge coefficient and this increases the draining capability. Theoretically, this inference sounds good. Practically, a large number of service inlets under a combination of StormPav units in a particular intersection should undergo practical analysis and simulation to discern their performance.

### **1.4 Objectives**

This project embarks on the following objectives:

- a) To determine the surface infiltration of StormPav cover that might be provided in a road intersection to allow the stormwater to be directed to an underground detention system; and
- b) To evaluate the drainage capability of the service inlets on road surfaces for minimal water ponding.

### **1.5 Scopes**

This project concentrates on the hydrological processes of stormwater movement from road surfaces to underground storage. However, the internal flow within the cylinder part of StormPav system is excluded but represented as the outflow of multi-hole orifice plate. This is because the study is aimed to determine the surface infiltration of the top covers

and the drainage capability of its service inlet. In the previous study, Mah (2016) had reported StormPav has a storage capacity  $0.19 \text{ m}^3/\text{m}^2$  of pavement area catering for 3-hour 10-year Average Recurrence Interval (ARI) design storm. Therefore, only surface infiltration from the permeable pavement is reported here.

The strain and stress of the precast concrete blocks in supporting traffic loads are not within the scope here. This shall include accelerated test for the concrete blocks subjected to millions of traffic cycle that in itself is a different field than hydrology.

## **1.6 Thesis Structure**

The first chapter of this thesis is an introduction to the study. It consists of the general view of the topic that illustrates the background and motivation of the study, a problem statement, objectives and scope of the study.

The second chapter is literature review, in which important terms and necessary information are explained in detail. This chapter consists of the elaboration of OSD, permeable pavement, precast-concrete stormwater detention system, StormPav system, multi-hole orifice plate and flow visualization through CFD simulations.

The third chapter discusses the methodology and the procedures used in order to achieve the objectives of this study. This chapter explains the methods adopted for the research, which include model building in both CFD and laboratory methods, together with the assumptions made.

The fourth chapter covers the results obtained from the usage of methods adopted in Chapter 3. The results are elaborated and evaluated in order to investigate the potential of transforming a conventional road intersection into a green StormPav system incorporating

with the stormwater management. Then, the last chapter concludes the findings of this project and presents recommendations for future studies.

## **CHAPTER 2**

### **LITERATURE REVIEW**

#### **2.1 On-Site Detention**

OSD is a structural element used for flood mitigation purposes. This facility is designed for temporary storage of rainwater that usually provided for redevelopment or new development schemes. With this facility, the site discharge of stormwater can be limited to pre-development levels by using outlet restriction devices (Beecham et al., 2005; Singapore PUB, 2010). In order to attenuate the peak discharge, OSD storage is one of the measures that can be used to harvest and store stormwater momentarily during a storm event. Then, the system releases the captured runoff at a controlled rate to the downstream drainage system. As such, the drainage system is capable for higher intensity storms and any uncertainties due to weather change (Singapore PUB, 2010).

In practice, an OSD storage can be installed on above ground, underground or a combination of both within a property boundary (refer to Figure 2.1). Generally, above ground OSD storage is adopted as depression to landscaped areas, impervious areas, flat roofs and surface tanks. The installation of this storage system is easier and more economical than underground OSD, but it occupies valuable land space (DID, 2002). On the other hand, underground OSD has small footprint area for storage of runoff (see Figure 2.2). Furthermore, the OSD system can be configured as online and offline systems, where the differences in functionality between these two systems are further discussed in Table 2.1.

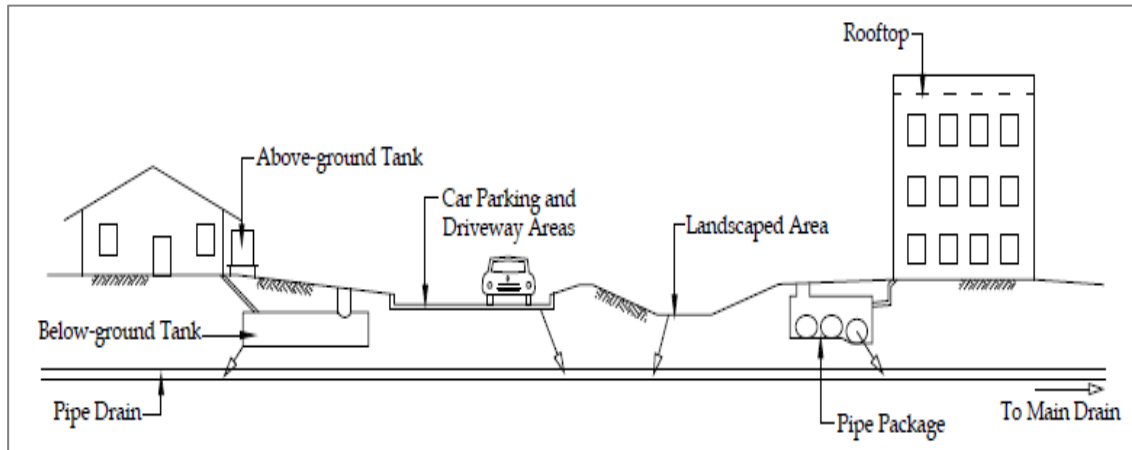


**Figure 2.1:** Typical OSD Facilities (DID, 2012)

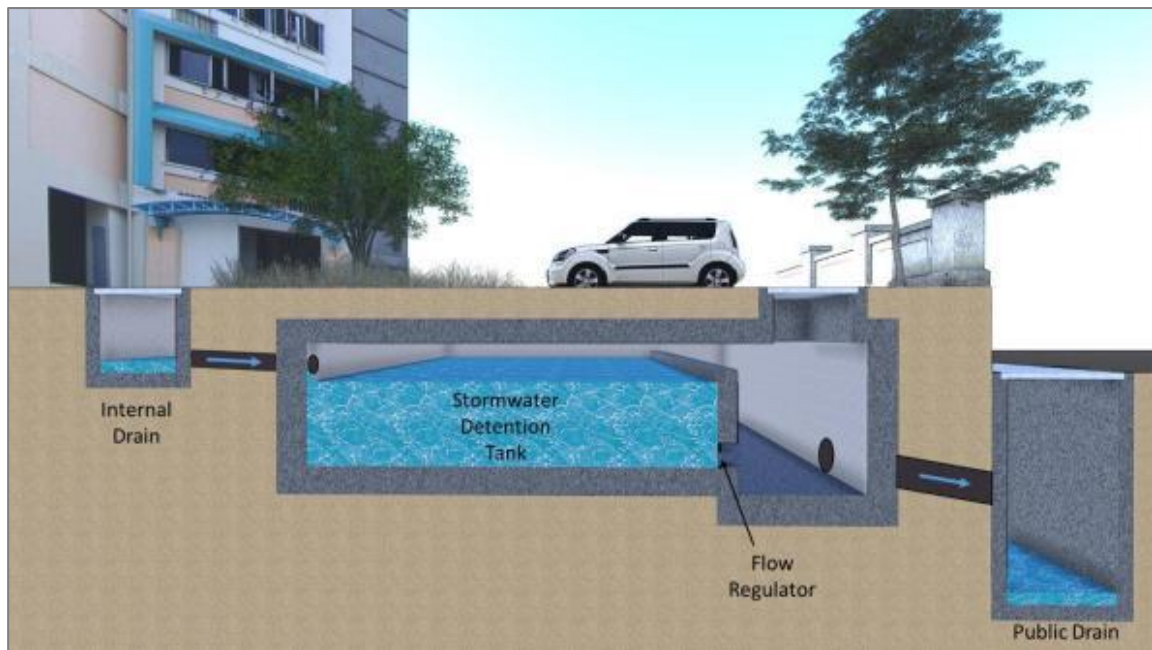


**Figure 2.2:** Schematic Diagram of Underground OSD Storage (Singapore PUB, 2010)

**Table 2.1:** Configuration of Underground OSD Storage (Singapore PUB, 2010)

| Online Detention System                                                                                                                                                                                                                                                                                                                                                                                                                                           | Offline Detention System                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                    |
|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <ul style="list-style-type: none"> <li>• Receiving drain directs runoff from contributing catchment area to the detention system for temporary storage and then, discharges at a controlled rate through a flow control device like an orifice.</li> <li>• No mechanical and electrical components are required for operation, but sufficient elevation difference between the inlet and outlet point is essential for the system to work effectively.</li> </ul> | <ul style="list-style-type: none"> <li>• Only a small portion of runoff is stored in this system. This happens because the receiving drain only diverts the excess flow to the detention system through a flow regulator such as side flow weir if the flow exceeds its maximum allowable peak runoff in the conduit.</li> <li>• A control system like pump and water level sensor are recommended for this system to activate the discharge after the storm event or to subside the water level in conduit.</li> <li>• Maintenance works of mechanical and electrical control system should be done regularly so as to ensure reliable operation of the system, especially during storm events.</li> </ul> |

## **2.2 Permeable Pavement**

In the late 1960s, permeable pavement is invented as an alternative to traditional impervious asphalt and concrete surfaces, in which stormwater is directed to underground storage in the form of an OSD (Thelen & Howe, 1978; Bean et al., 2007; Hansen, 2008). This pavement is also known as porous pavement, a kind of load bearing pavement that allows for water penetration or infiltration process. In recent years, this facility is rapidly adopted as a green engineering technology in urban areas to retard the flow velocity and volume of peak runoff similar to an OSD (GCCC, 2005). Due to its effectiveness in stormwater quantity and quality control, permeable pavement is ideally suited for sites with low traffics such as parking lots, low traffic roads, driveways, walkways and pedestrian plazas (CVC & TRCA, 2010). So far, this facility is not applied to heavy volume roads like highway and road junctions because of its limitations in the strength of pavement as the presence of air voids lower its strength. Therefore, this project is attempted to overcome the concern by proposing an interlocking system of high strength precast concrete modular units beneath the road intersections. Meanwhile, the concept of permeable pavement is also applied here so that the road system acts as a ‘thirsty pavement’ to take out the surface runoff and then keep it within the underground storage.

### **2.2.1 Types of Permeable Pavement**

As issued in the following writing, permeable pavement that comes with several design variations are illustrated in Figure 2.3, although they share the same goal for stormwater infiltration (Dietz, 2007):

- Monolithic structure: Surface course of this pavement can be existed as porous asphalt or concrete structure, which is customarily filled with many air voids that permit the stormwater to drain through and store in the underlying aggregate storage layer;
- Block structure: This pavement is permeable interlocking concrete blocks by which itself is impervious, but allows for water penetration through the gaps provided between them. Commonly, the gaps are 10% of the respective surface area and filled with pea gravels or sand; and
- Grid or lattice structure: Precast concrete or durable plastic grids are used for this structure. It is mostly permeable because it provides void spaces that can be filled either with crushed stones or topsoil and planted with grass, which encourage rapid infiltration and restore natural behaviour of the water cycle.



(a) Pervious Concrete

(b) Concrete Blocks

(c) Plastics Grids

**Figure 2.3:** Various Kinds of Permeable Paving (CVC & TRCA, 2010)

## 2.2.2 Components of Permeable Pavement

The common features of permeable pavement include a storage layer which is filled with gravels and topped with a porous surface layer (refer to Figure 2.4). As the top layer of the structure, the pavement functions like a sponge to be saturated with stormwater due to the presence of interconnected void spaces (Bean et al., 2007). As mentioned in the previous section, the pavement is either modular (clay or concrete blocks) or monolithic in structure (permeable asphalt or concrete) which is usually laid on a bedding layer of coarse sand.

Beneath these, a layer of aggregate functions like an underground OSD that shares similarity in stormwater detention and further infiltration of stormwater to the underlying native soil. Basically, this storage layer must be sufficiently thick as it acts as a support base to the pavement structure in supporting the traffic loads. Usually, the layer of aggregate is covered with geotextile fabrics at both ends, either at top or bottom for a better performance. Through this, the separation between bedding layer, aggregate layer and underneath filter layer are provided to maintain the water quality. As the final layer, fine materials or sands are commonly used to filter and infiltrate storm runoff to the surrounding soil or dispose to underground piped drainage system (GCCC, 2005).

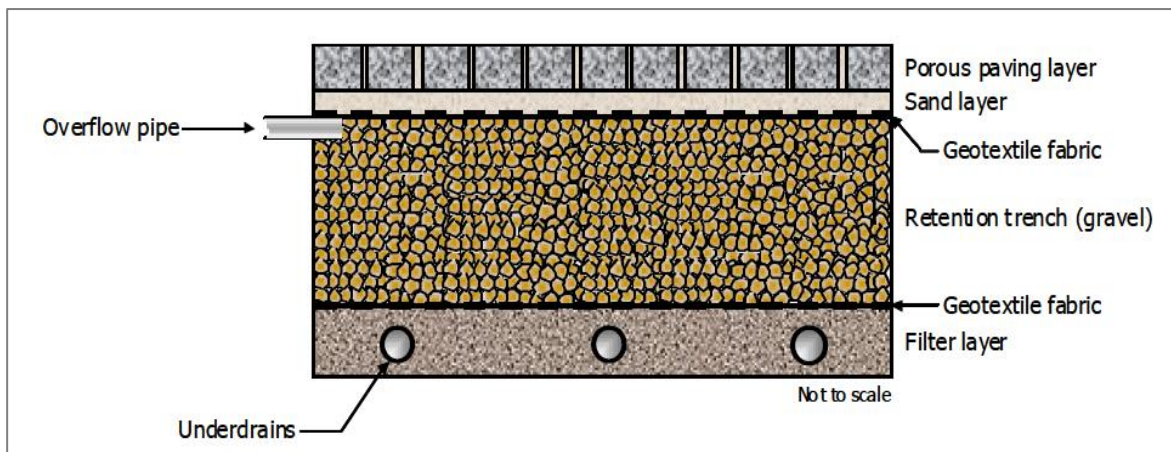


**Figure 2.4:** Typical Porous Paving Section (GCCC, 2005)

### 2.2.3 Surface Infiltration

Based on the supportive literature in the previous section, stormwater could be penetrated to underground storage through internal voids or spaces that are provided on the road surface. The presence of these opening cells is significant to make the pavement with high porosity and permeability. Basically, permeability or surface infiltration of permeable pavement works according to the principle of capillary action, where the water is travelled

through the narrow spaces of interconnected voids. As stated by Park et al. (2014), the performance of permeable pavement can be varied in terms of surface infiltration. Furthermore, Ong et al. (2016) defined the term of surface infiltration as “a measure of the water flows through the pore spaces or fractures” in the porous medium. However, this determination is prominently dependent on the void content for assuring a good surface infiltration of the pavement (Teraiya, 2015).

By taking permeable concrete as an illustration, the void content is usually ranging from 15% to 35% of the concrete mix (Teraiya et al., 2015). However, typical void content of permeable asphalt is almost the same as the former, at least 16% of air void content is specified to the total mix volume (Hansen, 2008). The surface infiltration of permeable pavement increases with its void content. However, it should be noted that high void content is adversely affecting the strength of pavement. Practically, infiltration can be determined through the falling head method (Teraiya, 2015). This method is a laboratory setting that allows the water to flow through a porous medium so that the rate of water level to drop from initial water head to final water head can be defined (see Figure 2.5). Then, obtained parameters are applied in Darcy’s First Law to calculate the coefficient of permeability,  $k$  value as expressed in Equation 2.1 (Neithalath et al., 2006):

$$k = \frac{A_1 L}{A_2 t} \log \left( \frac{H_1}{H_2} \right) \quad (\text{Eq. 2.1})$$

where

$k$  = Coefficient of water permeability (cm/s);

$A_1$  = Cross-sectional area of the sample (cm<sup>2</sup>);

$A_2$  = Cross-sectional area of the cylinder tube (cm<sup>2</sup>);

$L$  = Length of the soil sample (cm);

$t$  = Time interval to get head differences (sec);

$H_1$  = Initial water head (cm); and

$H_2$  = Final water head (cm).

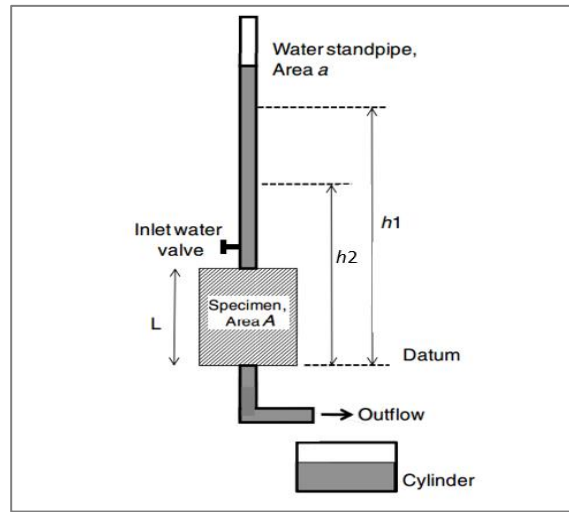


**Figure 2.5:** Falling Head Method for Permeability Testing (Assaad & Harb, 2013)

Besides, it is important to make sure that the practice of permeable pavement should meet the requirements that are recommended by the local authorities. As tabulated in Table 2.2, recommended values of surface infiltration for permeable pavement are varied in different countries due to weather variations. As a reference point, the design of permeable pavement should have a surface infiltration that ranges from 20 to 21,500 mm/hr.

**Table 2.2:** Recommendations of Surface Infiltration for Permeable Pavement

| Source                                  | Recommended Values for Surface Permeation                                                                                                                                                  |
|-----------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| ASLA <sup>2</sup>                       | 140+ in/hr (3,500+ mm/hr)                                                                                                                                                                  |
| Credit Valley Conservation <sup>3</sup> | 900 – 21,500 mm/hr                                                                                                                                                                         |
| United Kingdom <sup>4</sup>             | 600 mm/hr                                                                                                                                                                                  |
| Malaysia <sup>5</sup>                   | For highest rainfall intensity of 598.9 mm/hr, average 4.2 minutes per 10cm depth (1430 mm/hr); for lowest rainfall intensity of 12.4 mm/hr, average 4.3 hours per 10 cm depth (24 mm/hr). |

Note:

<sup>2</sup> American Society of Landscape Architect

<sup>3</sup> Toronto and Region Conservation, Canada, <http://creditvalleyca.ca>

<sup>4</sup> Institute for Infrastructure and Environment, Heriot-Watt University, UK

<sup>5</sup> Hamzah et al., 2012 from School of Civil Engineering, Universiti Sains Malaysia

### 2.3 Precast Concrete Stormwater Detention System

Precast concrete detention or retention system is invented to replace antiquated sewer systems. Typically, these precast modules are installed in the parking lots, individual homes or any public garages. Once in place, the precast structure is responsive to cater the storm runoff in the subsurface either for ecological reuse or direct disposal.

Furthermore, this precast technology is also known as Industrialized Building System (IBS), which involves quick procedure of installation works, as compared to cast in-situ method. When these individual precast modules reach the site, they can be immediately installed and backfilled to final grade without any postponement of waiting for the curing process. In terms of structural integrity, the precast system is a secure system which behaves a proven strength that is able to continuously support high external loadings.

Besides that, most of the precast system provides internal clear spans and open galleries to the workers or machineries to do the maintenance works of cleaning up the sediments and debris throughout its service life (see Figure 2.6). Surely with these reasonable factors, precast stormwater systems are sustainably and economically to be practiced in urban stormwater management as it offers a perfect solution for monitoring and ensuring the quality of surface runoff. Also, this invention is beneficial to the environment as it could perform better when comes together with other precast sanitary system.



**Figure 2.6:** Illustration of Precast System for Underground Detention (<http://precast.org>)

## **2.4 StormPav**

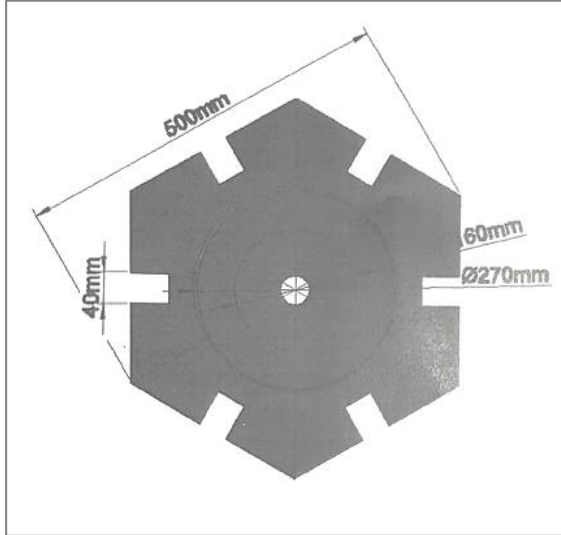
StormPav is one of the precast concrete products that combines the main idea of OSD and permeable pavement. Its components are made up of grade 50 concrete so that it can bear at least 10 tons of traffic loads (representative load that carried by a wheel of a truck). Contrary to the precast product mentioned in Section 2.3, it can be applied in heavy traffic areas such as highway, roundabouts and traffic light intersections. Additionally, multiple units of StormPav which are assembled on the flat subgrade is capable of enhancing the stormwater detention capacity during downpour. With these features, StormPav is a multi-functional product that is suitable for urban roads.

### **2.4.1 Mini OSD Unit**

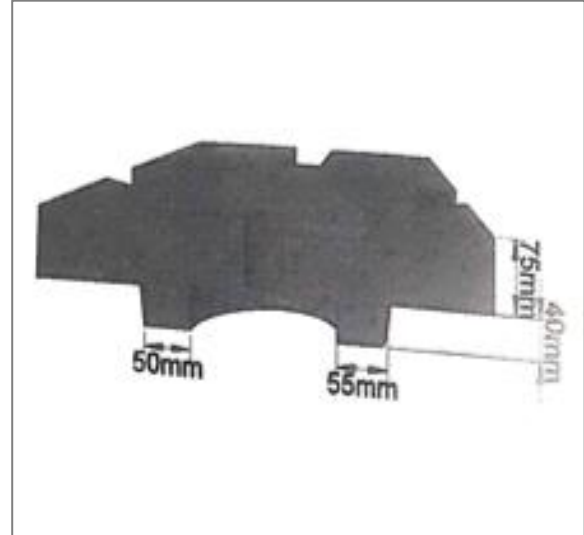
With the aim to mitigate the impacts of urbanization, StormPav system is a green infrastructure (GI) system which can be categorised as an interlocking concrete pavement (ICP). In the context of structural and hydrological aspects, StormPav is invented as the reinforced and unreinforced precast concrete blocks that promote a green and composite pavement for stormwater management as well. As shown in Figure 1.1, the arrangement of two hexagonal plates and a hollow cylinder chamber that forms a single mini sized OSD cell only occupies a landscape area of  $0.1624 \text{ m}^2$  which is available for  $0.005 \text{ m}^3$  of storage volume (see detailed dimensions in Figure 2.7).

In terms of functionality, the top cover of StormPav unit works as the road pavement and its bottom plate is the foundation that helps in soil stabilisation. Then, the middle cylinder functions like an OSD to cater the storm runoff. Due to the restriction of available landscape area in a city, StormPav is designed as modular cell that is flexible and can be easily suited to any sites. For installation purposes, individual units can overlay on native

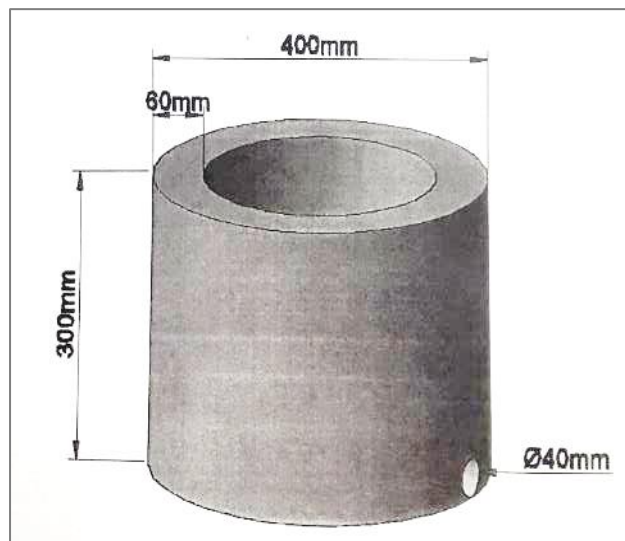
soil. Then, the bottom layer of hexagonal blocks are tied to accommodate monolithic foundation while the top layer to traffic movement.



(a) Plan View of Hexagonal Cover



(b) Cross-section of Cover



(c) Hollow Cylinder Chamber

**Figure 2.7:** Detailed Information of StormPav Components

## 2.4.2 Case Studies on the Applications of StormPav

Applications of StormPav are reported and discussed in the following writings.

### StormPav for Urban Road (Mah, 2016)

This study outlined the investigation done on StormPav. The author subjected the precast product to 10-year ARI design storm with 3 hours continuous red-alert rainfall. The detention storage of StormPav was found to be able to fully capture the rainwater. From this, the height of the cylinder was determined at 0.3 m with a capacity to hold water at  $0.19 \text{ m}^3/\text{m}^2$  of pavement area. His investigation was based on a concept presented in figure below.

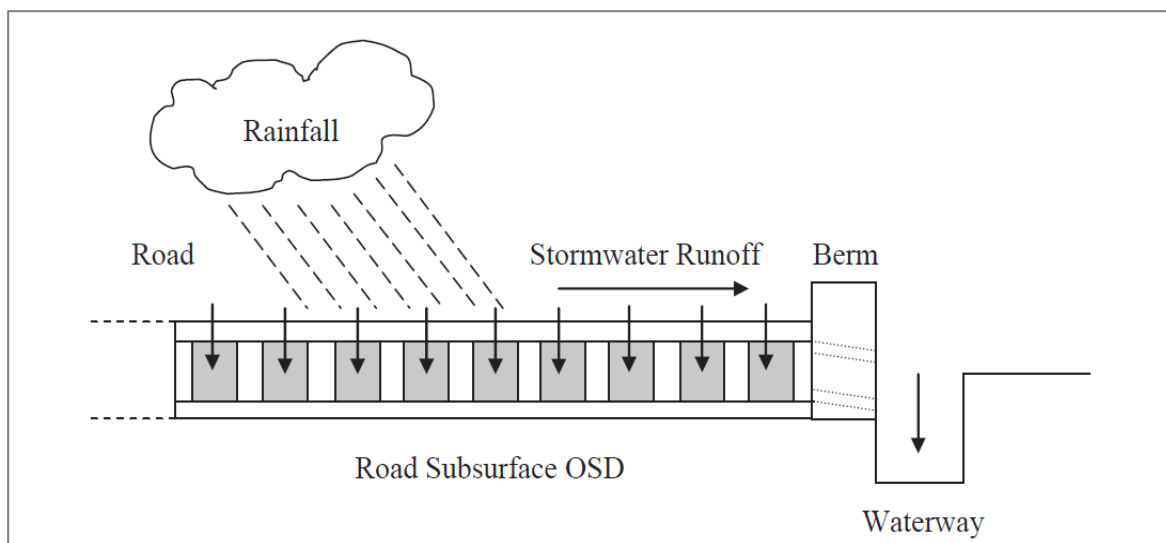


**Figure 2.8:** Interlocked OSD Units for Stormwater Management (Mah, 2016)

### StormPav as Individual Lot OSD (Ngu et al., 2016)

In this study, individual lot OSD system was adapted to a residential car porch with the dimensions of 4.33 m and 4.625 m in length and width respectively. With this wide surface area of car porch, there are at least two cars that can be fitted into. In order to optimise the utilisation of such surface area, authors mentioned that an OSD system can be installed beneath the car porch for stormwater management. As the span of this empty space was very wide (which is over 4 m), modular units of StormPav was preferred than a large OSD tank. This concept secured a firm platform which was not easy to collapse (Ngu et al., 2016).

Through simulation, Computational Fluid Dynamics (CFD) modelling proved that a critical flow was found in the inlet region with a maximum velocity of 0.3 m/s, especially 1m apart from the inlet hole (see Figures 2.9 and 2.10). In addition, Figure 2.11 also depicts that the turbulent flow did not affect the performance of the OSD system since it only happened in the vicinity of the inlet, while other regions were remained as the laminar flow.

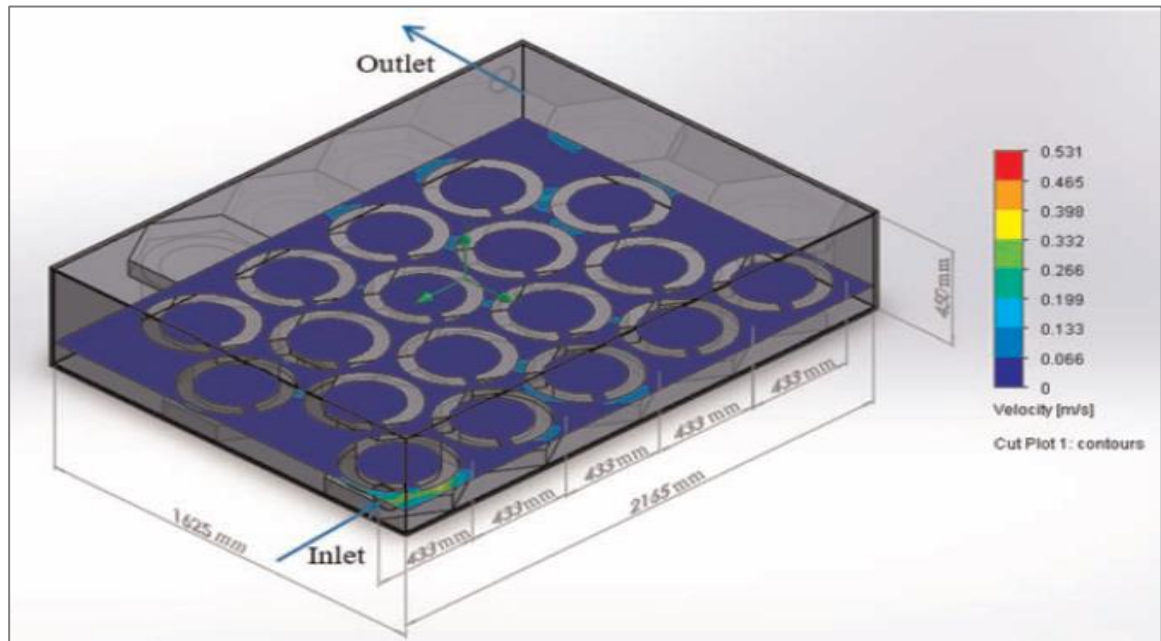


**Figure 2.9:** Simulated Flow Pattern inside the OSD System (Ngu et al., 2016)

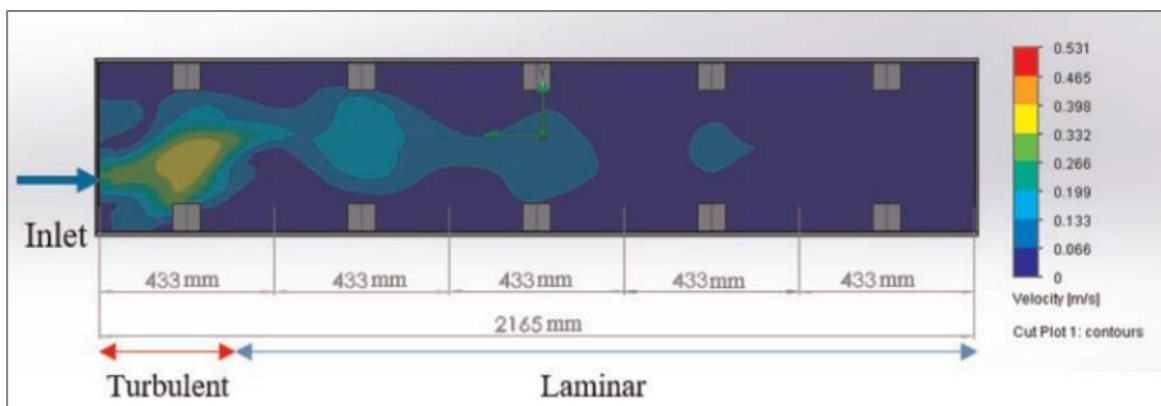


**Figure 2.10:** Front Cut Plot of OSD System with Inflow of 4.74 l/s (Ngu et al., 2016)

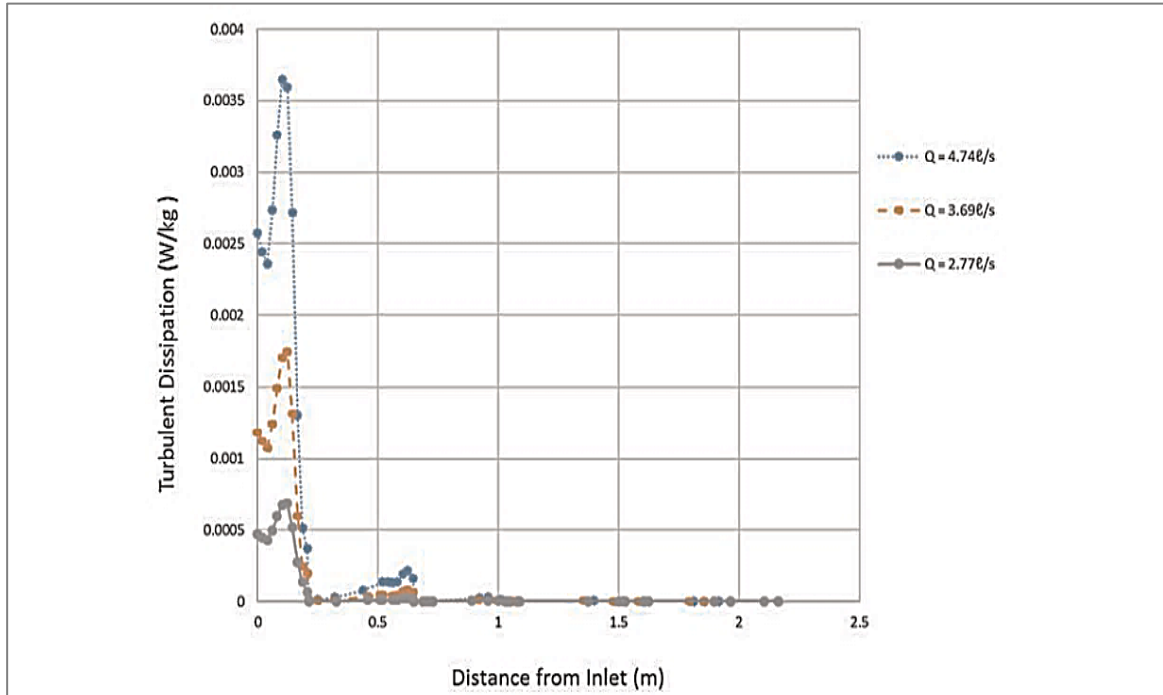


**Figure 2.11:** Graph of Turbulent Dissipation against the Distance from Hole (Ngu et al., 2016)

### StormPav for Road Intersection

From the above studies, StormPav is applicable to both traffic and non-traffic areas such as road and car porch. However, it is not yet investigated to be practiced for road intersection where the pavement would suffer more damages due to the repeated “move and stop” actions of running vehicles and poor drainage system (these issues are discussed in Section 1.2). A wide surface area like road junction would be a good choice to be investigated for OSD and surface infiltration.

## 2.5 Multi-hole Orifice Plate

As highlighted in Section 1.1, the service inlet on a single hexagonal plate of StormPav is the opening area for surface infiltration. When these plates are assembled together, they form a flat surface with many holes that allow the water to infiltrate into the

underground OSD. It can be said that the interlocked hexagonal plates function as a multi-hole orifice plate, which poses a discharge rate to the system to drain stormwater. Contrary to pavers that adhere to Darcy's law (Section 2.2.3), StormPav uses the principle of orifice that is significantly different than the former. This is the research gap for such a type of permeable pavement called StormPav. Basic information of multi-hole orifice plate is explored below.

### **2.5.1 Applications of Orifice Plate**

In today's industrial applications, orifice plate or orifice meter is one of the essential instruments used for controlling and measuring the fluid flow rate accurately within a system as an integral part or in whole. Due to the advantages of its compact sizes and weight, this application has been widely practiced in industrial plants, which usually involves gas and liquid systems. For multi-purpose industrial applications, various design of orifice plates are basically classified as single-hole and multi-hole devices (see Figure 2.12).

In general, a single-hole orifice plate is adapted to the pipe flanges as it provides a hole that permits the flow to pass through it. In a more logical way, it performs a lower discharge coefficient as compared to a multi-hole orifice plate. Due to the restriction of flow through a single-hole, the pressure loss at the upstream and downstream region of the plate is relatively high (Singh & Tharakan, 2015). This was noticed and proved by an experimental study of Testud et al. (2007). Obviously, a significant level of noise and high vibration of structures are noticeable in the use of single-hole orifice plate. On the other hand, cavitation noise (also known as whistling effect) that had been generated from the implosions of bubbles within a turbulent flow through the multi-hole orifice plate is much more silent than the former one. As a result of flow attenuation, multi-hole orifice plate appears to have

different potential applications in regulating the effects of flow cavitation in the turbulent flows (Zhao et al., 2011).



(a) Single-hole Orifice Plate

(b) Multi-hole Orifice Plate

**Figure 2.12:** Illustrations of Various Types of Orifice Plate  
(<http://www.piping-engineering.com>)

### 2.5.2 Flow through Orifice Plate

In most cases, the orifice plate is adapted to the pipe flange as a flow regulator to limit the incoming flow. However, its performances and applications can be different due to various design and configuration of the orifices. For flow measurement, velocity of the flow at orifice can be predicted by using Bernoulli's equation. Basically, this determination is done by assuming the flow is continuity (means no changes in density) and incompressibility (means the flow in the pipe is constant) (refer to Figure 2.13). Then, Equation 2.2 is developed to govern the flow through the orifice (Reader-Harris, 2015):

$$q_m = \frac{C_d \varepsilon}{\sqrt{1-\beta^4}} \frac{\pi d^2}{4} \sqrt{2\rho \cdot \Delta P} \quad (\text{Eq. 2.2})$$

where

$q_m$  = Mass flow rate (kg/s);

C = Discharge coefficient;

$\varepsilon$  = Expansibility factor (incompressible fluids are considered as 1);

$\beta$  = Diameter ratio ( $d/D$ );

$d$  = Orifice diameter (m);

$D$  = Pipe diameter (m);

$\rho$  = Density of the fluid ( $\text{kg/m}^3$ ); and

$\Delta P$  = Pressure differential across the orifice (Pa).

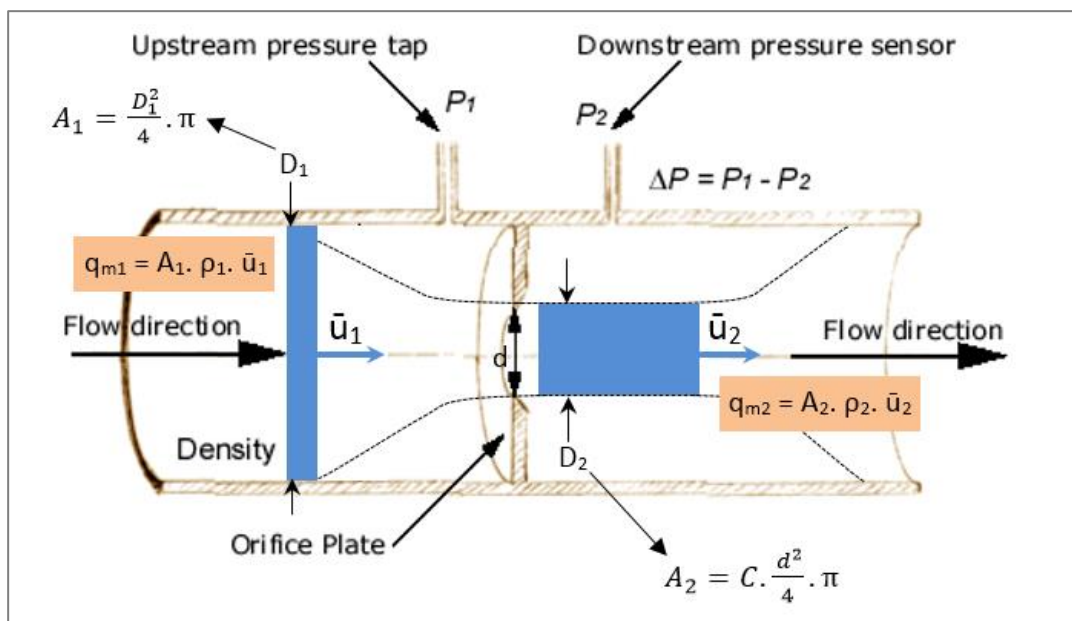


**Figure 2.13:** Flow Parameters of Orifice Design

## 2.6 Flow Visualization through CFD

CFD is a modern tool used in both academic research and industrial applications. This tool can be interesting and beneficial to the users as it emerges various modern engineering practices in a computational model. Therefore, this approach has becoming more attractive to the scientists and engineers in science application areas. CFD works as a practical approach in theoretical development of computational sciences on how the governing equations can be constructed to solve problems while various approximations are

made in the study. Through this model, the specific terms in the governing equations are presented in more precise way and further exploration might help to realize new findings of theoretical development (Tu et al., 2012). As an example, hydrodynamic equations of a complicated flow system can be solved by simulation based on the fundamental principles of fluid dynamics, as expressed in the followings (Anderson, 2009).

### **Conservation of Mass (Continuity Equation):**

Physical principle:  $\left\{ \begin{array}{l} \text{Rate of increase of} \\ \text{mass in fluid element} \end{array} \right\} = \left\{ \begin{array}{l} \text{Net rate of flow} \\ \text{of mass into element} \end{array} \right\}$

Continuity equation:

Conservative form:  $\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{V}) = 0$  (Eq. 2.3)

Non-conservative form:  $\frac{\partial \rho}{\partial t} + \rho(\nabla \cdot \vec{V}) = 0$  (Eq. 2.4)

### **Conservation of Linear Momentum (Newton's Second Law):**

Physical principle:  $\{ \text{Sum of forces} \} = \{ \text{Rate of change of momentum} \}$

Navier-Stokes equation:

$$\rho \left[ \frac{\partial \vec{V}}{\partial t} + (\vec{V} \cdot \nabla) \vec{V} \right] = -\nabla p + \nabla \cdot \bar{\tau} + \rho \vec{f}$$
 (Eq. 2.5)

### **Conservation of Energy (First Law of Thermodynamics):**

Physical principle:  $\left\{ \begin{array}{l} \text{Rate of change of} \\ \text{energy of a fluid particle} \end{array} \right\} = \left\{ \begin{array}{l} \text{Rate of heat addition} + \\ \text{Rate of work done} \end{array} \right\}$

Energy equation:

$$\rho \left[ \frac{\partial h}{\partial t} + \nabla \cdot (h \vec{V}) \right] = -\frac{Dp}{Dt} + \nabla \cdot (k \nabla T) + \phi$$
 (Eq. 2.6)

Note: These governing equations are solved based on the following variables:

- Velocity vector  $\vec{V}$ ;
- Pressure  $p$ ;
- Temperature  $T$ ;
- Density  $\rho$ ;
- Thermal conductivity  $k$ ;
- Body force per unit  $\vec{f}$ ;
- Viscous stress tensor  $\bar{\tau}$ ;
- Dissipation function  $\Phi$ ;
- Enthalpy  $h$  (related to specific internal energy as  $h = e + p / \rho$ ).

### 2.6.1 Case Studies of CFD Simulation

This section reviews three examples on the applications of CFD in flow simulation to predict and analyse dynamic flows.

#### Flow Pattern of an Orifice Meter (Shah et al., 2012)

Orifice meter is a common device that used for flow measurement of liquids, gases or slurries due to its measurement of simplicity and flexibility in any working circumstances. Basically, this device works to reduce the flow area of the fluid system so that the effects of pressure and velocity variations in the system could be minimised. Otherwise, the efficiency and productivity of industrial applications would be affected by the inaccuracy of flow measurement. In this regard, CFD modelling was performed in this study to have a better understanding of the flow pattern of orifice plate so that further improvement can be done in the future.

In the simulation, water was used as the working fluid passing through an orifice plate but with different flow rates. Typical geometry of orifice meter used in CFD modelling was illustrated in Figure 2.14. For numerical analysis, governing equations in standard k- $\epsilon$  turbulence model were used to simulate a steady state flow through the orifice meter.

Furthermore, effects of skin friction and form friction were taken into the consideration by the model with wall function. Besides that, grid independence study was performed to find a proper mesh size for the working system. As shown in Figure 2.15, unstructured hexahedral meshes were used for the flow simulation in a 12.3 mm diameter pipe. After that, CFD simulations with different inflow rates were performed by using OpenFOAM-1.6 solver. In order to prove that CFD method could be an alternative to experiments, simulation data were cross-checked and validated by reliable experimental data.

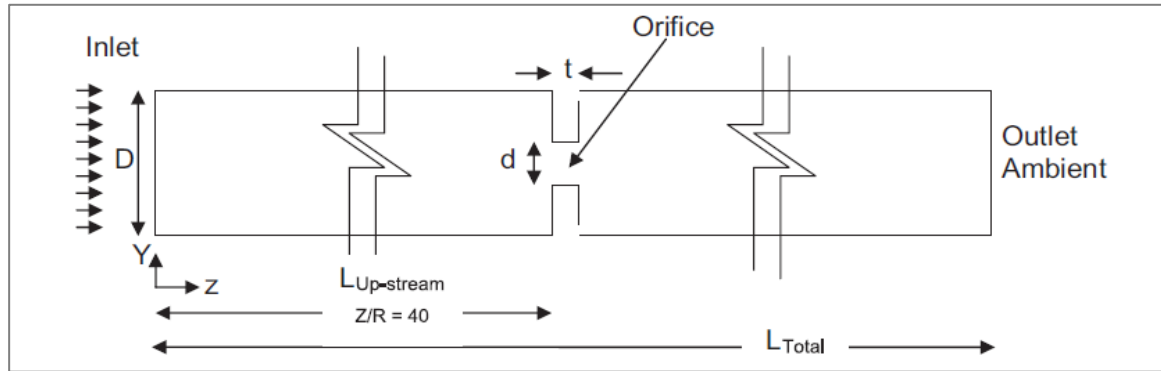


**Figure 2.14:** Typical Orifice Geometry Used for Simulation (Shah et al., 2012)

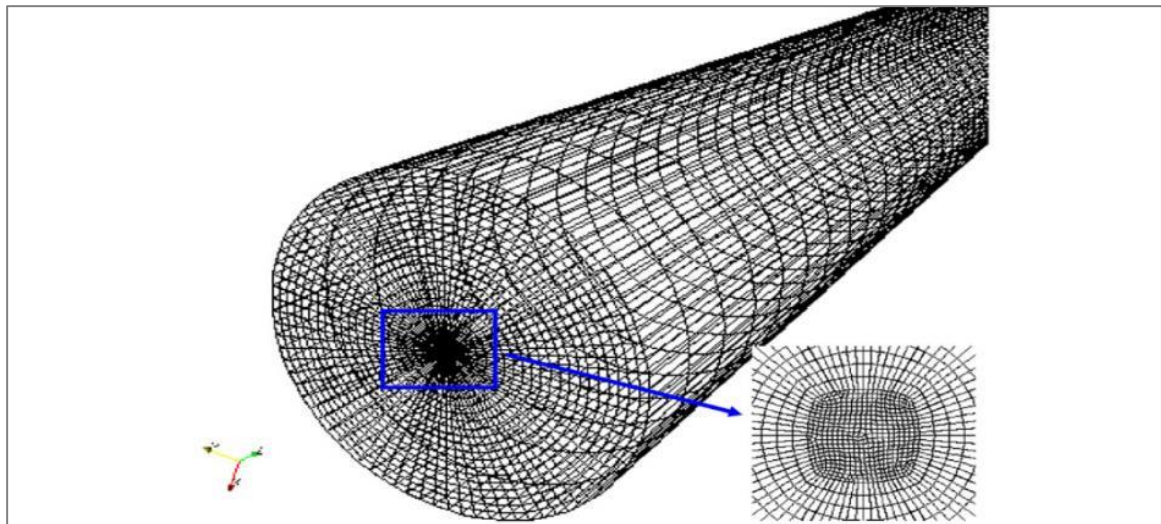


**Figure 2.15:** Typical Unstructured Hexahedral Mesh for 12.3 mm Pipe Diameter (Shah et al., 2012)

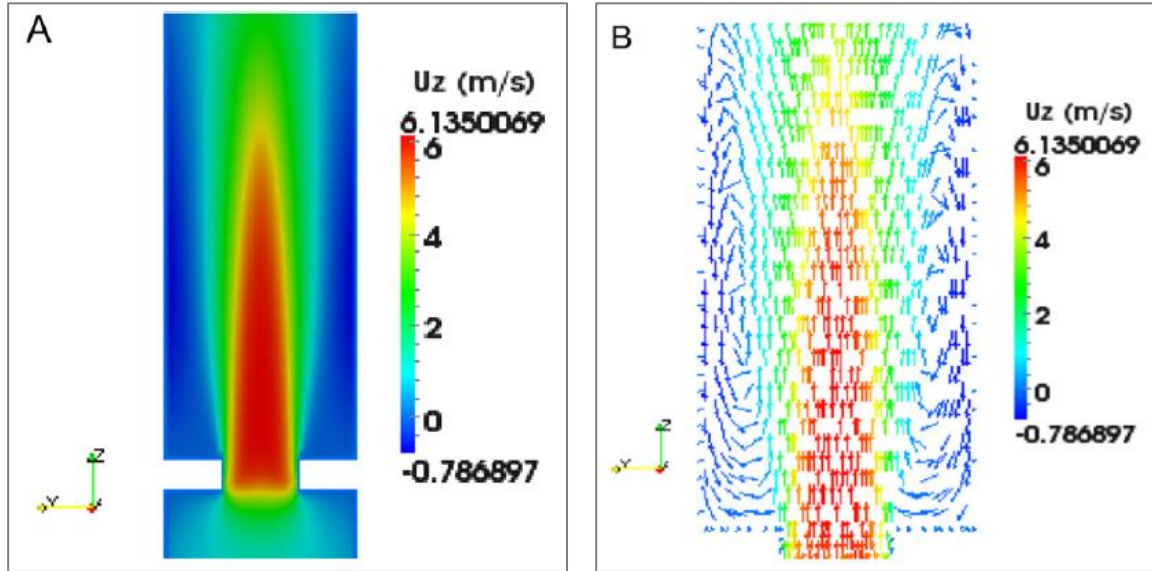
From both modelling and experimental efforts, the performance of orifice meter was examined in terms of energy balance, flow pattern,  $k$  and  $\varepsilon$  profiles, sensitivity analysis of  $k$ - $\varepsilon$  turbulence model parameters, discharge coefficient and pressure drop-velocity relationship. Among these, Bernoulli equation was used to determine overall energy balance of the system, as tabulated in Table 2.3. From the observation, the rate of turbulent energy dissipation increased with inlet velocity. Moreover, CFD results also showed that the predictions of turbulent energy dissipation rate would be more accurate if a finer mesh was used to simulate the flow (case no.4 was repeated for two different mesh sizes). Overall, the predicted simulation results matched well with that of experimental study since the values of turbulent energy dissipation rate were varied within 5%.

**Table 2.3:** Energy Balance of Orifice Flow System (Shah et al., 2012)

| Case No. | Inlet velocity (m/s) | Turbulent Energy Dissipation Rate (W) |              | Mesh Size           |
|----------|----------------------|---------------------------------------|--------------|---------------------|
|          |                      | CFD Simulation                        | Experimental |                     |
| 1        | 0.376                | 0.2426                                | 0.2532       | 1,047,360 hexahedra |
| 2        | 0.482                | 0.5903                                | 0.6212       | 1,047,360 hexahedra |
| 4a       | 0.755                | 1.1466                                | 1.3190       | 351,360 hexahedra   |
| 4b       | 0.755                | 1.2496                                | 1.3190       | 1,047,360 hexahedra |

Next, the flow pattern of this study was illustrated in the velocity contour plot and velocity vector plot, as shown in Figure 2.16. As indicated by velocity contour plot, the boundary layer of flowing fluid was separated symmetrically at the downstream side of orifice meter when it passed through a narrow gap of orifice plate. Then, this caused the formation of a free flowing jet in downstream fluid. Furthermore, turbulent mixing and recirculation zones can be observed in the velocity vector plot just at the downstream of orifice meter. Figure 2.17 also indicates that a fully developed turbulent flow was occurred at the upstream of orifice meter at a maximum value of 0.85 for  $N$  ( $u_{\text{average}}/u_{\text{maximum}}$ )

obtained from the axial velocity profile upstream of orifice at an axial distance of  $z = 0.15\text{m}$  from entrance. In short, the expected flow characteristics of orifice meter were fully exploited by CFD simulation.



(a) Velocity Contours

(b) Velocity Vectors

**Figure 2.16:** Flow Patterns of Orifice Meter (Shah et al., 2012)

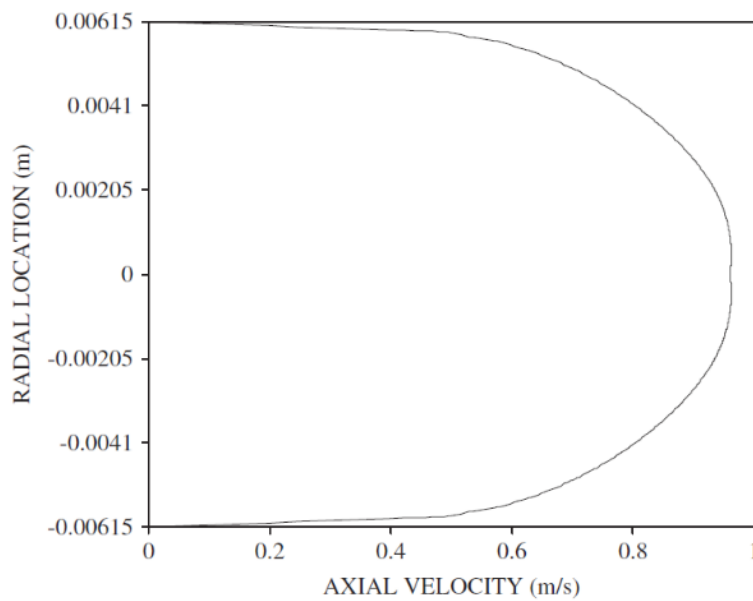


**Figure 2.17:** Axial Velocity Profile at Upstream of Orifice at  $z = 0.15\text{ m}$  (Shah et al.,

2012)

In addition, Table 2.4 presented the simulated and experimental values of discharge coefficient of orifice meter. By making a comparison, a good agreement can be seen between experimental data and CFD prediction. For this determination, the ratio of actual flow to the theoretical flow is determined by the pressure loss of the system obtained from both studies and then, recorded as the values of discharge coefficient. Both results were sufficient to prove that CFD simulation can be an alternative tool to replace the experimental method in solving the fluid flow problems.

**Table 2.4:** Tabulation of Discharge Coefficient of Orifice Meter (Shah et al., 2012)

| Case No. | Q* (m/s) | $\Delta P^*$ (N/m <sup>2</sup> ) | Inlet Velocity* (m/s) | Velocity at Throat* (m/s) | Pipe Reynolds Number* | Discharge Coefficient |                |
|----------|----------|----------------------------------|-----------------------|---------------------------|-----------------------|-----------------------|----------------|
|          |          |                                  |                       |                           |                       | Experiment            | CFD Simulation |
| 1        | 44.67    | 5,680                            | 0.376                 | 2.275                     | 4489                  | 0.6657                | 0.6253         |
| 2        | 57.33    | 10,866                           | 0.482                 | 2.920                     | 5762                  | 0.6177                | 0.6128         |
| 3        | 80.00    | 23,461                           | 0.673                 | 4.074                     | 8040                  | 0.5866                | 0.6035         |
| 4        | 89.67    | 29,511                           | 0.755                 | 4.567                     | 9012                  | 0.5863                | 0.5996         |

#### **Flow Characteristics of Multi-Hole Orifice Flow Meter (Singh & Tharakan, 2015)**

This study performed a CFD analysis of flow prediction through a multi-hole orifice plate. For making a comparison, both single-hole orifice (SHO) and multi-hole orifice (MHO) plates were designed to have a similar total flow area and beta ratio (ratio of total orifice area to pipe area) of 0.5, but with different orifice sizes and configuration. As demonstrated in Figure 2.18, SHO had a central circular hole of 10.6 mm diameter while MHO had a central hole of 5.0 mm diameter which surrounded by eight circular orifices of 3.3 mm. Then, the plates were imported into CFD tool for mesh generation, where it was important to govern the stability and accuracy of the flow measurement. Moreover, governing equations of k- $\epsilon$  turbulence model were employed for measurement of turbulence flow. With the aid of

ANSYS CFX-10 model, these complicated hydrodynamics equations were solved to discretize the convection, turbulent kinetic energy and turbulent dissipation of the system.

For the validation of CFD model, the performances of SHO and MHO were tested experimentally by using demineralized water. As shown in Figure 2.19, water was initially kept in a high pressure water tank. As a flow regulator, ball valves were provided in the feed line and meanwhile, another 1 m length of pipe was located at the downstream of orifice plate to allow for a fully developed flow. Furthermore, pressure transducers and turbine flow meter were installed in the system for the measurement of static pressure and volume flow rate respectively. As a result, CFD outcomes matched well with the experimental results because there were not much differences of the values of pressure drop in both studies (see Table 2.5).

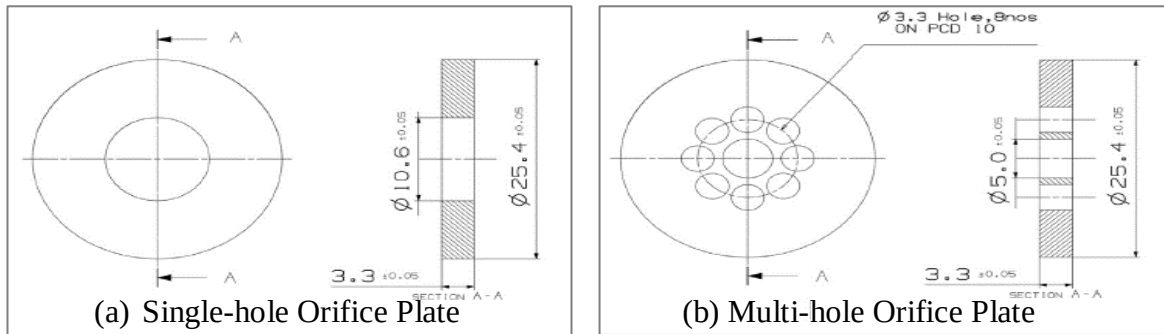


**Figure 2.18:** Configuration of Orifice Meter in Numerical Analysis (Singh & Tharakan, 2015)

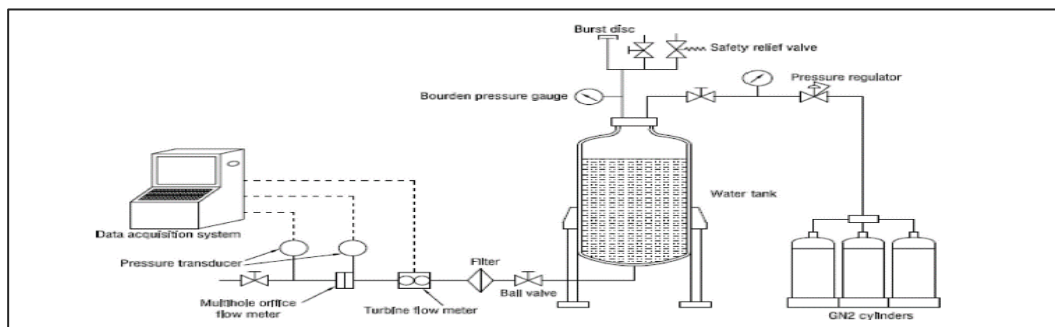
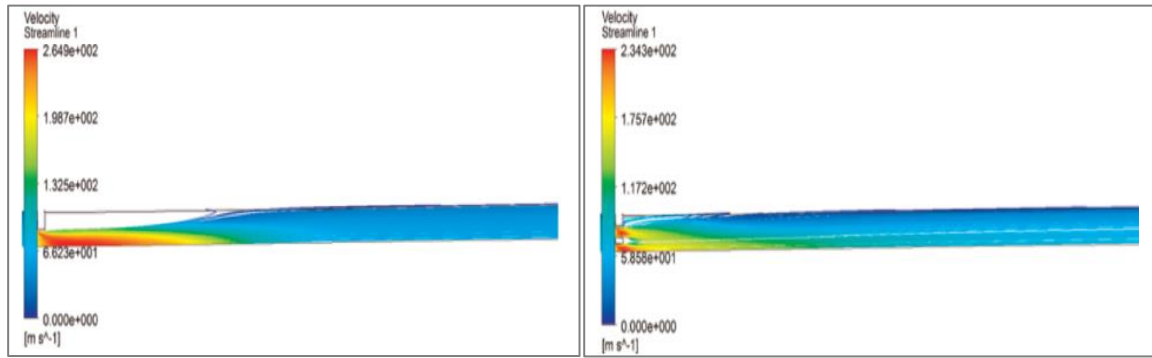


**Figure 2.19:** Experimental Set-Up for Orifice Meter (Singh & Tharakan, 2015)

**Table 2.5:** Comparison of Experimental and Simulation Results (Singh & Tharakan, 2015)

| <b>Orifice Plate</b> | <b>Volume Flow Rate, Q (l/s)</b> | <b>Upstream Pressure, P<sub>1</sub> (bar)</b> | <b>Downstream Pressure, P<sub>2</sub> (bar)</b> | <b>Experimental Pressure Drop, ΔP<sub>e</sub> (bar)</b> | <b>Pressure Drop in CFD Result, ΔP<sub>c</sub> (bar)</b> |
|----------------------|----------------------------------|-----------------------------------------------|-------------------------------------------------|---------------------------------------------------------|----------------------------------------------------------|
| SHO                  | 0.47                             | 34.56                                         | 34.39                                           | 0.17                                                    | 0.17                                                     |
|                      | 1.15                             | 29.55                                         | 28.39                                           | 1.16                                                    | 1.10                                                     |
|                      | 2.27                             | 43.52                                         | 38.99                                           | 4.52                                                    | 4.29                                                     |
|                      | 3.29                             | 42.94                                         | 33.56                                           | 9.38                                                    | 9.21                                                     |
| MHO                  | 1.48                             | 34.37                                         | 34.07                                           | 0.30                                                    | 0.29                                                     |
|                      | 2.53                             | 39.50                                         | 37.19                                           | 2.30                                                    | 2.16                                                     |
|                      | 4.21                             | 38.28                                         | 30.46                                           | 7.83                                                    | 7.47                                                     |
|                      | 5.15                             | 31.69                                         | 9.39                                            | 22.3                                                    | 21.6                                                     |

In addition, the modelling outcomes also showed that MHO would perform better than SHO. Firstly, the recovery of flow in MHO is faster than SHO (refer to Figure 2.20). Particularly for MHO, the variation of velocity streamlines at downstream were relatively small. This leads to a better turbulent mixing in the vicinity of orifices at MHO, as compared to SHO. Next, MHO gave a larger discharge coefficient at the downstream flow over a wide range of Reynolds numbers. As illustrated in Figure 2.21, the highest value of discharge coefficient for both SHO and MHO are 0.81 and 0.67 respectively. From this study, the effort of distributing the flow area into multiple numbers of orifice had successfully improved the discharge capabilities of orifice plate. This happened because a smaller size of eddies were generated at the downstream of orifices which might lead to a higher pressure recovery for MHO to produce more streamlines (refer to Table 2.6). Therefore, it can be said that MHO had more potential applications than SHO, specifically in the measurement of rigorous flows (Singh & Tharakan, 2015).



(a) SHO (b) MHO  
**Figure 2.20:** Velocity Streamlines at Downstream of Orifice Plate  
 (Singh & Tharakan, 2015)

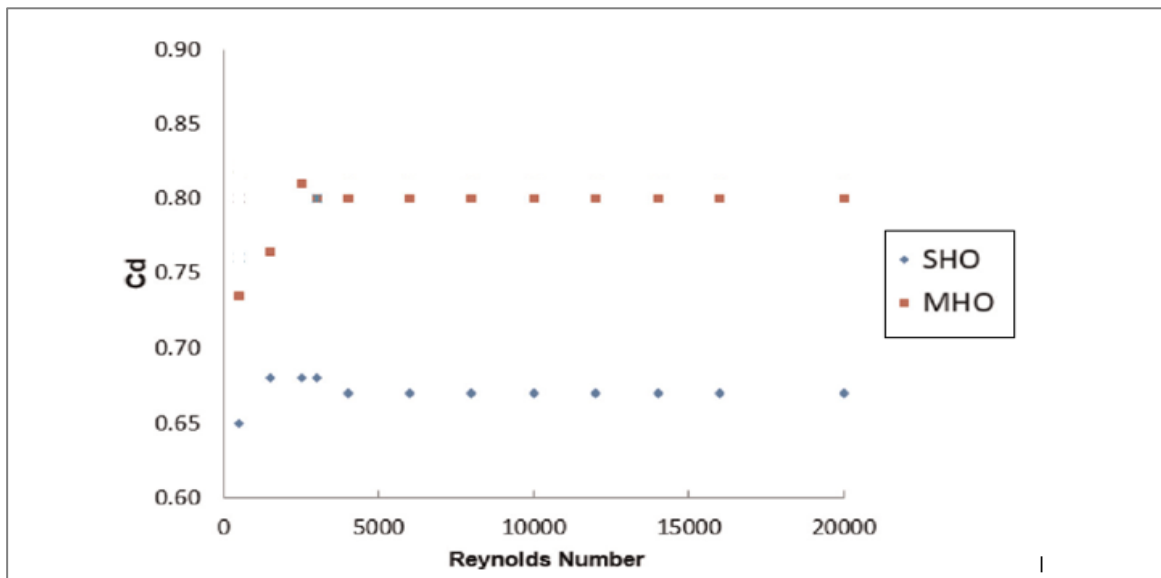


**Figure 2.21:** Comparison of Discharge Coefficients between SHO and MHO  
 (Singh & Tharakan, 2015)

**Table 2.6:** Pressure Recovery between SHO and MHO (Singh & Tharakan, 2015)

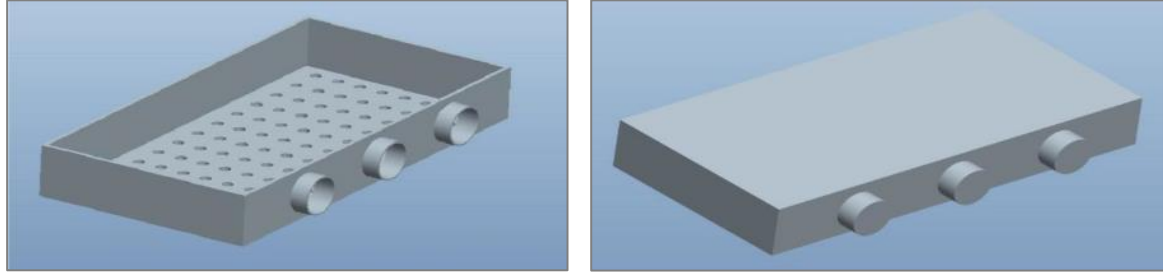
| Reynolds Number    | Pressure Recovery (%) |     |
|--------------------|-----------------------|-----|
|                    | SHO                   | MHO |
| $Re \leq 2000$     | 65                    | 85  |
| $2000 < Re < 3000$ | 68                    | 88  |
| $Re > 4000$        | 67                    | 87  |

### **Fluid-Flow in Liquid Distributor (Sui et al., 2013)**

In the industrial applications, liquid distributor is a component of solution dehumidifier that is usually located on the top of wet curtain or packed tower. This facility plays an important role to provide a uniform distribution of liquid flow over the curtain packing so that the performance of solution dehumidifier can be fully exploited. Therefore, many types of research were conducted in the past to improve the performance of liquid distributor. In this study, an orifice plate liquid distributor – a new kind of liquid distributor which belongs to gravity-type liquid distributor was invented and its performance was accessed by CFD simulation. However, it should be noted that deformations of the structure might happen due to a heavy fluid dynamic load that is acting on the system. This directly affects the flow field of the liquid distributor by changing the orifice size and dimension if the structural deformation happens. For that reason, fluid-solid coupled theory was applied in this study to have a proper control of established model. As concerned by the study, the velocity distribution of outlet orifices was expected from the simulation.

As demonstrated in Figure 2.22, a simplified model of orifice plate liquid distributor with a dimension of 150 mm × 100 mm × 20 mm was used for CFD simulation and experiments. With a total flow of 2.3 m<sup>3</sup>/hr, 104 orifices with a diameter of 5 mm each were provided on the liquid distributor. In this case, multi-field solver (MFS) was used for flow simulation so that the velocity contour plots of the proposed model can be obtained. As shown in Figure 2.23, water ponding was occurred inside the liquid distributor at a certain water level (when Z = -10 mm). Especially at the inlet region, reflux was found near the inner wall of liquid distributor although the water was discharged into the system with a constant speed. Meanwhile, a free flowing jet was formed at the outflow from the middle inlet pipe. Moreover, there were no obvious changes of outflow velocity at the outlets of

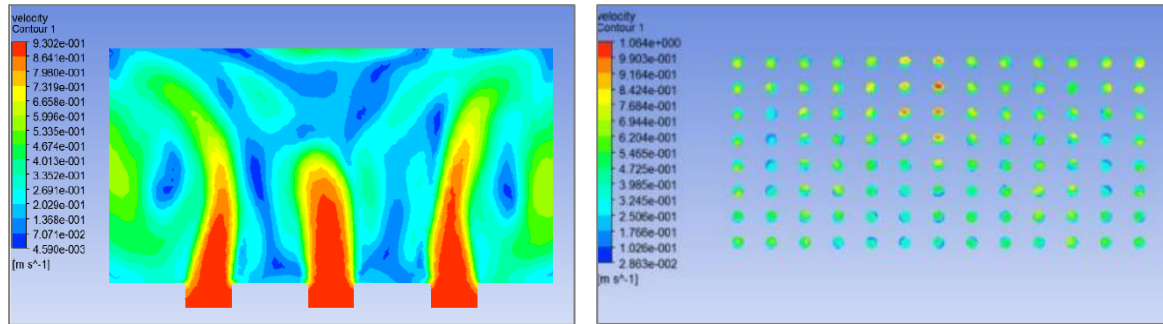
liquid distributor (when  $Z = -20$  mm). Generally, the outflow velocity of orifices was found to be consistent and the average speed of liquid distributor was 0.8 m/s throughout the entire system.



(a) Orifice Plate Liquid Distributor

(b) Liquid Model

**Figure 2.22:** Simplified Model of Liquid Distributor (Sui et al., 2013)



(a)  $Z = -10$  mm

(b)  $Z = -20$  mm

**Figure 2.23:** Velocity Contour Plot of Liquid Distributor (Sui et al., 2013)

In order to validate the simulation results, a simple physical model was built and tested under the same flow condition of CFD simulation. Experimentally, water was pumped up from water tank to the liquid distributor and then, returned back to the tank again when it passed through the orifice plate. For the flow measurement, 18 orifices were selected accordingly and the passing fluid was catered in a measuring cylinder so that the capacity of the orifice plate liquid distributor can be defined (see Figure 2.24). As a result, the volume flow values of outlet orifices of simulation study were larger than experimental data. However, the analysis showed that the liquid distributor would perform as expected because

both experimental and simulation studies gave the same variation trend of data curves in Figure 2.25. This reflected the actual working condition of orifice plate liquid distributor under observation and proved that the orifice plate could distribute and maintain the fluid flow uniformly during its service period.

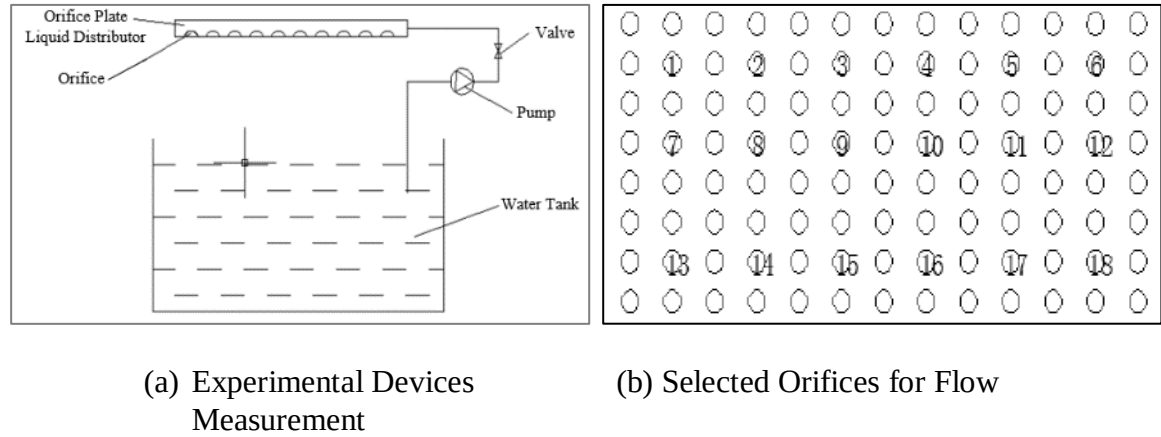


**Figure 2.24:** Experimental Set-Up of Orifice Plate Liquid Distributor (Sui et al., 2013)

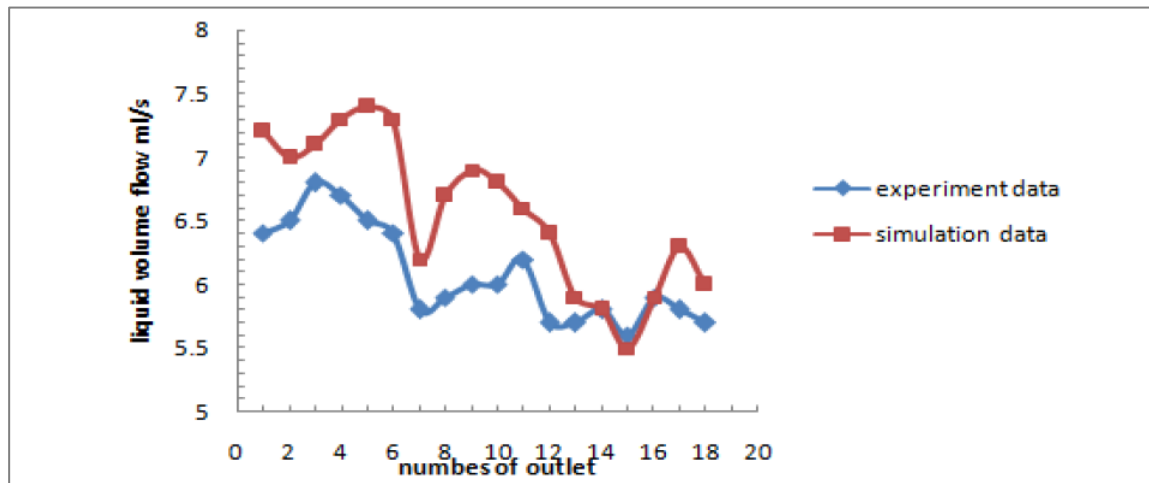


**Figure 2.25:** Experimental and Simulation Data Curves at Outlet Orifice (Sui et al., 2013)

## 2.6.2 Summary of Case Studies

This section summarizes the previous case studies of CFD applications in predicting the flow pattern of moving fluid. As covered in the first part of Section 2.6.1, predictions of

CFD analysis on orifice meter had successfully reflected the actual flow phenomenon in a dynamic flow. With the advancement in CFD, high accuracy and precise results were obtained from the numerical simulation and matched well with the experimental data. Therefore, CFD modelling efforts were done in this project to compare with experimental data in order to obtain a better explanation for the flowing condition on StormPav covers (see further discussed in Section 3.5 and Section 3.6).

Due to the necessity to improve the performance of orifice meter for industrial applications, a centralised orifice that was provided on the plate is modified into multiple holes but with an identical total flow area. Then, the flow analysis of both single-hole and multi-hole orifice plate were analysed by using CFD tool. As the result, CFD analysis had successfully proved that multi-hole orifice plate would perform better than single-hole orifice plate. It dedicated that the multi-hole orifice plate is able to work beyond the limitation of single-hole orifice plate, by reducing the pressure loss of entire system in a great advance. At the same time, the discharge coefficient of multi-hole orifice plate was higher than single-hole orifice plate. Likewise in the StormPav system, it can be said that the assembling of hexagonal covers that appears as a multi-hole orifice plate would work better than a single orifice storage system. As expected by this study, multiple numbers of service inlet would allow for quick draining of stormwater to underground storage system so that the surface ponding can be avoided.

Moreover, flow pattern of the service inlets of StormPav system is expected to have a similar trend of result with the case study of orifice plate liquid distributor. This assumption is made because both of them are designed for the gravity flow through orifices with same orifice size and geometry. As discussed in the case study of liquid distributor, the system was purposely designed in the form of orifice plate so that a uniform distribution of liquids

could be obtained. With the aid of CFD simulation, the actual working condition of the orifice plate liquid distributor was analysed and the result had successfully proved that the device functioned as expected. Similarly to the service inlets of StormPav covers, the surface runoff is expected to be uniformly distributed into the service inlets for the determination of its surface infiltration.

## **CHAPTER 3**

### **METHODOLOGY**

#### **3.1 Introduction**

Based on the literature in previous chapter, StormPav system is invented for urban roads to support traffic movement and improve road drainage system. As illustrated in Figure 3.1, the assembling of StormPav units is able to form road pavement with a total height of 0.45 m from native soil layer. A mimic of natural soil layer is applied here so that the system would generate less runoff by infiltrating and storing excess runoff into an underground detention. In this case, a 40 mm diameter of service inlet is provided at the centre of each hexagonal cover for the vertical movement of stormwater from road surface to underneath layer. Theoretically, this is known as surface infiltration. Then, the stormwater is allowed for horizontal movement in the underground storage system as there is a similar size of service hole is provided at the side wall of each hollow cylinder in order to fill up the empty space between the cylinders. Lastly, the detained runoff is slowly discharged or further infiltrated into the native soil through another draining inlet at the bottom plate.

In other words, StormPav system is combining the features of permeable pavement and OSD. As an illustration, this system involves at least three hydrological processes, which are surface infiltration, detention and bottom infiltration. As concerned in this project, the focus is on surface infiltration of StormPav system so that the parameter is defined to assess the drainage capability of the service inlet. The first objective can be achieved by investigating the inlet for orifice flow, while the second objective can be achieved through CFD and experimental studies.

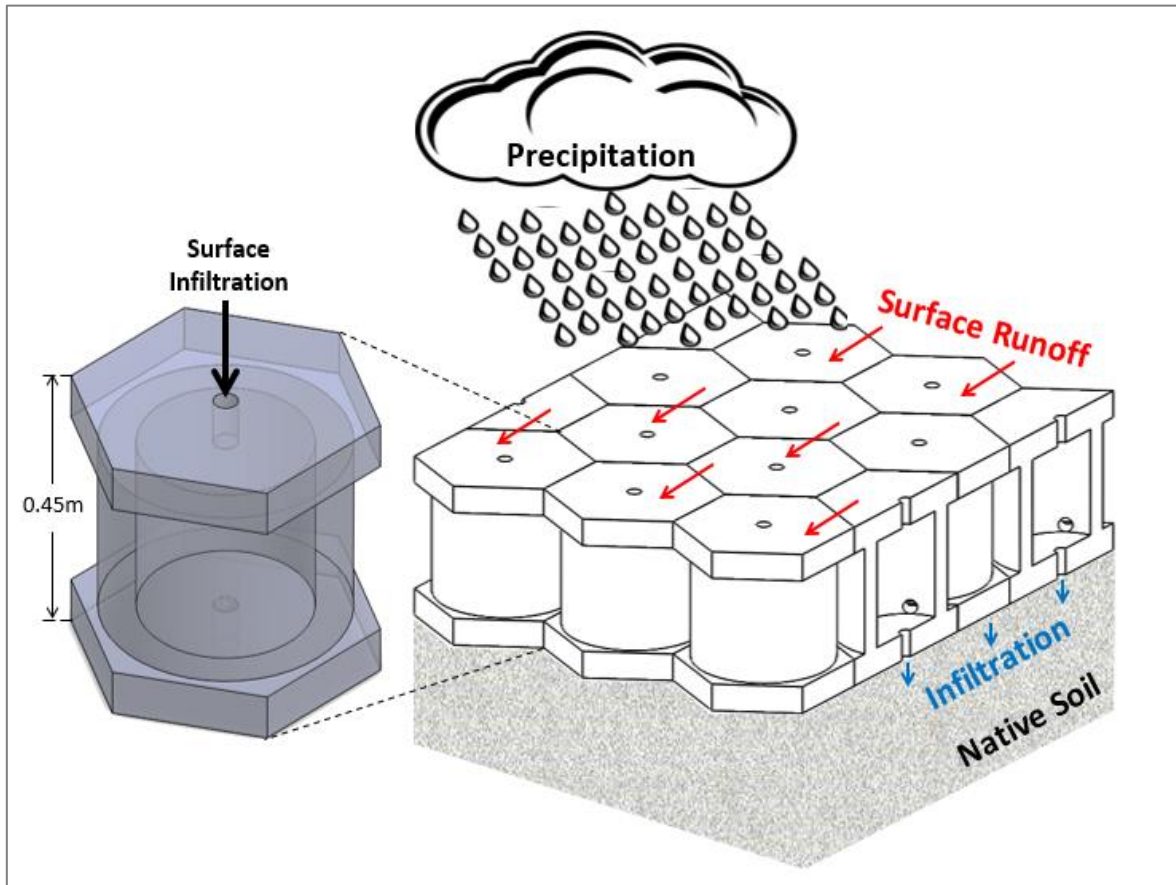


**Figure 3.1:** Concept of Stormwater Conveyance in StormPav System

### 3.2 Study Area

A signalised intersection along Kuching-Samarahan Expressway (near Taman Riveria) is chosen as the study area (see Figure 3.2). Complying with JKR Standard, this road is classified as Class U6 Urban Road with a total length of 10.5 km. Due to the rapid growth of population in Kota Samarahan, this route experiences heavy traffic congestion during peak hours. This happens because it is the main link that connects Kota Samarahan with many industrial and commercial areas of Kuching city, such as Sama Jaya industrial zone and Tabuan Jaya.

Currently, this road is undergoing expansion due to the increased traffic between these two regions. At the beginning of the year 2016, a new traffic light is installed at this

route in order to reduce the peak hour traffic jam. At this signalised intersection, traffic vehicles are required to slow down or stop repeatedly when approaching the intersection. Moreover, the punching force of the vehicles creates a great impact to the pavement layer to fatigue its structure.

This project is attempted to replace the traditional asphalt pavement of the mentioned intersection with StormPav system. The intersection covers a road surface area of 1050 m<sup>2</sup> (30 m length × 35 m width) and it requires at least 5544 of StormPav units to fill up the space (refer to Appendix A). With such a large landscape of StormPav system, its capability and effectiveness in managing the stormwater should be assessed to ensure a good merging of road intersection and stormwater management. Therefore, this intersection is equally divided into 20 sections with a similar dimension of 3.5 m width and 15 m length to ease the modelling process (see Figure 3.3). Through this, the modelling results is expected repetitive in nature due to similar geometry; and applicable to other sections or road junctions as the similar conditions are used for roadway applications.



**Figure 3.2:** Map View of Kuching-Samarahan Expressway and Proposed Intersection (<http://maps.google.com>)

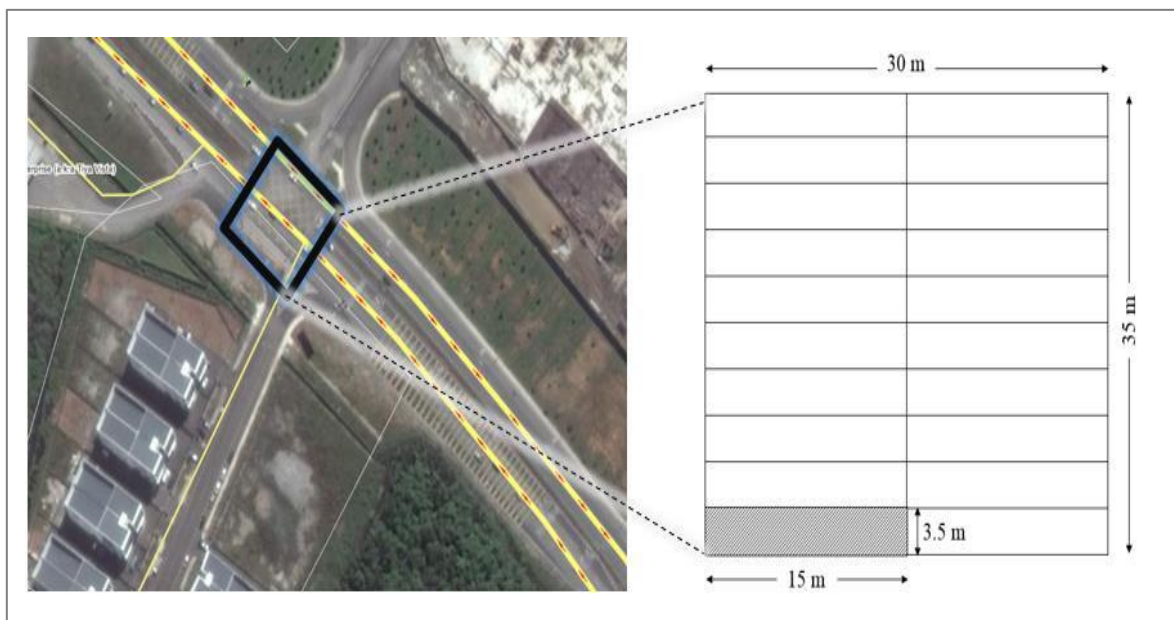


**Figure 3.3:** Distribution of Proposed Intersection for Modelling Purpose

### 3.3 Proposed Design

This section describes the intended small-scale model used for laboratory testing and CFD simulation. As illustrated in Figure 3.4, there are six (6) full units and two (2) half units of StormPav are grouped together to form the small-scale model. Due to the limited size of water tank that is available in the local market for experimental study, StormPav units are assembled and formed a perfect rectangular system with a dimension of 1.515 m and 0.875 m in length and width respectively. However, it should be noted that only six service inlets are taken into the analysis as the orifices of half plates are ignored in order to maintain the accuracy of flow measurement. In this regard, this model is first developed and analysed by CFD model and then, tested in the laboratory. In both studies, the road surface and road curb are modelled as a “big” rectangular cross-section that directs the storm runoff to underground storage (see Figure 3.5).

The principle of orifice flow is employed here to determine the surface infiltration of StormPav system. Basically, this idea is similar to flow through a single-stage multi-hole orifice plate in a pipe. As illustrated in Figure 3.6, the volumetric flow rate per orifice equals to each other, if they behave a similar geometry and cross-sectional area (Shah, et al., 2012; Barki et al., 2014; Singh & Tharakan, 2015). Orifices on the hexagonal plates are expected to have similar orifice flow rate since identical modular units are used. Therefore, it is reasonable to justify orifice flow of StormPav cover as the surface infiltration of entire system.

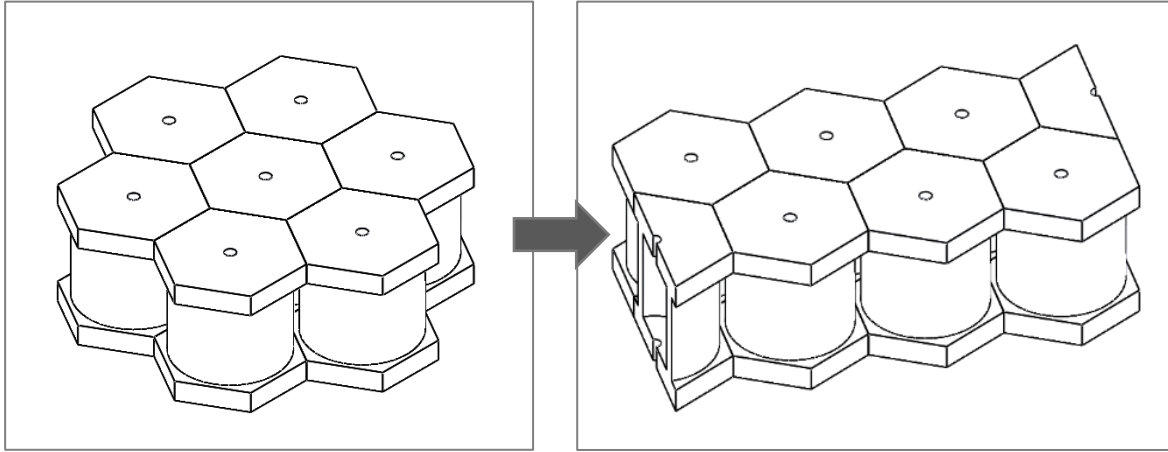


**Figure 3.4:** StormPav Units for Small-Scale Model

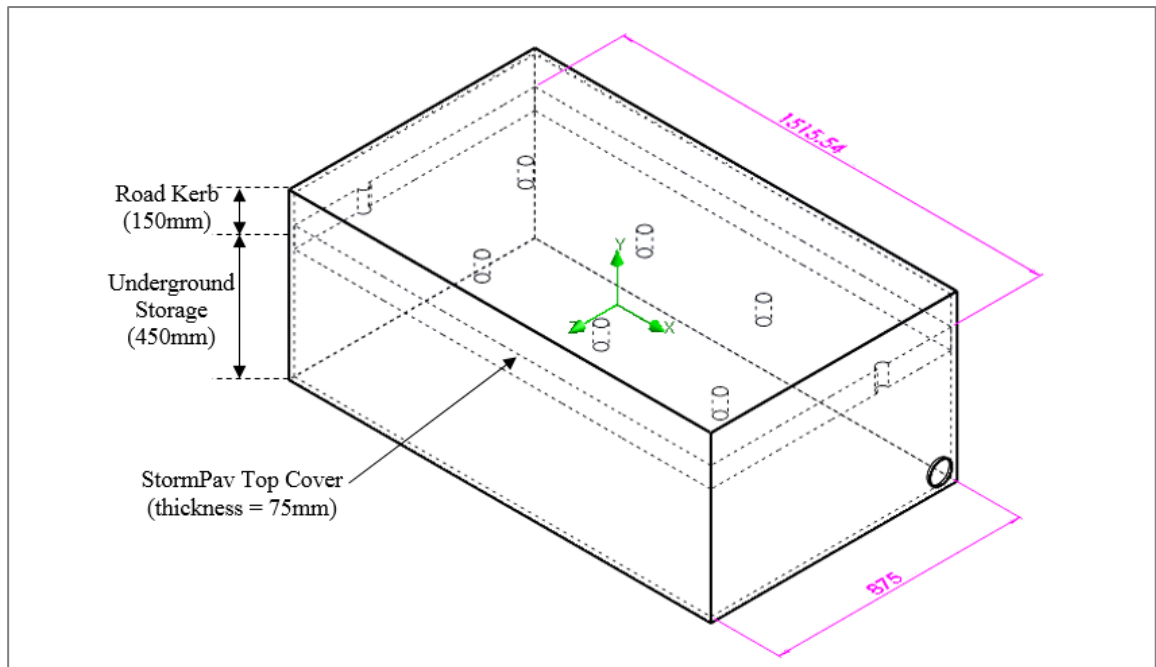


**Figure 3.5:** Modelling Approach for Small-Scale Model

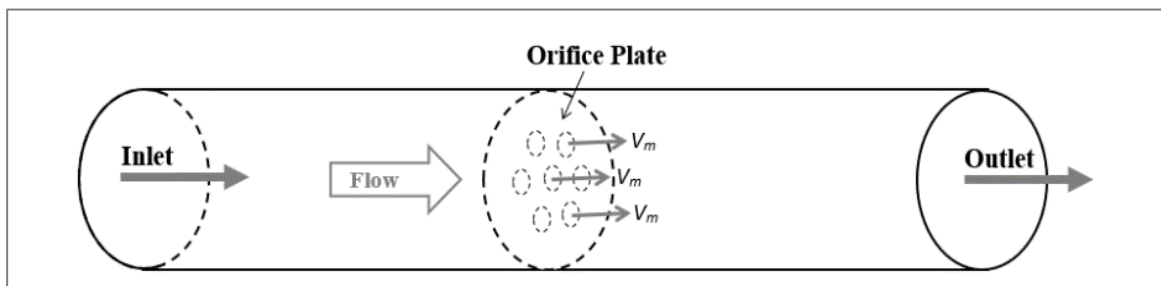


**Figure 3.6:** Flow through a Multi-Hole Orifice Plate in a Pipeline

### 3.4 Rainfall-Runoff Relationship

Relationship of design rainfall and surface runoff on the real system of selected intersection are analysed to have a proper control and conveyance of stormwater to underground OSD. For a major road like Kuching-Samarahan Expressway, normal practice of 15-minute 10-year ARI rainfall is used for runoff computation in this case. Rainfall intensity of 180 mm/hr is derived from the Intensity-Duration-Frequency (IDF) curve for Kota Samarahan provided by the Department of Irrigation and Drainage (DID) Sarawak (refer to Appendix B).

In order to make a realistic estimation of surface runoff, average temporal distribution of design rainfall is developed from the local storm data (refer to Appendix C). This is important to represent the typical variation of storm intensities during a typical storm burst (DID, 2002). For this case, the rainfall variability of 57.6 mm/hr, 90.0mm/hr and 32.4 mm/hr are obtained accordingly when 15-minute storm is divided equally into three number of time periods. After that, these three values are used to determine the values of surface runoff by using Rational Method (see Table 3.1). By doing so, different types of flow patterns (high, medium and low) are expected from the intensities, namely 90 mm/hr as red-alert storm, 57.6 mm/hr as heavy rain and 32.4 mm/hr as light rain.

**Table 3.1:** Design Rainfall and Surface Runoff

| Model                                   | Time Period | Rainfall Intensity (mm/hr) | Surface Runoff, Q (l/s) |
|-----------------------------------------|-------------|----------------------------|-------------------------|
| Laboratory Model<br>(0.875 m × 1.515 m) | 1           | 57.6                       | 0.02                    |
|                                         | 2           | 90.0                       | 0.03                    |
|                                         | 3           | 32.4                       | 0.01                    |
| Selected Intersection<br>(3.5 m × 15 m) | 1           | 57.6                       | 0.84                    |
|                                         | 2           | 90.0                       | 1.31                    |
|                                         | 3           | 32.4                       | 0.47                    |

### 3.5 CFD Approach

SolidWorks Flow Simulation 2015 is utilised to analyse the fluid flow pattern at the service inlets of StormPav system. The simulation provides first estimate the impact of fluid flow before physical modelling. Contrary to the traditional method, analytical procedure of complex flow could be complicated as it involves an iterative process, where the modification of the model should be done repeatedly in order to solve the problems. With the aid of computer technology like SolidWorks, the performance of StormPav system on how it behaves in the real world could be inspected. Then, the efficiency and performance of service inlet to infiltrate the stormwater into underground OSD can be improved, if further modification is required. For that reason, trial validation by CFD simulation is first performed using a small-scale model.

#### 3.5.1 Geometry Modelling

First of all, physical geometry of StormPav modular unit is developed in the model according to the dimensions that are presented in Figure 2.7. In this study, service inlets are combined to form a multi-hole orifice plate that is modelled inside a rectangular box to represent the cover-cum-pavement of StormPav system. In the modelling process, a new part of SolidWorks is first created for component design. Before starting with two-dimensional (2D) sketching, Top Plane and Top View are selected from the *Feature Manager design tree* and *View Orientation* drop down menu in the graphic window respectively. After that, the geometry file is extruded to three-dimensional (3D) of multi-hole orifice plate with a thickness of 75 mm. In order to make sure the model is a water-tight system that is eligible for flow analysis, a rectangular box is modelled at the boundary of multi-hole orifice plate

to represent the road curb and underground detention that exist in the real system (see Figure 3.7 to Figure 3.11).

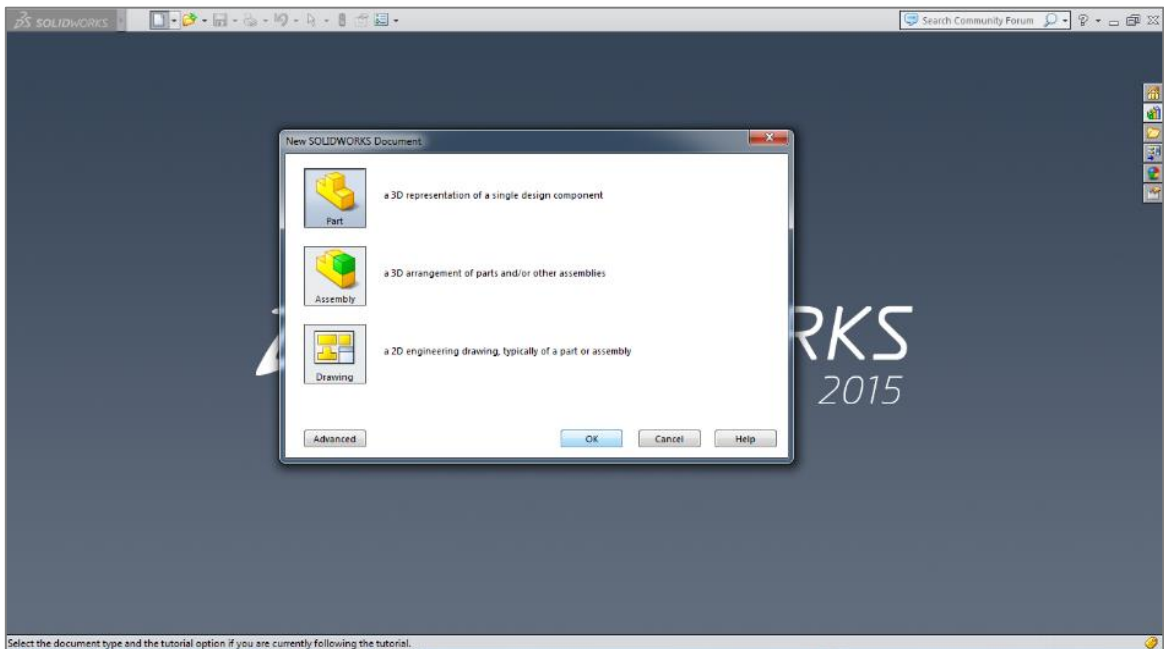


**Figure 3.7:** Creating the SolidWorks Part for the Proposed Design

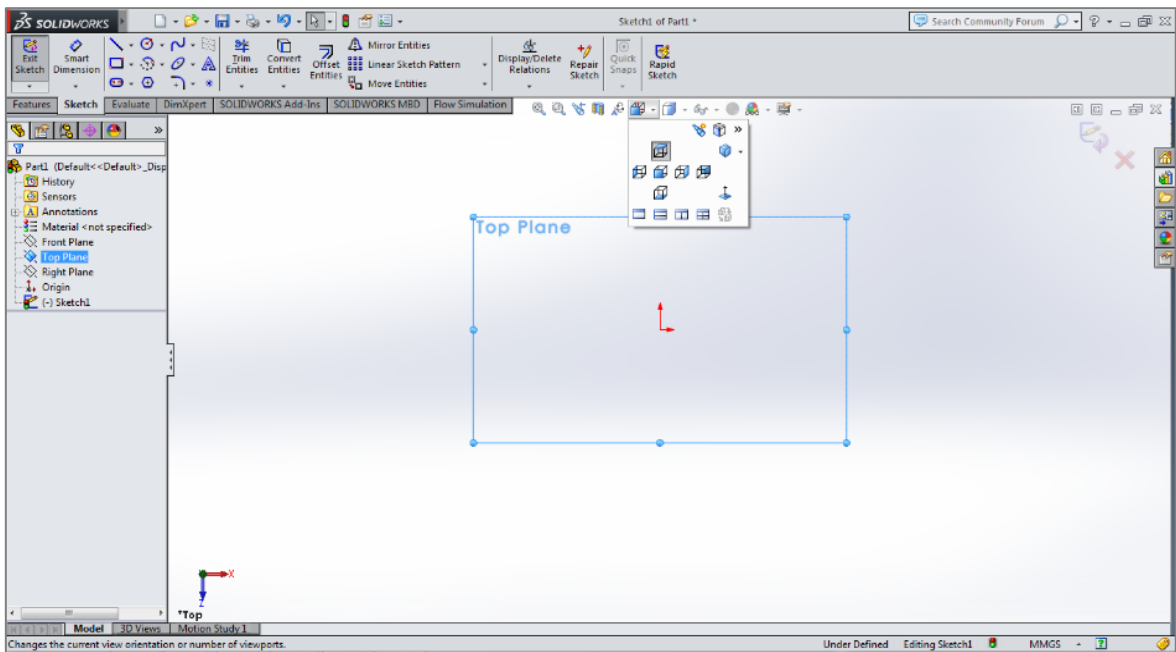


**Figure 3.8:** Selecting the Top Plane for 2D Sketching

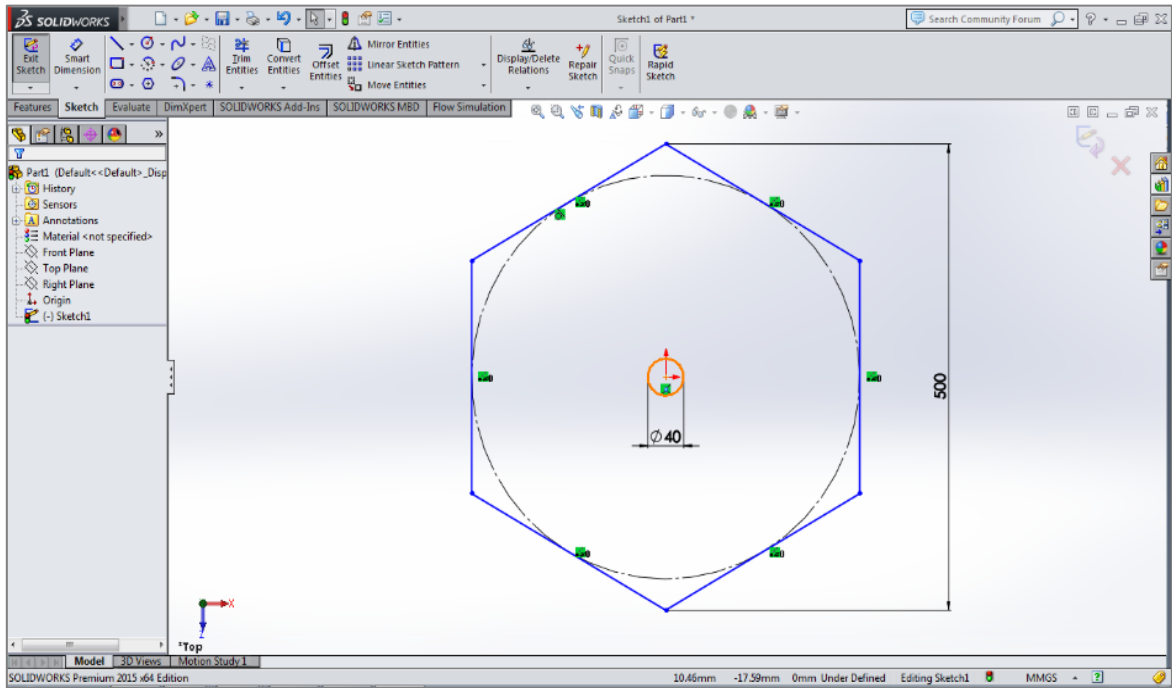


**Figure 3.9: Creating the Model Geometry**

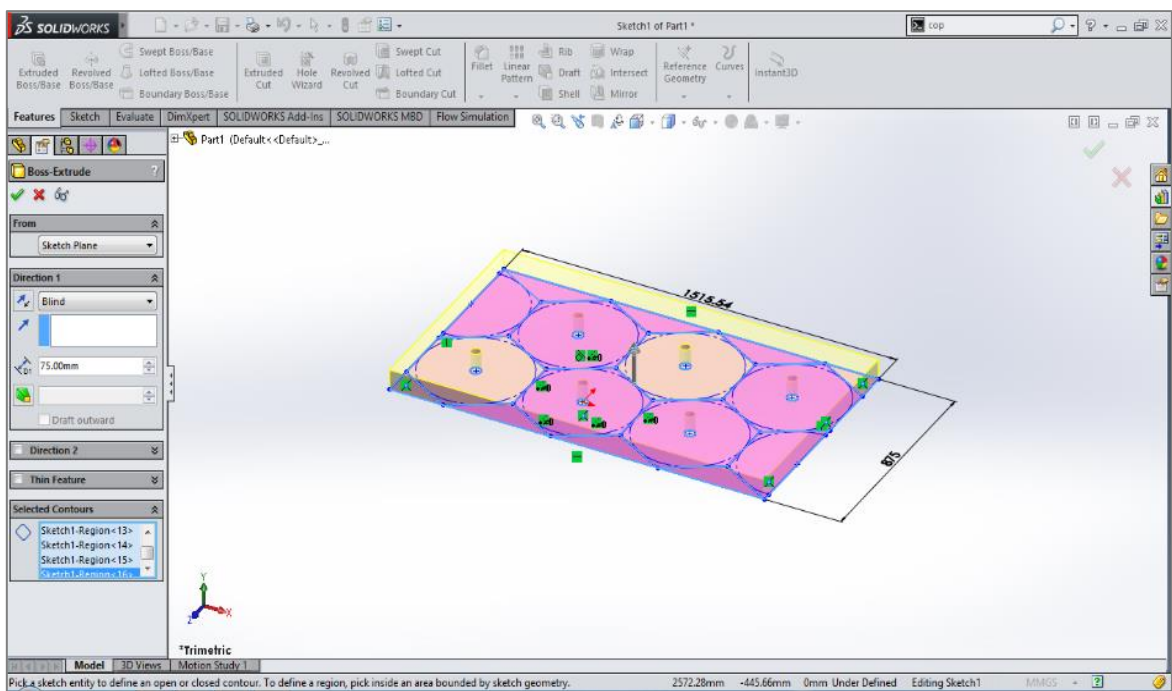


**Figure 3.10: Extrusion of Existing Geometry to Form a 3D Model**

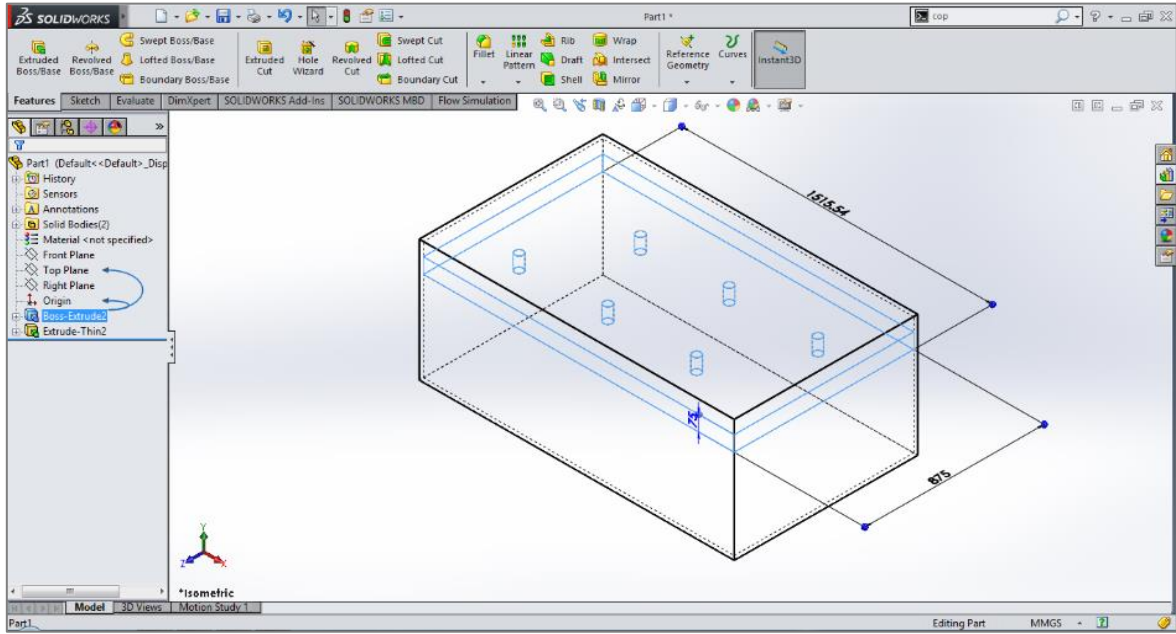


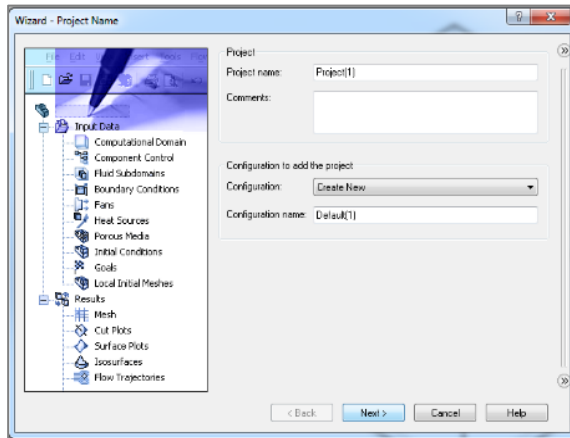
**Figure 3.11:** Completed 3D Small-Scale Model

### 3.5.2 Flow Simulation Project

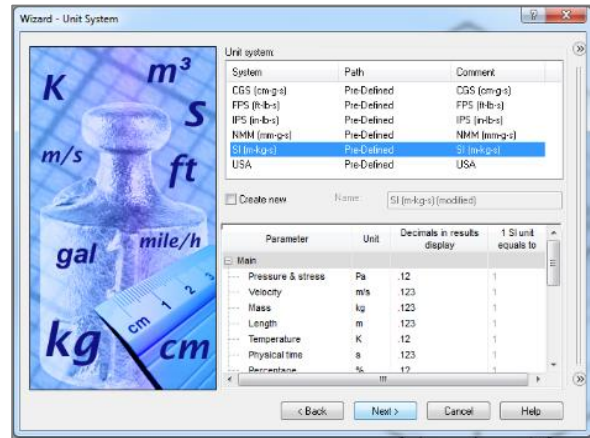
Subsequently, the 3D model that is developed from the previous section is transferred into SolidWorks Flow Simulation for flow analysis. The model is set to analyse the internal flow of the entire system and water is set as the working fluid of the model. Therefore, the physical properties of water are specified in the simulation, as shown in Table 3.2. Furthermore, the flow is infiltrated into underground OSD by gravity flow when it intercepts the orifices. Then, the wall condition and initial condition are specified for further analysis. For example, default pressure and temperature that are used in the modelling process are 101.325kPa and 20°C respectively (refer to Figure 3.12).

**Table 3.2:** Physical Properties of Water (Sharp, 2001)

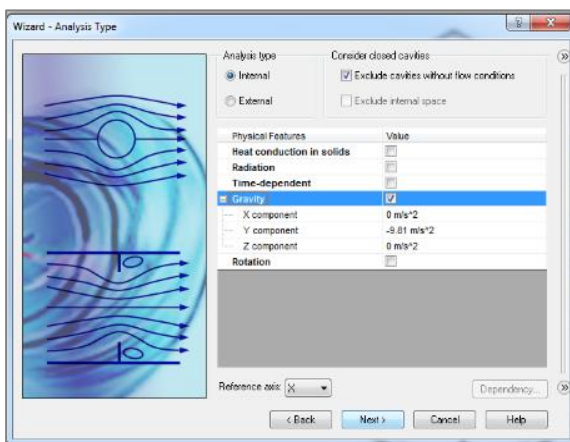
| Properties                    | Values                                 |
|-------------------------------|----------------------------------------|
| Density, $\rho$               | 998 kg m <sup>-3</sup>                 |
| Viscosity, $\mu$              | 1002 $\mu$ Pa s                        |
| Specific heat capacity, $C_p$ | 4.18 J g <sup>-1</sup> K <sup>-1</sup> |
| Molecular weight, $M$         | 18 g mol <sup>-1</sup>                 |



(a) Open a New Project



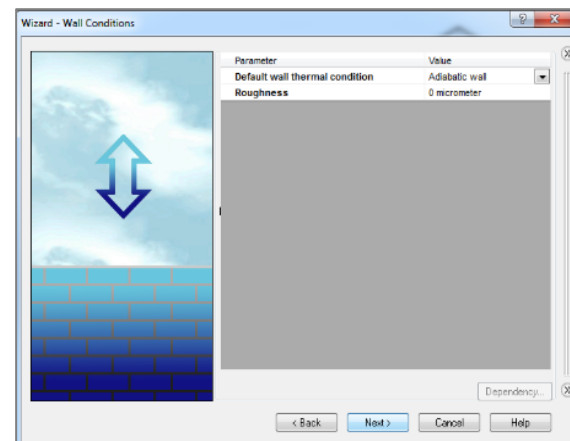
(b) Select the Unit System



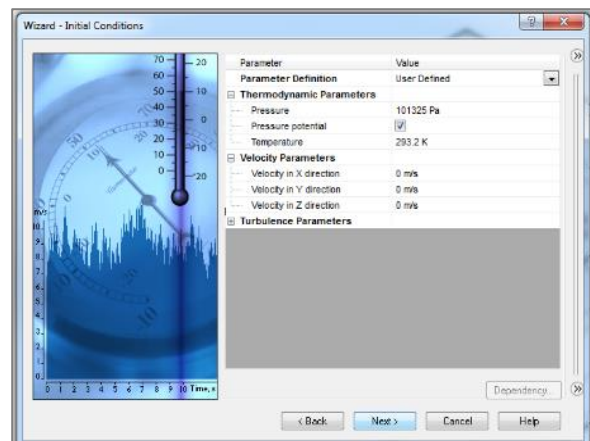
(c) Choose the Analysis Type



(d) Set the Default Fluid



(e) Set the Wall Condition



(f) Set the Initial Condition

**Figure 3.12: Creating a Flow Simulation Project**

### 3.5.3 Meshing

A good mesh helps to maintain the accuracy of fluid flow analysis. Therefore, meshing is a critical step in the flow simulation as it is directly

affecting the performance of CFD simulation. For CFD tool like SolidWorks, mesh is produced based on finite volume method (FVM) that is known as ‘cells’, but not the tetrahedral elements like finite element method (FEM). Through FVM, non-conforming meshes can be easily solved to provide a high accuracy of flow measurement in predicting its real-world behaviour. In this case, SolidWorks Flow Simulation provides a robust mesher to refine mesh size around the service inlet of StormPav cover by reducing its gap sizes. As shown in Figure 3.13, resolution of geometry (also known as basic mesh) is adjusted to keep a finer mesh around the orifice region to maintain the quality of mesh. Moreover, this helps to reduce the time required for analysis.

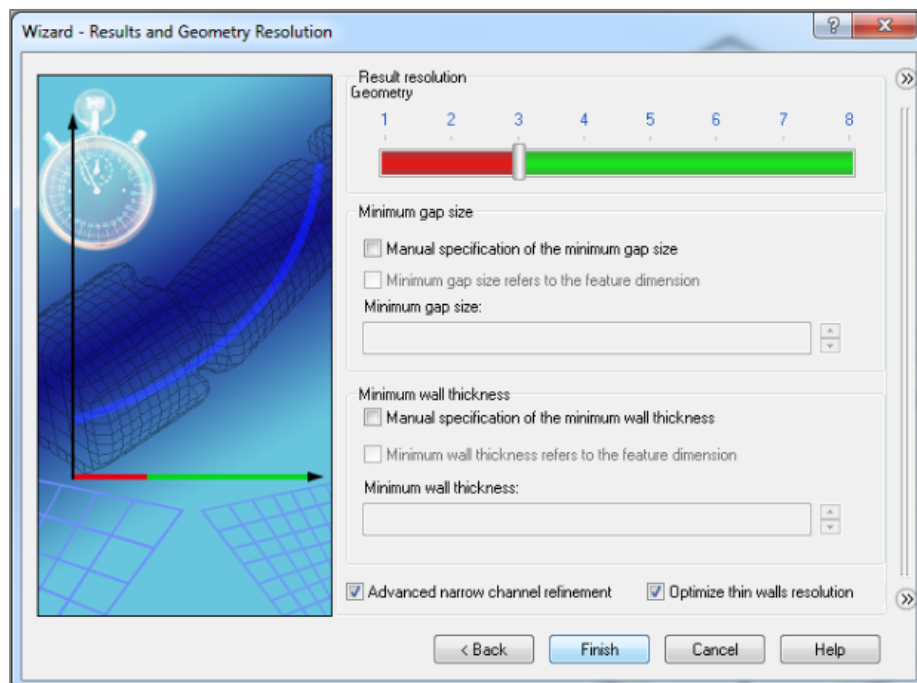


**Figure 3.13:** Meshing Element

### 3.5.4 Boundary Condition

This section is the most integral part of CFD simulation because it directs flow motion of the entire system. Prior to define the inlet and outlet, a model check is performed to ensure that a valid geometry is achieved for further analysis. At the same time, the fluid region of the system is recognised by CFD and concerned in the analysis, as illustrated in Figure 3.14. At the inlet region, surface runoff that has been generated from the rainfall intensity by using Rational Method (which is determined in Table 3.1) is inserted into the model as an inlet volume flow. Through this, the red arrows appear in the model to show its inlet boundary layer (refer to Figure 3.15 and Figure 3.16). Consecutively, pressure opening is set as the outlet boundary layer to discharge the flow domain, as represented by blue arrows (see Figures 3.17). Moreover, the wall boundary condition of this model is set to the adiabatic and non-slip conditions because no heat is transferred through the wall and the velocity of the fluid is measured tangentially to the wall itself. After that, certain *Goals* are specified in the modelling and this helps to define the main design objective for the simulation. As illustrated in Figure 3.18, parameters like maximum mass flow rate and maximum velocity are defined as Global Goals that are used for convergence control in the model.

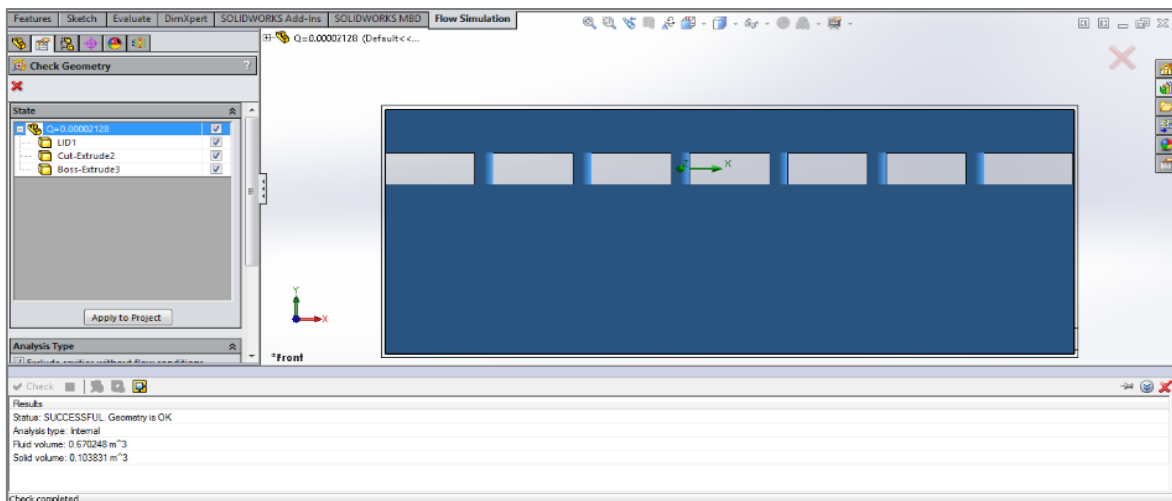


**Figure 3.14: Geometry Check and Recognition of Fluid Region**

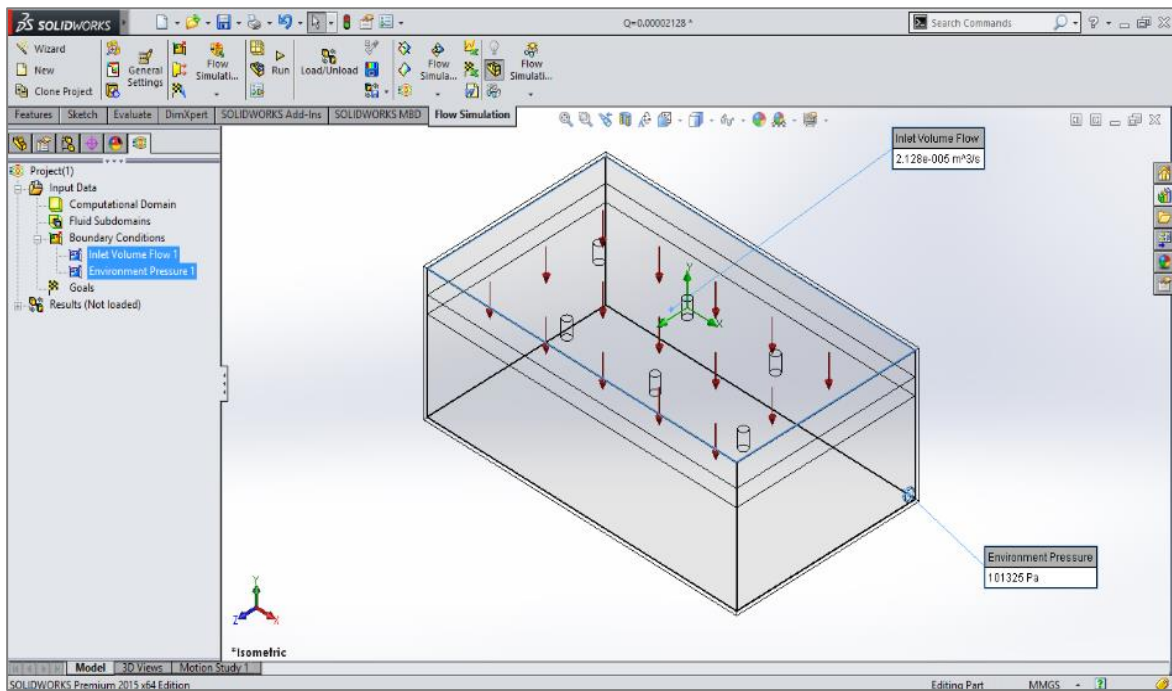


**Figure 3.15: Boundary Conditions of the Proposed Model**

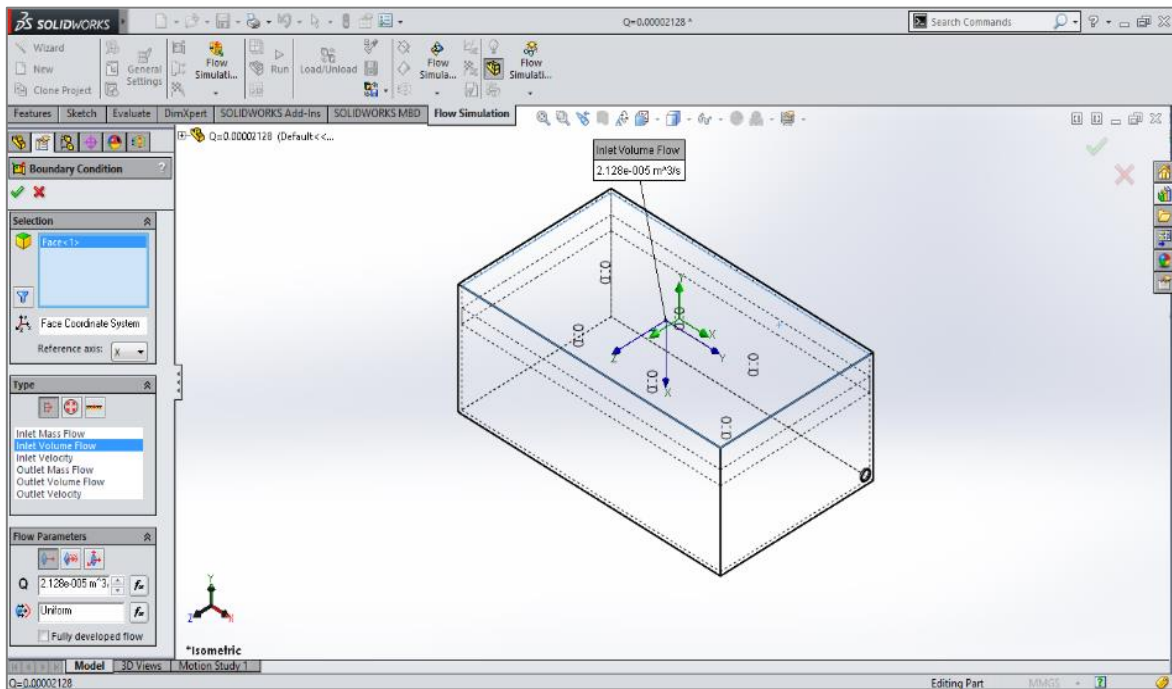


**Figure 3.16: Setting Up of Inlet Boundary Layer**

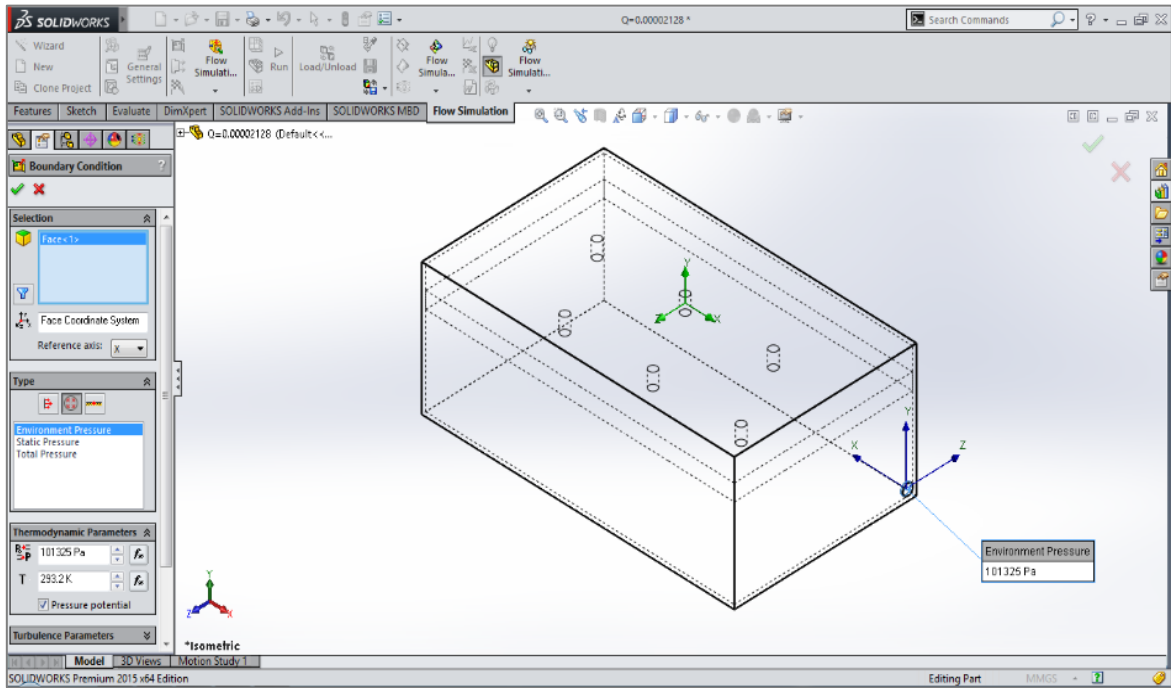
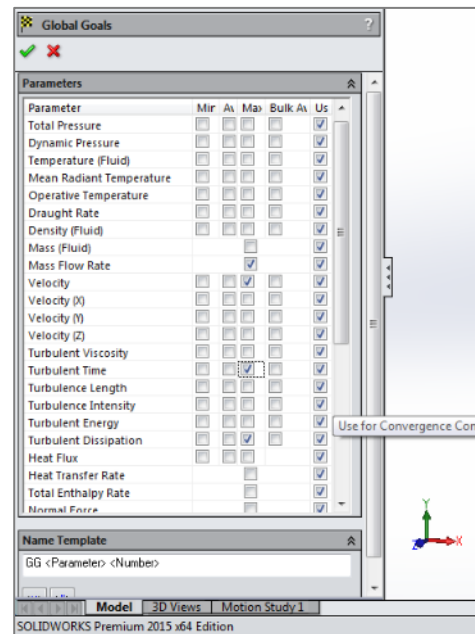
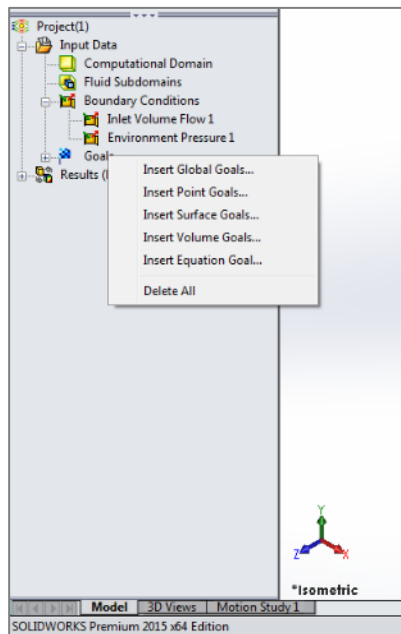


**Figure 3.17:** Setting Up of Outlet Boundary Layer



(a) Types of Goals

(b) Defining the Key Objectives for Simulation

**Figure 3.18:** Specifying the Modelling Goals

### 3.5.5 Flow Chart of CFD Approach

Figure 3.19 summarizes the steps in the CFD simulation.

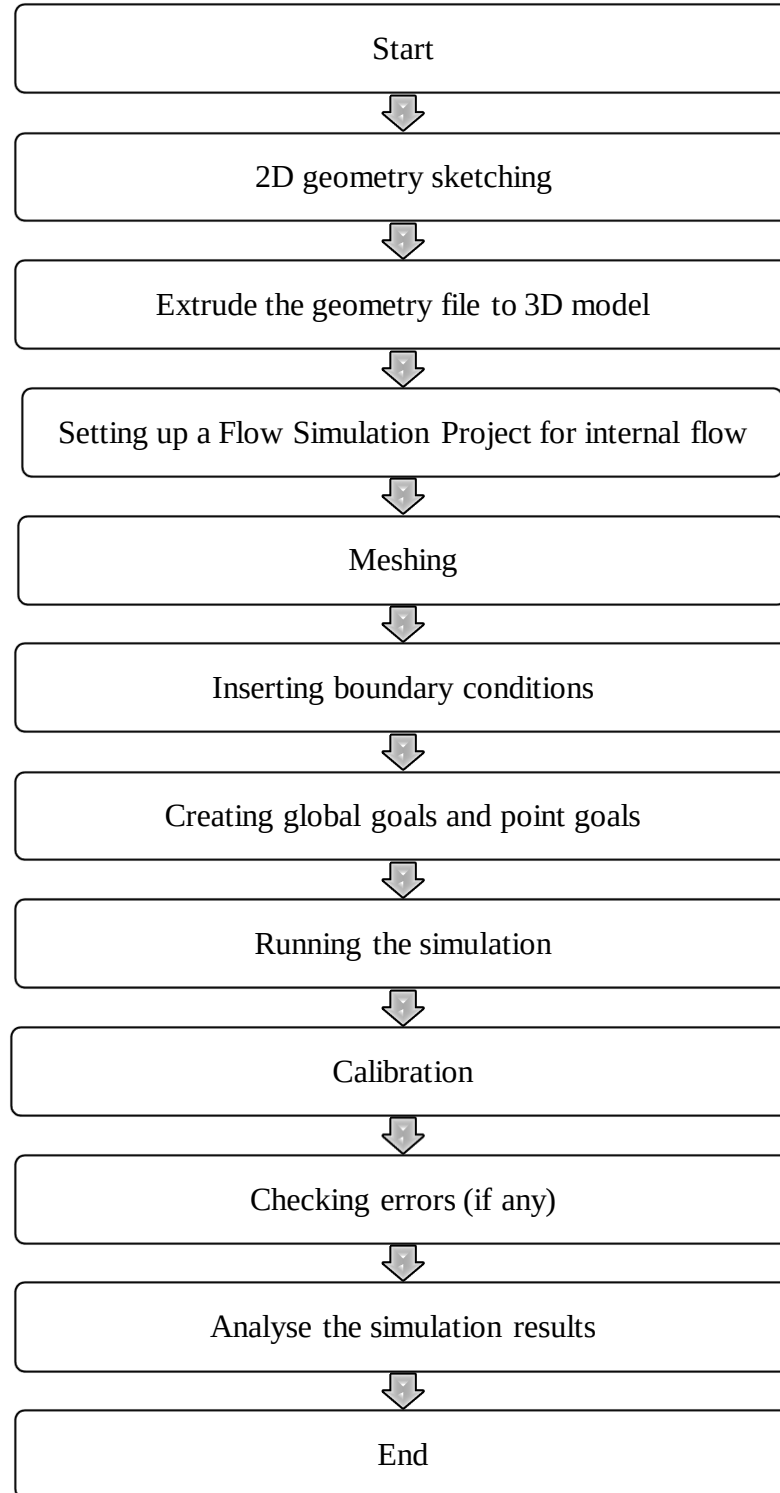


**Figure 3.19:** Summary of CFD Simulation

### 3.6 Laboratory Testing

Laboratory testing is conducted in the laboratory to verify the performance of CFD simulation in defining the infiltration capabilities of the service inlets of StormPav covers. Obviously, both studies are expected to demonstrate a similar trend of outcomes to achieve second objective of this study (refer to Section 1.4). For laboratory testing, the performance of proposed model with a dimension of 0.875 m width  $\times$  1.515 m length (refer to Section 3.3) that involves six full units and two half units of StormPav are assessed experimentally. However, the real laboratory-scale model (as illustrated in Figure 3.20) with only six full StormPav units are used and the fringes are covered to give a rectangular surface.

Moreover, gaps between the modular units in the real system are unavoidable. In order to make sure this physical model would perform a similar flow condition with CFD model, these gaps and sides were sealed by using sealant and covered with a layer of cloth tape. This is done to ensure that the system is totally imperviousness and water-tight for the determination of orifice flow. Generally, this experimental study is sufficient to prove the performance of StormPav system because actual-sized modular units are used. For that, as justified in Section 3.3, repetitive results are expected because of the identical geometry of modular units.

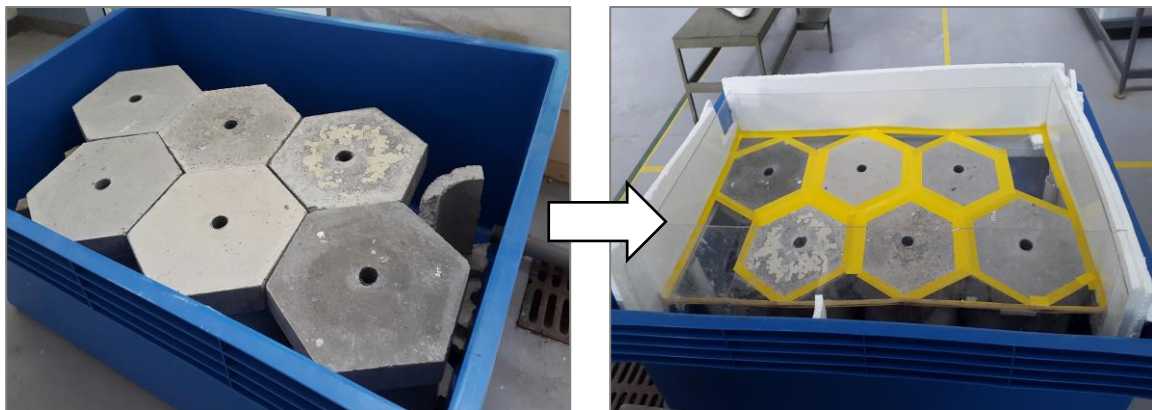


**Figure 3.20:** Installation of Physical Model

### 3.6.1 Calibration of Rainfall Simulator

To simulate rainy conditions with various rainfall intensities, a 1.50 m length  $\times$  1.00 m width  $\times$  0.24 m height of transparent water tank is specially fabricated in the laboratory and placed above the StormPav system (refer to Figure 3.21). As illustrated in Figure 3.22, the tank is functioned as a rainfall simulator that allows the water to drip through a perforated acrylic plate with 30 numbers of 2.0 mm diameter holes on the bottom panel. Fundamentally, the calibration of rainfall simulator is conducted by determining the time taken that is necessary for 5  $\ell$  of water to drain through the tiny holes on the perforated plate. In order to simulate various rainfall intensities, the flow rate of this equipment is controlled by the number of openings with cellophane tapes. As a result, it is discovered that the increasing number of openings allow water to drain faster from the simulator tank and thus, a shorter time is required for a higher flow rate (see Figure 3.23).

Besides that, this equipment can be known as a non-pressurised rainfall simulator in this case. In the testing process, the discharge of water through tiny holes are constant as it worked like a sprinkler system to distribute the flow uniformly on the StormPav covers. Through this, realistic rain events are simulated by this calibration. Based on the results obtained from the calibration of rainfall simulator, average flow rate (also considered as the runoff volume) is converted to rainfall intensity by dividing with its intercepting catchment area. By assuming that the total area of physical model is the catchment area of these rain events, various rainfall intensities are obtained by controlling the number of openings in the simulator tank. As tabulated in Table 3.3, rainfall intensity increases with the increment of average flow rate (see Table 3.3 and detailed calculations in Appendix D). In addition, this system is able to imitate the rainfall intensity over a range of 2.96 – 90.89 mm/hr, which can be used to represent rainfall (see Table 3.1).

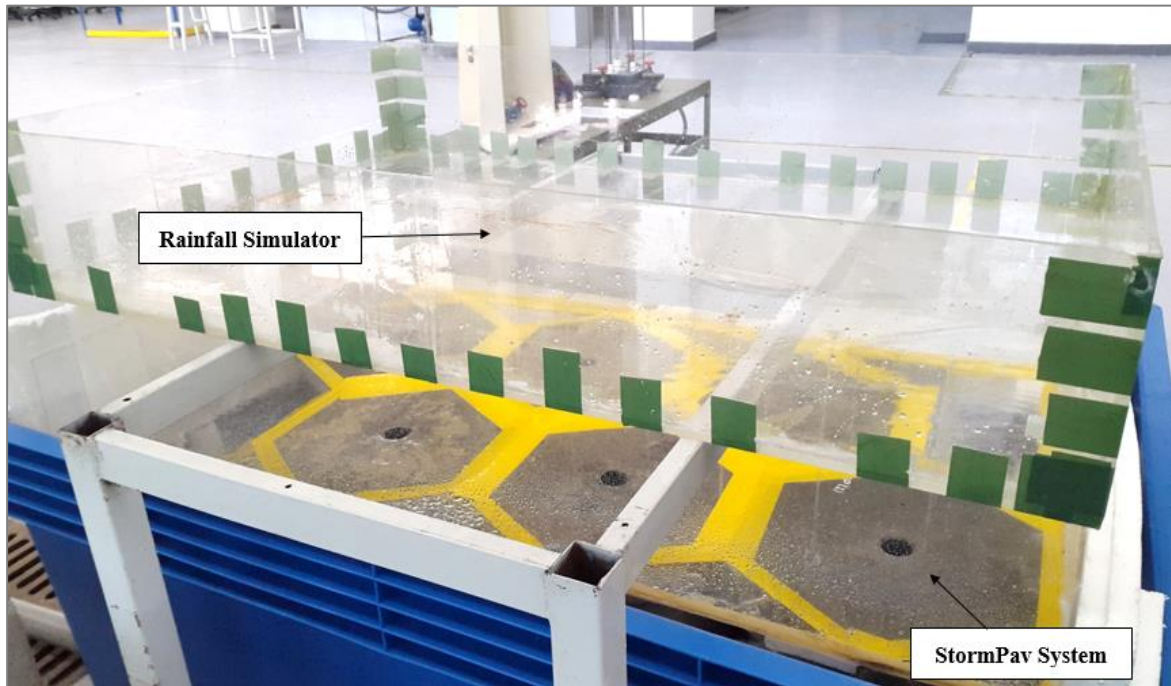


**Figure 3.21:** Experimental Set-Up



**Figure 3.22:** Simulating the Rain Intensity through Tiny Holes

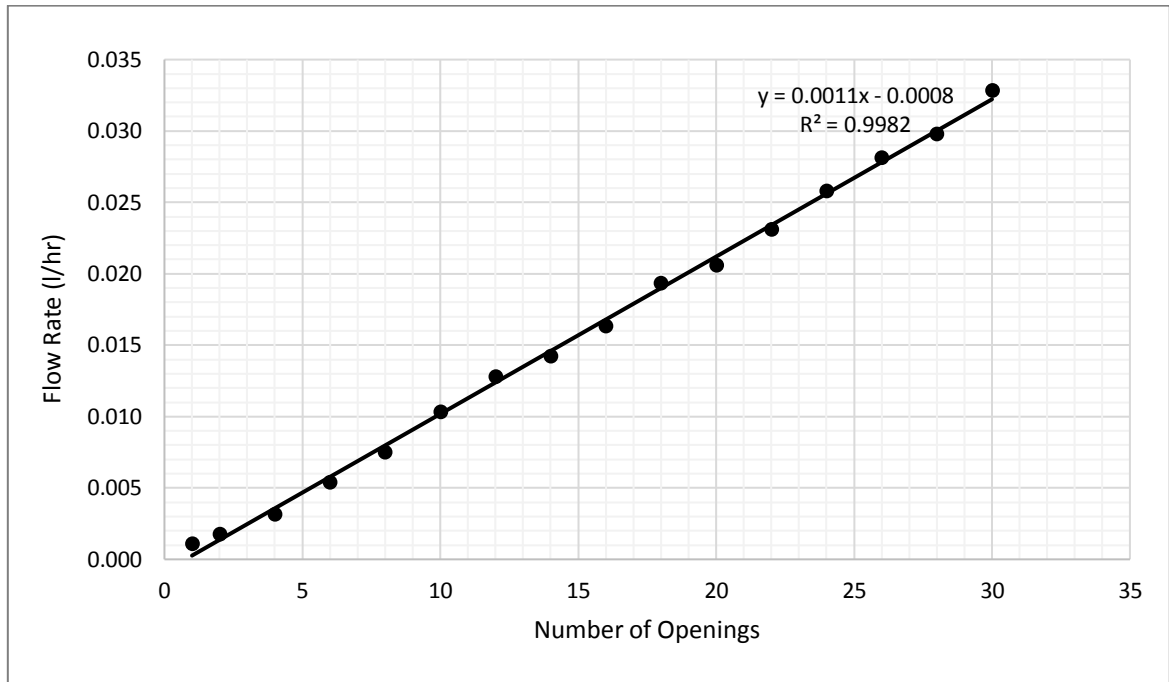


**Figure3.23:** Experimental Results of Rainfall Simulator in Various Openings

**Table 3.3:** Relationship between Number of Openings and Rainfall Intensity

| Opening | Average Flow Rate (l/s) | Rainfall Intensity (mm/hr) | Opening | Average Flow Rate (l/s) | Rainfall Intensity (mm/hr) |
|---------|-------------------------|----------------------------|---------|-------------------------|----------------------------|
| 1       | 0.0011                  | 2.96                       | 16      | 0.0158                  | 43.75                      |
| 2       | 0.0018                  | 4.85                       | 18      | 0.0194                  | 53.58                      |
| 4       | 0.0031                  | 8.58                       | 20      | 0.0206                  | 57.07                      |
| 6       | 0.0054                  | 14.93                      | 22      | 0.0231                  | 63.97                      |
| 8       | 0.0075                  | 20.77                      | 24      | 0.0258                  | 71.42                      |
| 10      | 0.0104                  | 28.66                      | 26      | 0.0281                  | 77.84                      |
| 12      | 0.0128                  | 35.47                      | 28      | 0.0298                  | 82.52                      |
| 14      | 0.0142                  | 39.43                      | 30      | 0.0328                  | 90.89                      |

### 3.6.2 Model Validation

In this laboratory testing, a full control of water volume (approximately 40 l of water) is first poured into the water flow simulator tank to simulate a realistic rain event. This can be done by controlling the number of openings that is appropriate for certain rainfall intensity by referring to Table 3.1 and Table 3.3. For example, all of the tiny holes should be opened or unclogged in order to have a rainfall intensity of 90 mm/hr for physical modelling. Then, about 0.3 l/s of surface runoff is generated on the hexagonal plates and directed to the service inlets for infiltration and temporary storage. For flow measurement, a measuring cylinder is located under an inlet hole to investigate time taken for the collection of 1 l water. From there, average flow rate ( $Q_{\text{output}}$ ) of a single hole could be obtained by dividing the amount of water collected with the time taken. Then, the Q value (in  $\text{m}^3/\text{s}$ ) is converted into flow velocity (in m/s, and then further convert into mm/hr) for the determination of surface infiltration rate by using the flow equation  $Q=AV$ . This measurement is sufficient for the analysis and determination of the flow rate of entire system since the modular units behave a similar orifice flow (as clarified in Section 3.3). Simultaneously, physical observation is done to determine the infiltration capabilities of service inlets in removing the surface runoff. Based on the rainfall conditions that are specified in Table 3.1, the experiments are repeated three times for each rainfall intensity in order to get an average value of orifice flow. Then, the obtained results are analysed and compared with the CFD results for validation.

### 3.6.3 Flow Chart of Physical Modelling

Figure 3.19 summarizes the steps in the physical modelling.

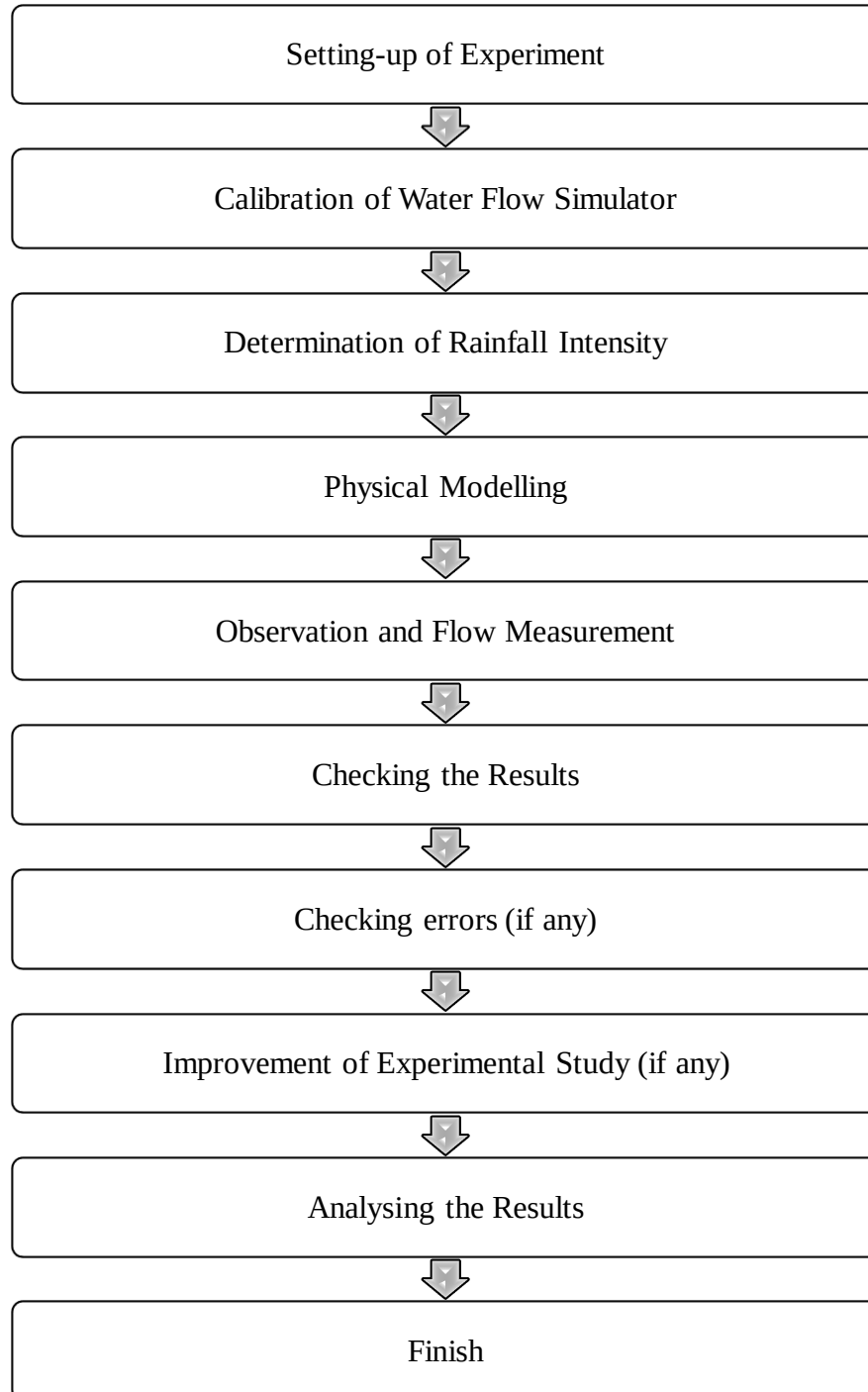


**Figure 3.24:** Summary of Laboratory Testing

## **CHAPTER 4**

### **RESULTS AND DISCUSSION**

#### **4.1 Introduction**

This chapter describes and discusses the investigations in this project and they are divided into four sub-sections. The first section describes how the meshing refinement is conducted to obtain an optimum mesh for a better result through the CFD technique. Then, the second one focuses on the performance of small-scale model in simulating the orifice flow of StormPav covers, with validation from the experimental data. Extending the simulation and findings, similar concept is applied in the third section to investigate the behaviour of StormPav system in a simplified road intersection model. By doing so, the surface infiltration and drainage capability of service inlets are defined for real application. With these reasonable data, multi-purpose road intersection is applicable to improve the road drainage system and roadway condition. Modelling scenarios that are considered in this project are listed as below:

- Modelling 1: Small-scale StormPav System (refer to Section 3.3); and
- Modelling 2: Simplified StormPav System in a Sectional Road Intersection (refer to Section 3.2).

#### **4.2 Mesh Refinement Study**

By adjusting the setting of “Level of Initial Mesh” in the robust mesher of the model (refer to Figure 3.13), different mesh sizes are generated from the model based on the mesh levels ranging from 1 to 4. Due to the complexity of solving a small structure like a service

inlet, a mesh refinement study is done before Modelling 1; and once the best mesh level is determined, the level is set to be constant for any simulation that follows.

The Solidworks Flow Simulation technology is based upon the use of immersed-body mesh, where such a mesh is defined as a set of cuboids (rectangular cells) that are adjacent to each other and to the external boundary of the computational domain, oriented along the Cartesian coordinates. In overall, increasing levels of mesh refinement consume more solving time to produce a better discretization of geometry model through refinement strategy, as tabulated in Table 4.1, Table 4.2 and Table 4.3. This is because a large amount of computer memory is required for multiple-iteration runs to obtain results with high accuracy. Therefore, finer meshes are generated only around the opening of orifice regions to maintain mesh quality of the model. Then, the results between these different meshes are compared to determine an acceptable level of accuracy.

Obviously, it can be observed that the trends of velocity versus orifice depth at different mesh levels are varied but its flow patterns are consistent at each level (see Figures 4.1 to 4.3). Particularly the plotting graphs of mesh level 3 and mesh level 4, a similar tendency of velocity profiles are obtained although their readings are slightly different. However, it is reasonable to deduce that the performance of the model is not much affected. More so in the tabulated data, the computed initial velocities passing through a 75mm depth of orifice are more or less 0.002 m/s, 0.004 m/s and 0.007 m/s at inflow rates of 0.01 l/s, 0.02 l/s and 0.03 l/s respectively. Commonly, mesh level 3 is chosen for normal practice; therefore choosing Mesh Level = 3 is sensible for CFD simulation of multiple orifices.

**Table 4.1:** Comparison of Simulation Results by Adjusting the Mesh Level  
when Surface Runoff = 0.01 l/s

| Level of Initial Mesh | Local Refinement |                | No. of Iterations | CPU Time (hour: min: sec) | Maximum Velocity (m/s) |
|-----------------------|------------------|----------------|-------------------|---------------------------|------------------------|
|                       | *Fluid Cells     | *Partial Cells |                   |                           |                        |
| 1                     | 1785             | 3799           | 70                | 0:00:22                   | 0.001709               |
| 2                     | 5997             | 6594           | 90                | 0:01:47                   | 0.002067               |
| 3                     | 18473            | 13239          | 102               | 0:02:27                   | 0.002527               |
| 4                     | 64870            | 27344          | 193               | 0:11:35                   | 0.002729               |

**Table 4.2:** Comparison of Simulation Results by Adjusting the Mesh Level  
when Surface Runoff = 0.02 l/s

| Level of Initial Mesh | Local Refinement |                | No. of Iterations | CPU Time (hour: min: sec) | Maximum Velocity (m/s) |
|-----------------------|------------------|----------------|-------------------|---------------------------|------------------------|
|                       | *Fluid Cells     | *Partial Cells |                   |                           |                        |
| 1                     | 1785             | 3799           | 71                | 0:00:28                   | 0.003132               |
| 2                     | 5997             | 6594           | 90                | 0:01:19                   | 0.003564               |
| 3                     | 18473            | 13239          | 114               | 0:02:43                   | 0.004414               |
| 4                     | 64870            | 27344          | 202               | 0:12:23                   | 0.004672               |

**Table 4.3:** Comparison of Simulation Results by Adjusting the Mesh Level  
when Surface Runoff = 0.03 l/s

| Level of Initial Mesh | Local Refinement |                | No. of Iterations | CPU Time (hour: min: sec) | Maximum Velocity (m/s) |
|-----------------------|------------------|----------------|-------------------|---------------------------|------------------------|
|                       | *Fluid Cells     | *Partial Cells |                   |                           |                        |
| 1                     | 1785             | 3799           | 83                | 0:00:28                   | 0.004820               |
| 2                     | 5997             | 6594           | 92                | 0:01:52                   | 0.005491               |
| 3                     | 18473            | 13239          | 118               | 0:02:47                   | 0.006778               |
| 4                     | 64870            | 27344          | 210               | 0:12:47                   | 0.007048               |

\*Fluid cells refers to the cells that are fully intersected with fluid bodies while the partial cells refer to the cells intersected the immersed boundaries (solid and fluid bodies).

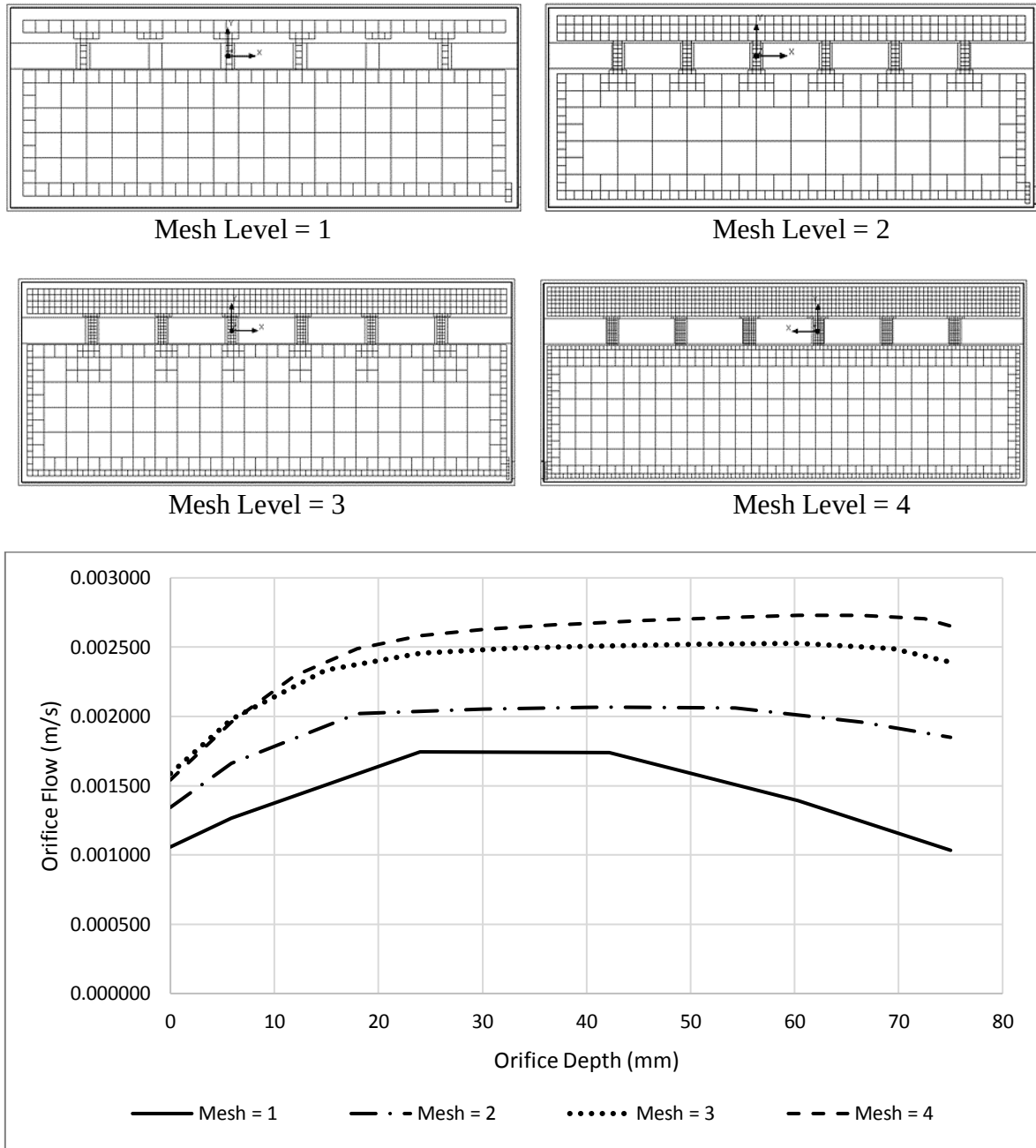


**Figure 4.1:** Mesh Plotting and its Resultant Velocity in Orifice when Surface Runoff = 0.01 l/s

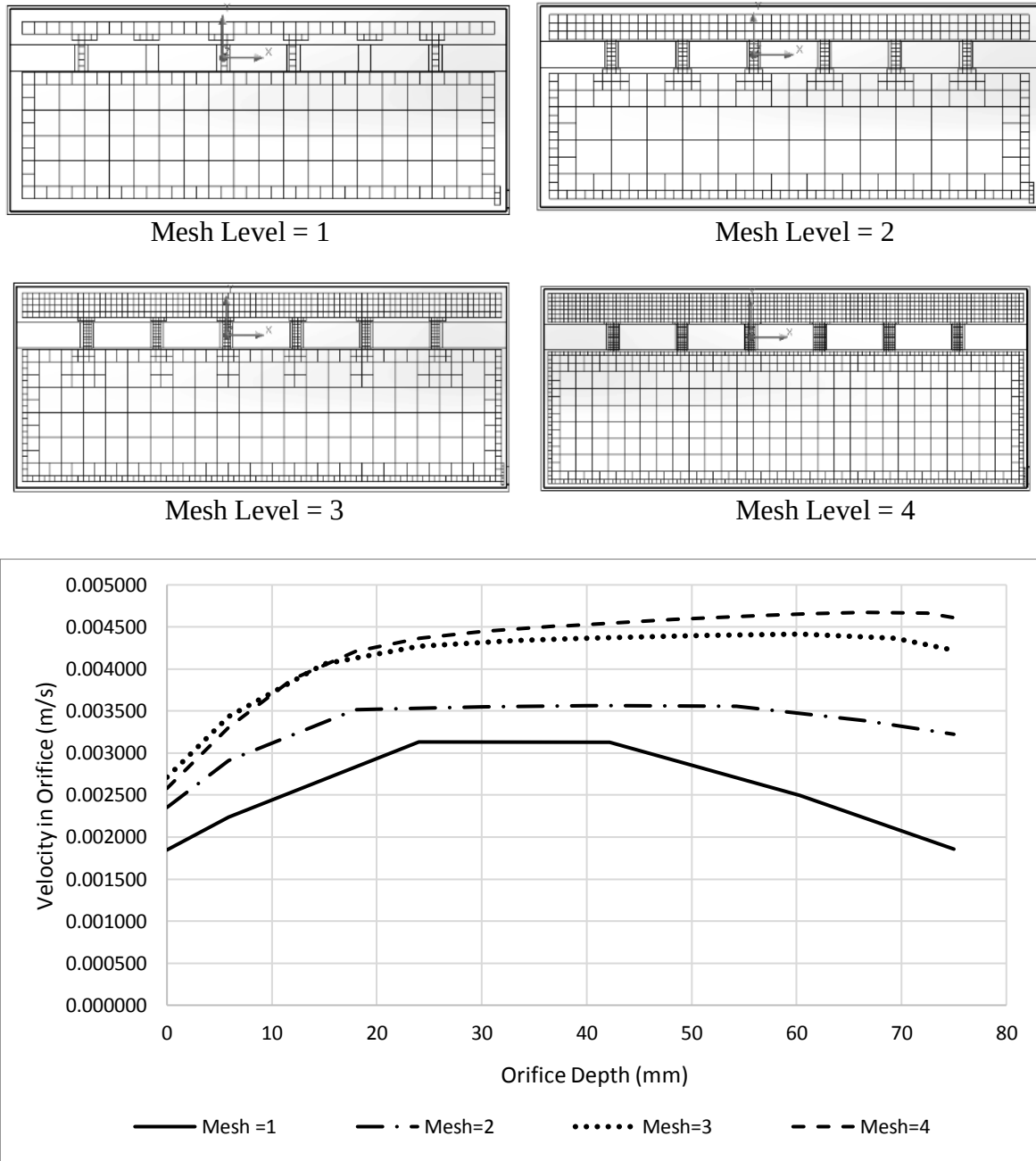


**Figure 4.2:** Mesh Plotting and its Resultant Velocity in Orifice when Surface Runoff = 0.02 l/s

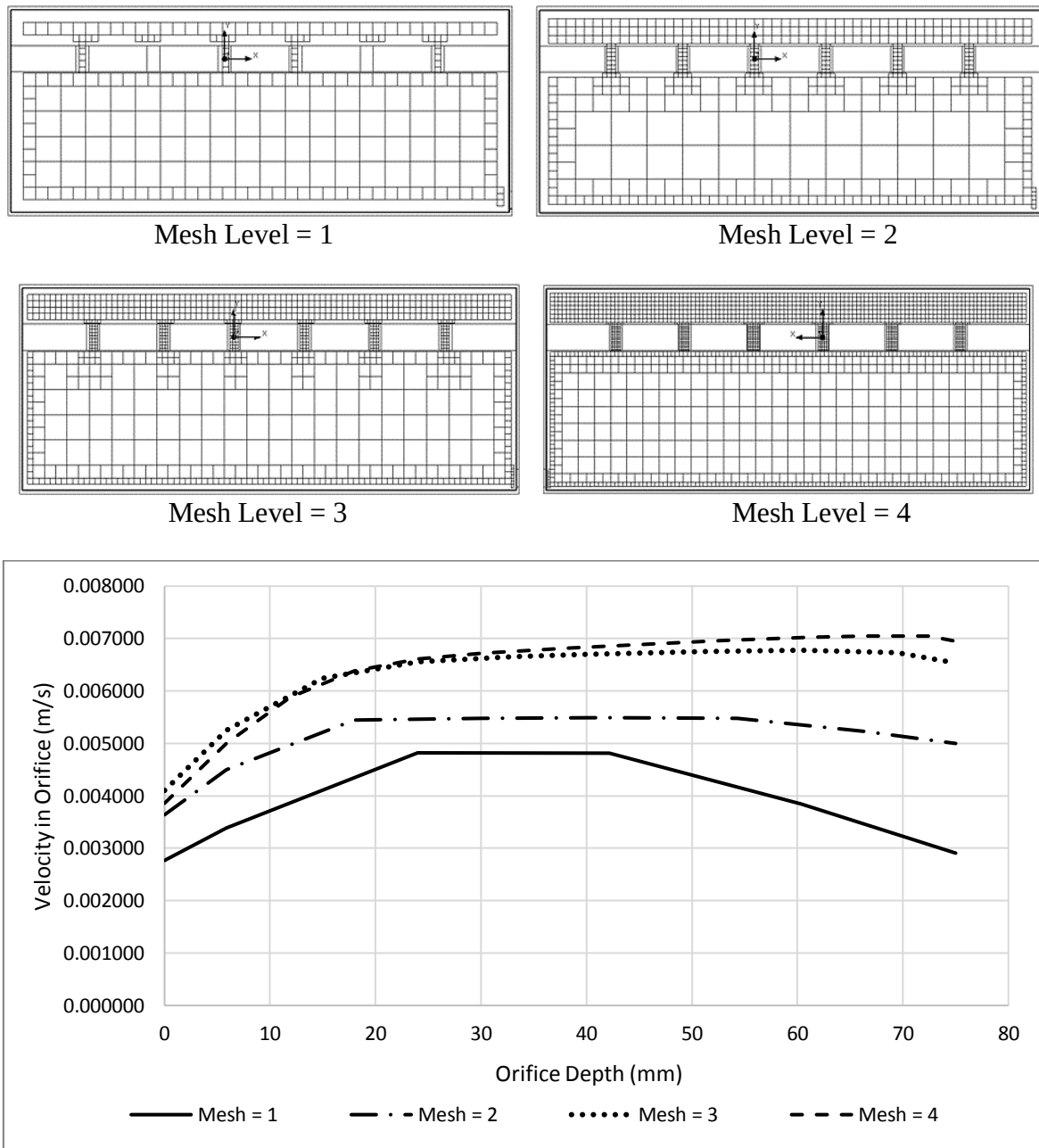


**Figure 4.3:** Mesh Plotting and its Resultant Velocity in Orifice when Surface Runoff = 0.03 l/s

### 4.3 Findings of Small-Scale Model

This section emphasises on the performance of small-scale StormPav system to infiltrate the storm runoff through its service inlets. During a typical rain event, the variations of peak runoff are predictable as the changing of rainfall intensities happened at different storm durations. Taking the 15-minute design storm as example, 0.01 l/s, 0.02 l/s and 0.03 l/s of peak runoffs are generated by the small-scale model for three different time blocks (see Table 3.1). With six (6) service inlets that are created in this model, its surface infiltration to remove the runoff from pavement surface is investigated through Modelling 1, with verification from laboratory works.

As illustrated in Figure 4.4, CFD results show that the storm runoff is running on the pavement surface with a minimum velocity of 0.0001 m/s. Due to the presence of orifices, stormwater is infiltrated into the service inlets by gravity action. As investigated in Figure 4.5, the stormwater is moving toward the orifices with an increasing velocity and then, infiltrated through the orifices at an initial velocity of 0.0007 m/s, 0.0012 m/s and 0.0015 m/s when the surface runoff are 0.01 l/s, 0.02 l/s and 0.03 l/s respectively. In other perspective, these orifices are acting as a flow regulator to infiltrate the storm runoff from top cover to underground chambers at a controlled rate. Moreover, the results also illustrated that the running water on StormPav covers is uniformly distributed through the orifices, as justified in Section 3.3.

As illustrated in Figures 4.6 and 4.7, average flow velocity in the service inlets are found to be consistent at 0.0021 m/s, 0.0038m/s and 0.0057 m/s when the surface runoff are 0.01 l/s, 0.02 l/s and 0.03 l/s respectively (refer to Figure 4.8 and Appendix E). The CFD simulation has no obvious changes of velocity between the orifices since similar modular units are assembled together to form a flat surface. Therefore, it is crucial to group the

StormPav units at a same platform level in order to have a uniform distribution of storm runoff to avoid water ponding on certain areas.

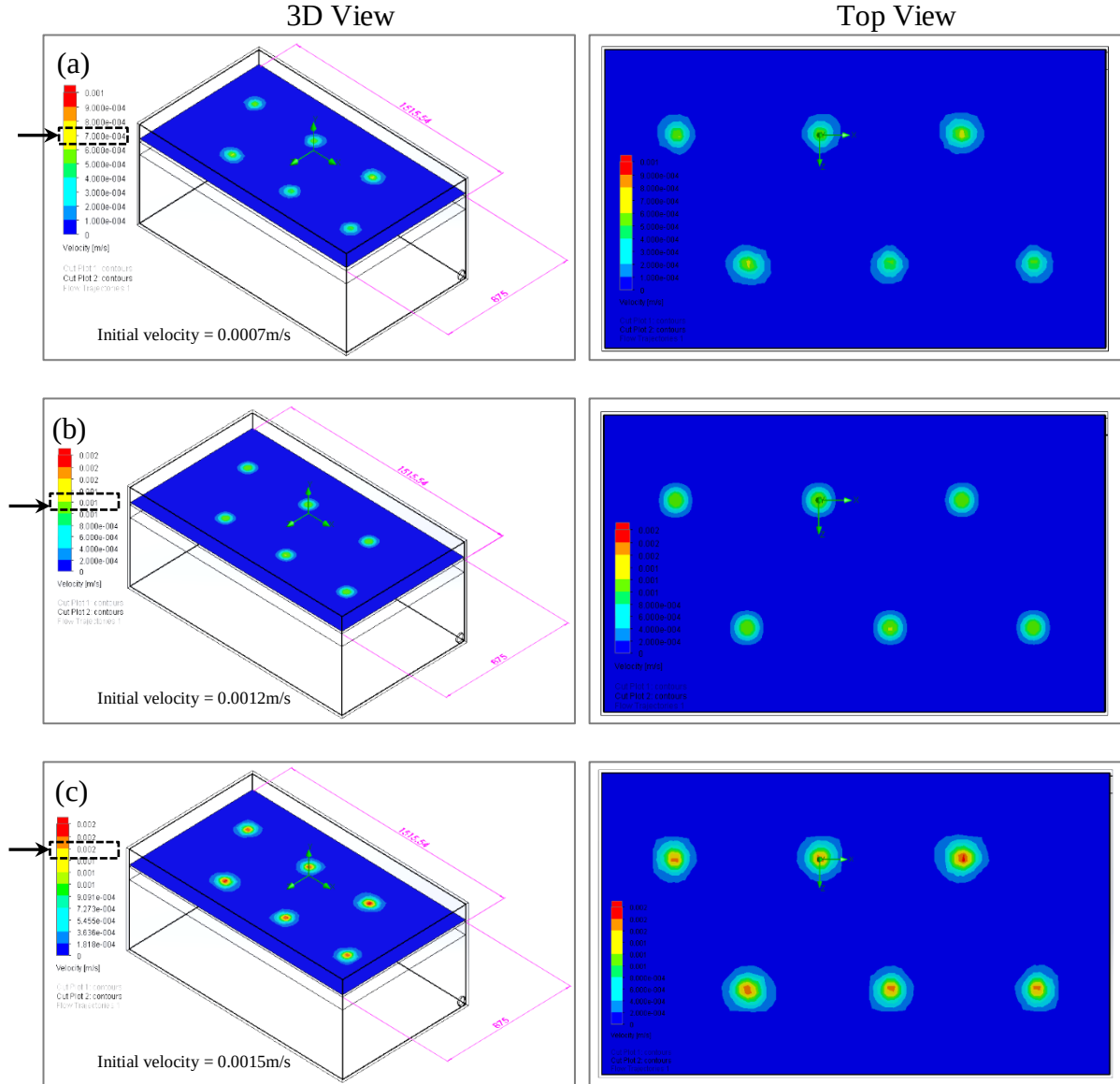


**Figure 4.4:** Velocity Profiles of Stormwater Flow at the Top Opening of Orifice Plate when Surface Runoffs are (a) 0.01 l/s, (b) 0.02 l/s and (c) 0.03 l/s

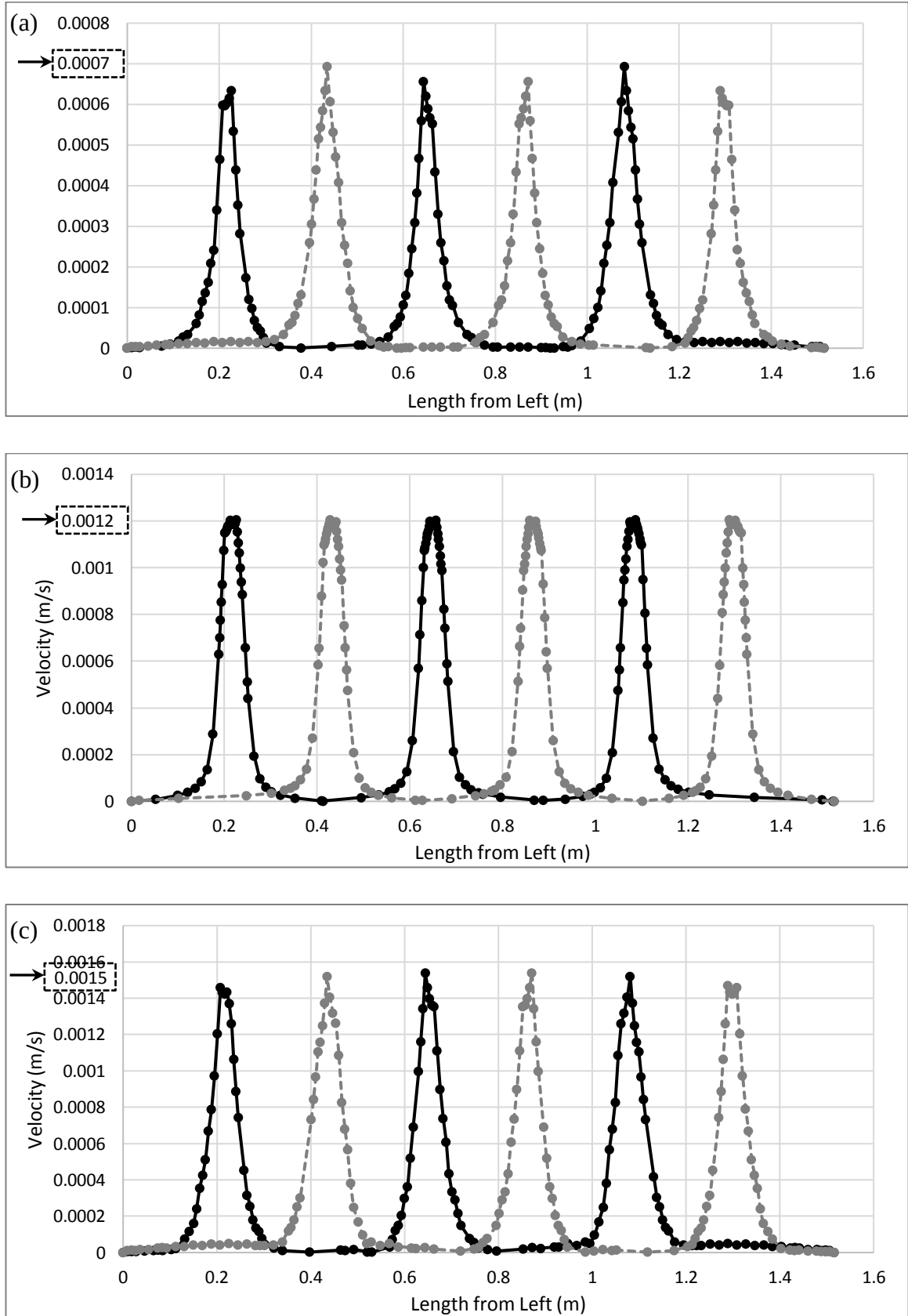


**Figure 4.5:** Initial Velocity at the Top Opening for Six Orifices when Surface Runoffs are (a) 0.01 l/s, (b) 0.02 l/s and (c) 0.03 l/s

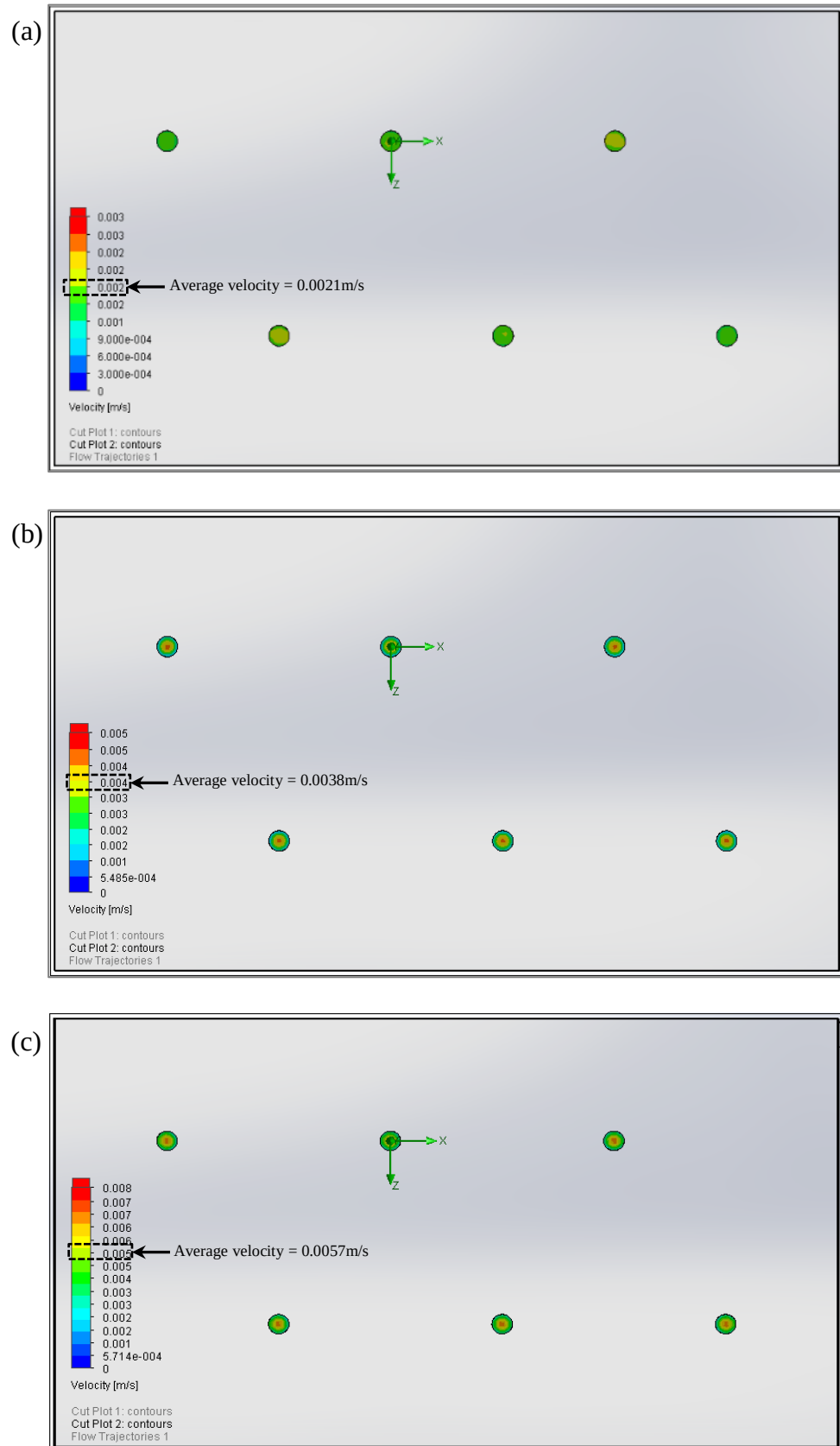


**Figure 4.6:** Top Cut Plots when Surface Runoffs are (a) 0.01 l/s, (b) 0.02 l/s and (c) 0.03 l/s

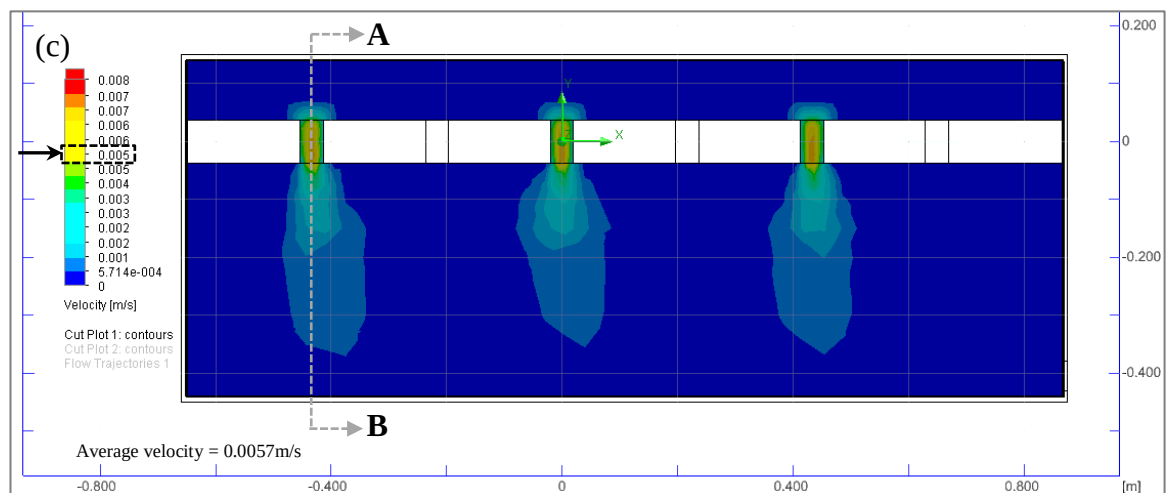
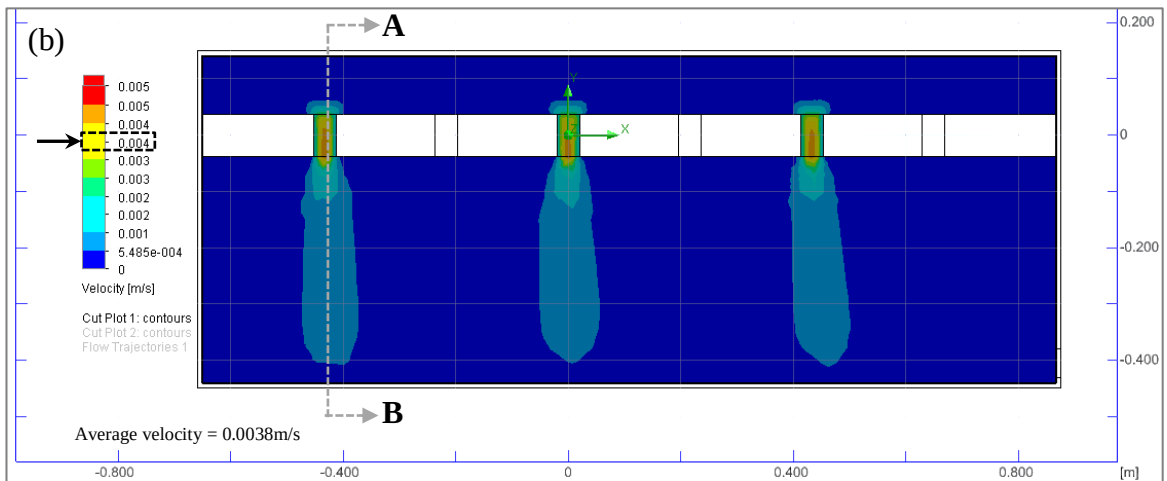
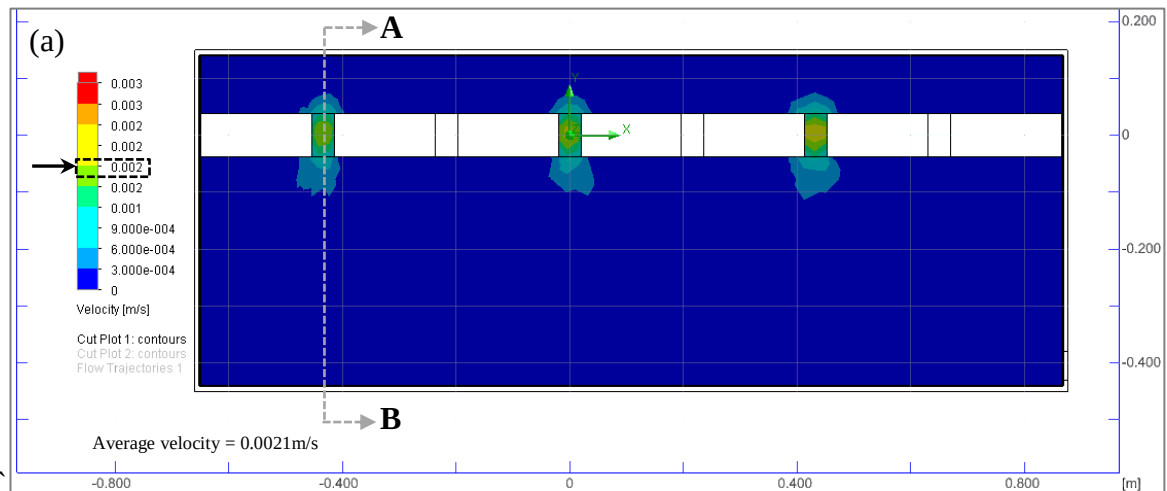


**Figure 4.7:** Cross-Sectional Cut Plots when Surface Runoffs are (a) 0.01 l/s, (b) 0.02 l/s and (c) 0.03 l/s

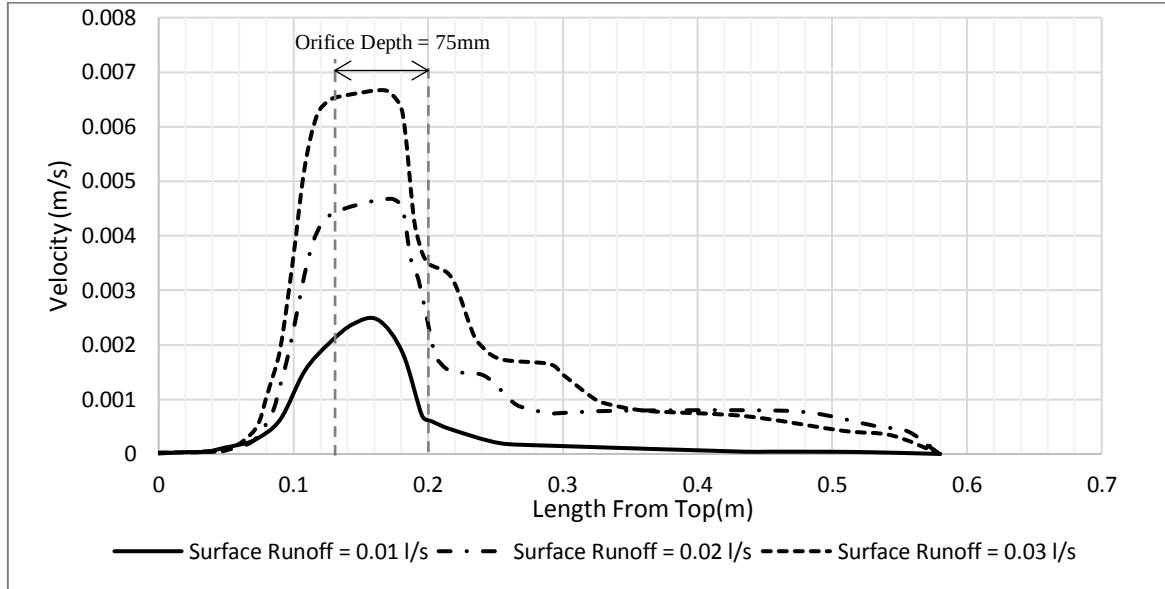


**Figure 4.8:** Flow Phenomenon for Section A-B in Small-Scale Model

Furthermore, both simulation and experimental data show that the orifice flow is highly dependent on rainfall intensity, as the more runoff generated, the more infiltration rate through the orifices. However, the values of simulation results are found to be larger than experimental data. For example, CFD results show that each service inlet has the highest surface infiltration rate of 20520 mm/hr (by converting the obtained velocity) at an inflow rate of 0.03  $\text{l/s}$ , while the average value of experimental results is 15% lesser than that. Similarly, the surface infiltration that obtained in the laboratory is 4% lower than CFD data for both inflow rates of 0.01  $\text{l/s}$  and 0.02  $\text{l/s}$  (refer to Tables 4.4 and Table 4.5).

**Table 4.4:** Summary of Small-Scale Model Results by CFD

| Storm Duration (min) | Rainfall Intensity (mm/hr) | Surface Runoff, $Q_{in}$ (l/s) | Velocity through Orifice (m/s) | Surface Infiltration (mm/hr) |
|----------------------|----------------------------|--------------------------------|--------------------------------|------------------------------|
| 5                    | 32.4                       | 0.01                           | 0.0021 $\pm 20\%$              | 7560 $\pm 20\%$              |
| 5                    | 57.6                       | 0.02                           | 0.0038 $\pm 20\%$              | 13822 $\pm 20\%$             |
| 5                    | 90.0                       | 0.03                           | 0.0057 $\pm 20\%$              | 20520 $\pm 20\%$             |

**Table 4.5:** Summary of Small-Scale Model Results by Laboratory Testing

| <b>Storm Duration (min)</b> | <b>Rainfall Intensity (mm/hr)</b> | <b>Surface Runoff (l/s)</b> | <b>Velocity through Orifice (m/s)</b> |          |          |                | <b>Surface Infiltration (mm/hr)</b> |
|-----------------------------|-----------------------------------|-----------------------------|---------------------------------------|----------|----------|----------------|-------------------------------------|
|                             |                                   |                             | <b>1</b>                              | <b>2</b> | <b>3</b> | <b>Average</b> |                                     |
| 5                           | 35.47                             | 0.0128                      | 0.0021                                | 0.0020   | 0.0023   | 0.0021         | 7560                                |
| 5                           | 57.07                             | 0.0206                      | 0.0037                                | 0.0038   | 0.0036   | 0.0037         | 13320                               |
| 5                           | 90.89                             | 0.0328                      | 0.0050                                | 0.0048   | 0.0053   | 0.0051         | 18360                               |

In this regard, CFD simulation analyses the model as a full flow system in which the orifices are full of stormwater. Bear in mind that the CFD is taking the StormPav system as a rectangular pipe flow. As illustrated in Figure 4.7, this phenomenon can be seen in the simulation results as there are three (3) water ponding scenarios to enable the running water to have a full flow in all orifices. However, water ponding is not observed in the laboratory testing as the stormwater infiltrates into the underground chambers through the edges of orifices. As demonstrated in Figure 4.9, rainfall simulator in the laboratory testing is using the dripping method. As volume of water on the pavement surface is more critical to represent the surface runoff than the drop sizes, this method is appropriate.

As such, the author identifies a limitation of the CFD simulation of flow through StormPav system. Surface infiltration by CFD are 15% higher compared to the laboratory testing. In fact, CFD has a constraint in simulating flow only at the edges of orifices. Having said so, it is common in flow modelling of environmental system that a correlation of 0.6 is acceptable when comparing the modelled and observed hydrographs (for example in the engineering manual of US Army Corps of Engineers), in which a difference of up to 40% is accepted due to complexity in the actual environmental processes. Based on the mentioned precedence, the difference of up to 15% demonstrated in the CFD could be taken as acceptable as well.

In term of safety factor, the overestimation of CFD is practical for real world application, where the unexpected conditions could be happened during undesirable weather. As an example, the occurrence of flash flood could cause the full flow through orifices. Therefore, the variation of simulation results and experimental data around  $\pm 20\%$  is acceptable and CFD modelling is appropriate to determine the performance of service inlets in the StormPav system.



**Figure 4.9:** Physical Observation in Laboratory Testing

#### **4.4 Findings of Simplified Road Intersection Model**

Based on the preceding investigation, a simplified model that acts as a part of the selected road intersection is simulated as Modelling 2. With an area of  $52.5 \text{ m}^2$  of StormPav system, about 311 orifices are involved in this simulation as a large number of modular units are needed to fill up the spaces. In order to reflect the actual system at study site, similar concept of Modelling 1 is applied here to determine the surface infiltration of multi-orifice road intersection to dispose the storm runoff from road surface. This part is important to

achieve the second objective of this study as the road catchment and number of orifices are much greater than the previous simulations.

As reported in Table 3.1, 0.47 l/s, 0.84 l/s and 1.31 l/s of surface runoff are first generated when subjected to the same design rain. Consistent with the previous section, CFD results show that the stormwater is uniformly distributed through the orifices and the changing of infiltration rate is much affected by the rainfall intensity. At the opening of each service inlet, the stormwater is infiltrated through the orifice at an initial velocity of 0.0004 m/s, 0.0007 m/s and 0.0009 m/s when the inflow rates are 0.47 l/s, 0.84 l/s and 1.31 l/s respectively (see Figures 4.10 and Figure 4.11). Within each orifice, the stormwater is infiltrated into and discharged from the orifice with an increasing and decreasing of velocities due to the changes of volume of water over time. Particularly at the mid span of each orifice, average velocity of the infiltrated stormwater is consistent at a reading of 0.0014 m/s, 0.0025 m/s and 0.0040 m/s when the surface runoffs are 0.47 l/s, 0.84 l/s and 1.31 l/s respectively. Besides that, full flow through orifices is observed in the simulation outcomes as a high water depth of 102.5 mm is retained on the pavement surface (see Figure 4.12 to Figure 4.14 and Appendix F).

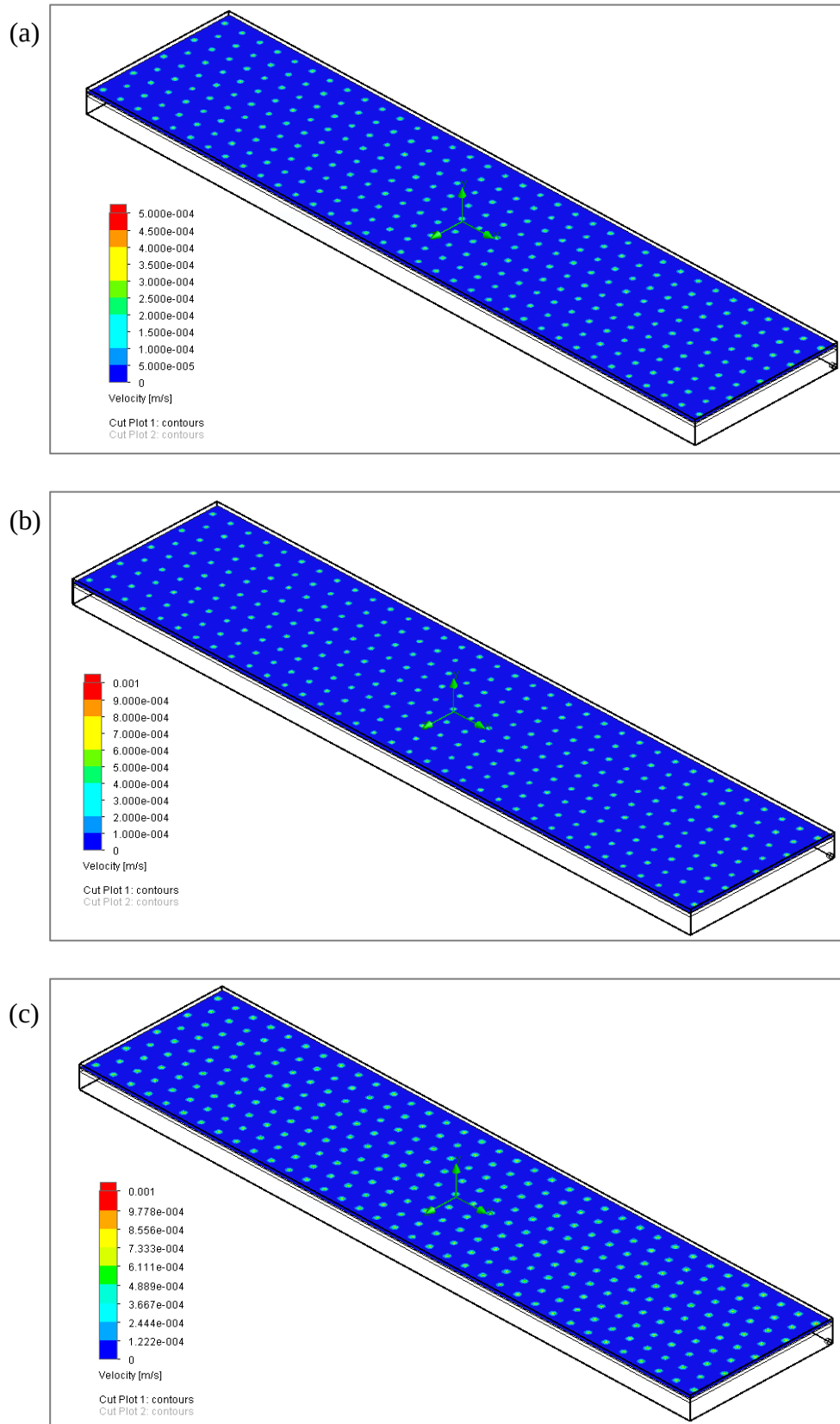


**Figure 4.10:** 3D View of Velocity Profiles when Surface Runoffs are (a) 0.47 l/s, (b) 0.84 l/s and (c) 1.31 l/s

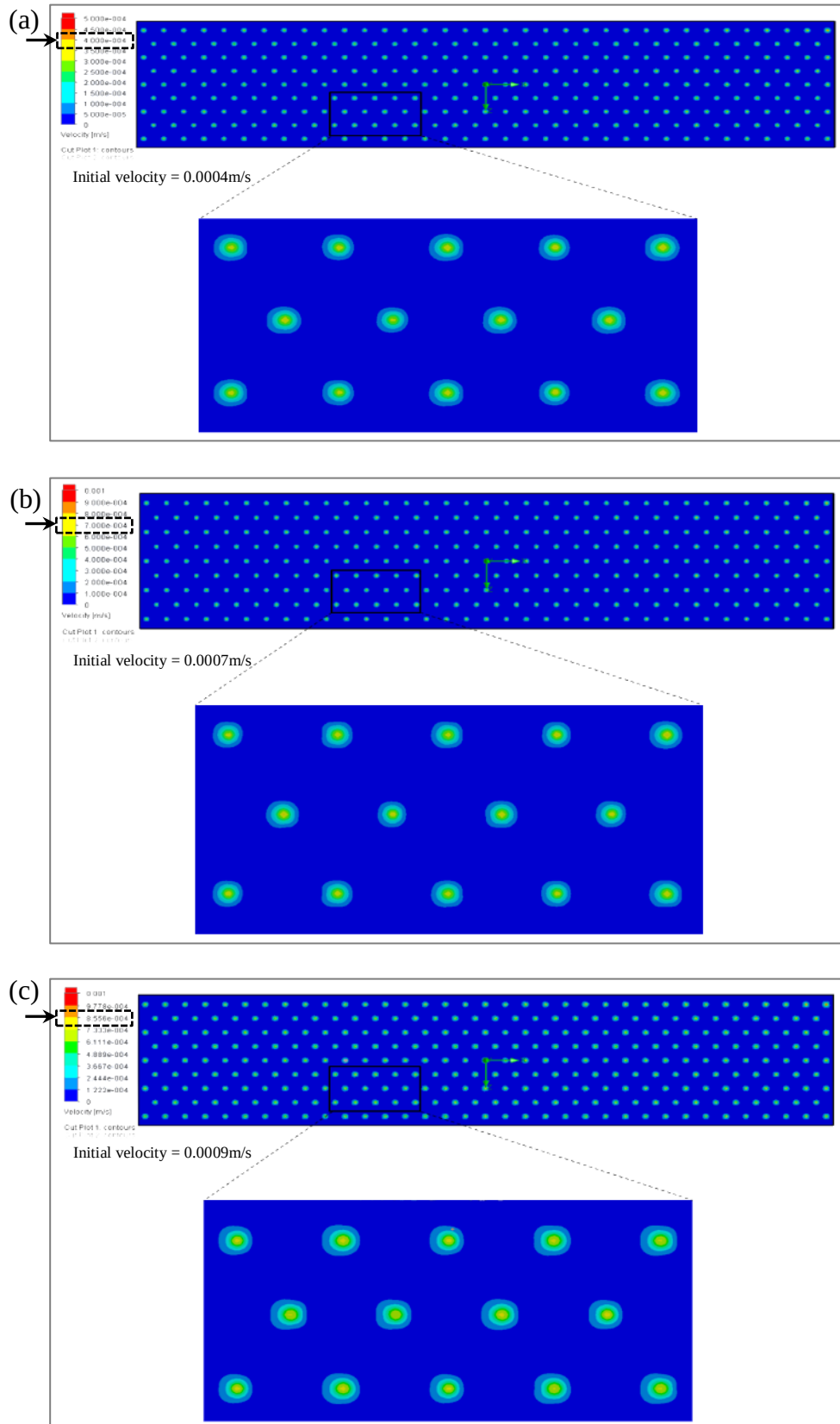


**Figure 4.11:** Top View of Velocity Profiles when Surface Runoffs are (a) 0.47 l/s, (b) 0.84 l/s and (c) 1.31 l/s

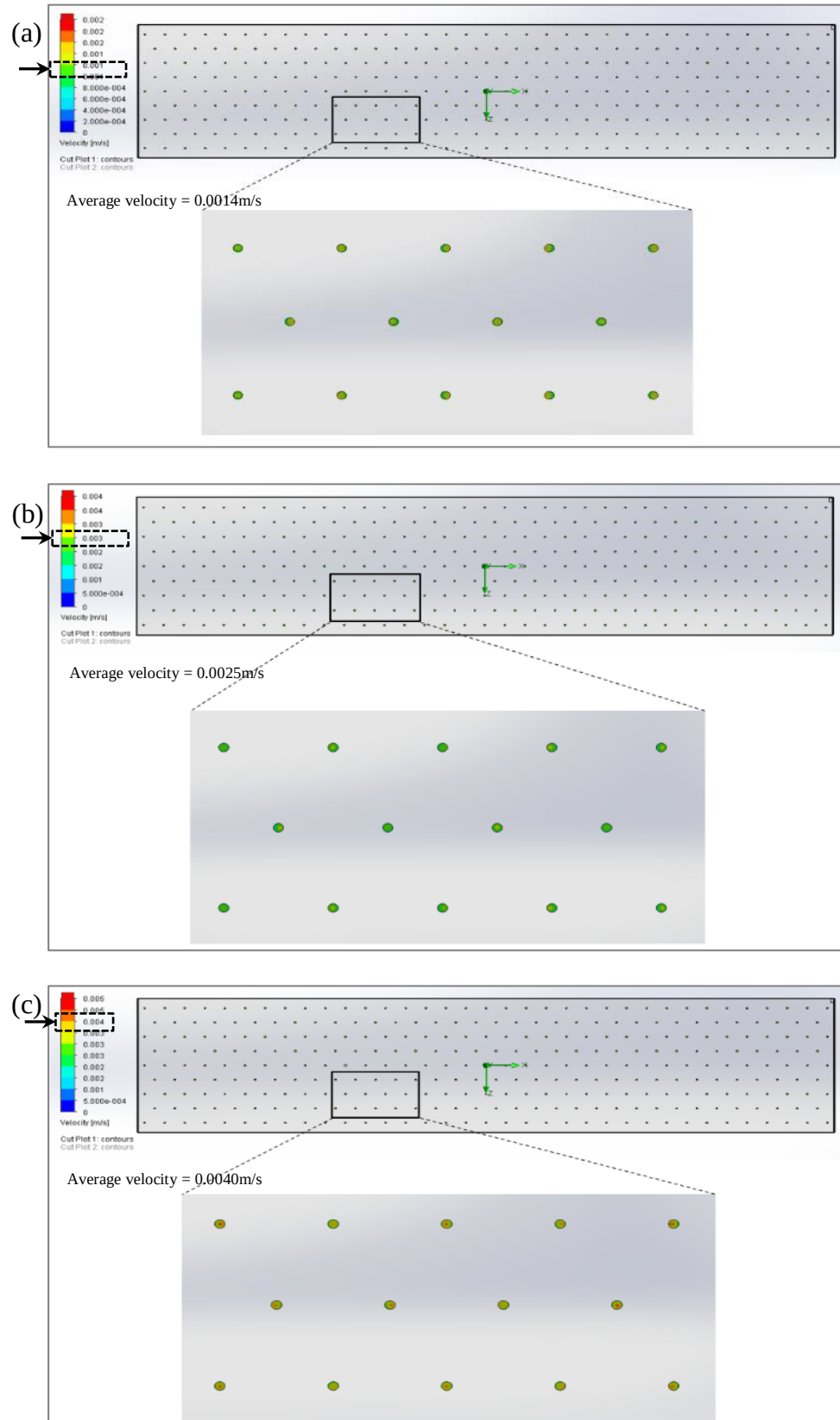


**Figure 4.12:** Top Cut Plots when Surface Runoffs are (a) 0.47 l/s, (b) 0.84 l/s and (c) 1.31 l/s

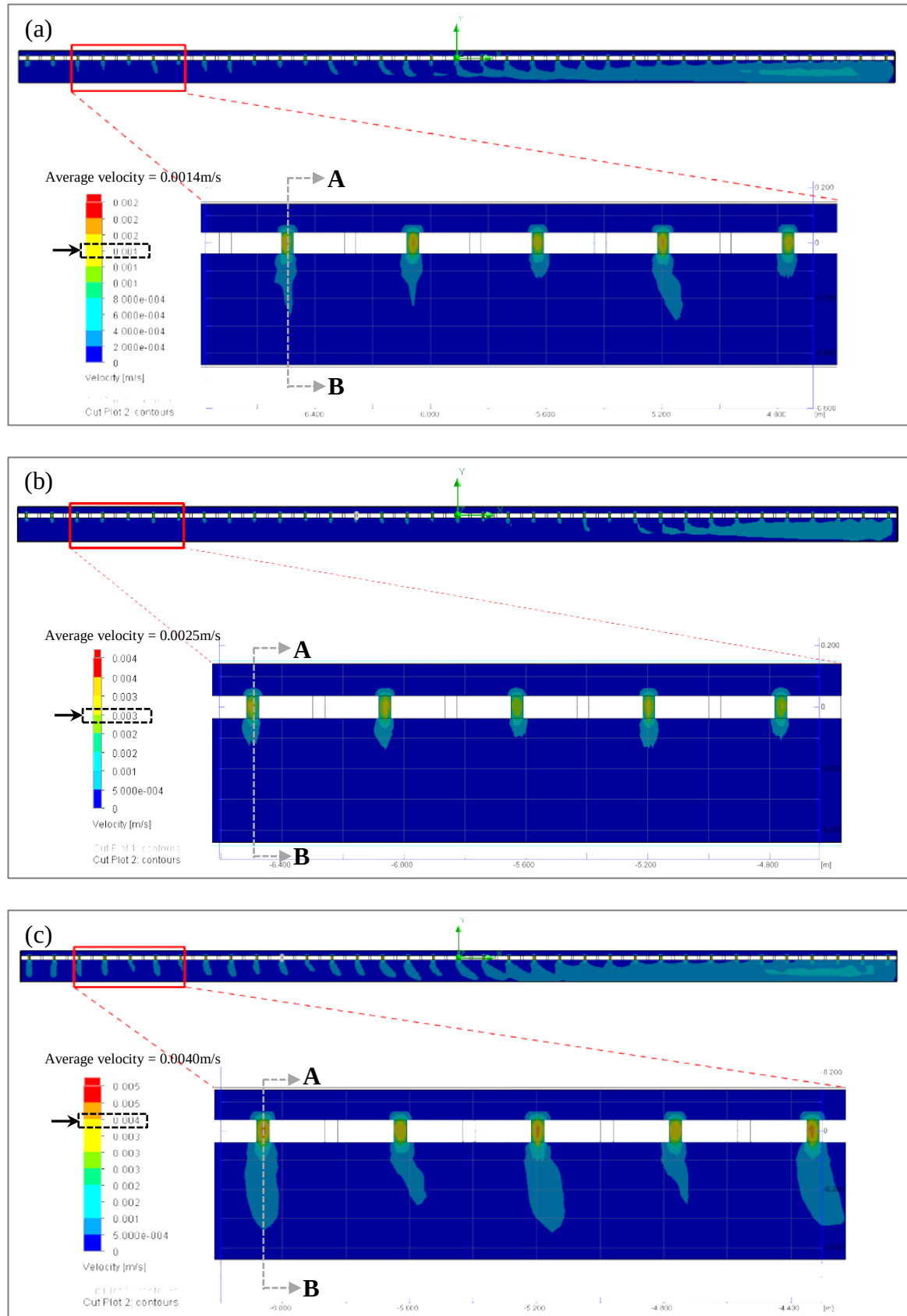


**Figure 4.13:** Cross-sectional Plots when Surface Runoffs are (a) 0.47 l/s, (b) 0.84 l/s and (c) 1.31 l/s

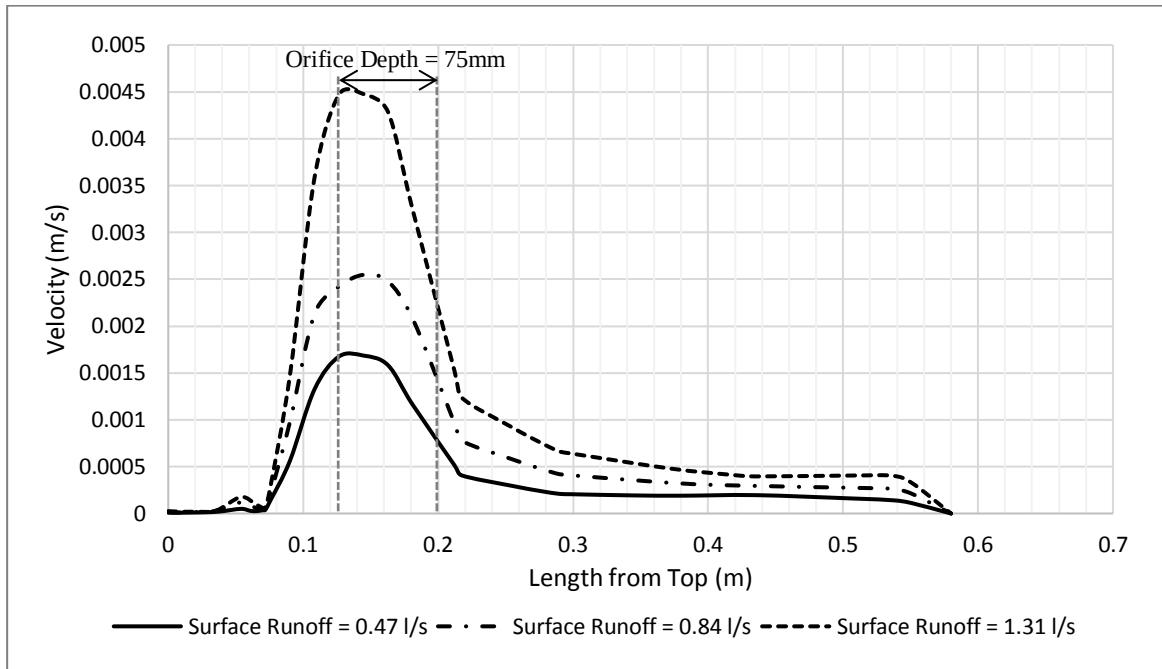


**Figure 4.14:** Flow Phenomenon for Section A-B in the Simplified Road Intersection Model

As tabulated in Table 4.6, 15840 mm/hr of surface infiltration is the outcome when subjected to the worst surface runoff (1.3 l/s) in predicting the surface infiltration of StormPav system in the section of road junction under study. This is done as a test against weather variability, since weather nowadays is rather unpredictable. In order to cater for climate change, the service inlets of this model should be able to infiltrate the stormwater effectively during a heavy downpour. Based on the present investigation, the service inlets of StormPav system have a higher ability to cope with unexpected rainfall as it has a good draining capability to infiltrate a larger amount of surface runoff.

**Table 4.6:** Summary of Simplified Road Intersection Model Results by CFD

| <b>Storm<br/>Duration<br/>(min)</b> | <b>Rainfall<br/>Intensity<br/>(mm/hr)</b> | <b>Surface<br/>Runoff<br/>(l/s)</b> | <b>Velocity<br/>through Orifice<br/>(m/s)</b> | <b>Surface<br/>Infiltration<br/>(mm/hr)</b> |
|-------------------------------------|-------------------------------------------|-------------------------------------|-----------------------------------------------|---------------------------------------------|
| 5                                   | 32.4                                      | 0.47                                | 0.0017 $\pm 20\%$                             | 6120 $\pm 20\%$                             |
| 5                                   | 57.6                                      | 0.84                                | 0.0025 $\pm 20\%$                             | 9000 $\pm 20\%$                             |
| 5                                   | 90.0                                      | 1.31                                | 0.0044 $\pm 20\%$                             | 15840 $\pm 20\%$                            |

#### 4.5 Application in Full-Scale System

This section summarizes the CFD results that are obtained from two modelling scenarios and describes how they can be related to the full-scale application. Referring to Figure 4.15, each model is presented in such a manner to illustrate their differences in model scale. Industrial orifice plates are normally manufactured following the size of pipeline and are governed by Equation 2.2. However, small-scale and simplified intersection models demonstrate a trait peculiar to industrial orifice plates. As the number of orifice increases, the size of its surface area also increases, in which this could never happen in the pipeline industry to accommodate increasing pipeline sizes. In another word, the StormPav system presents a case of unprecedented use of orifice plate that no longer supported by the mentioned equation. Direct application of modelling results of the two scenarios are not feasible here.

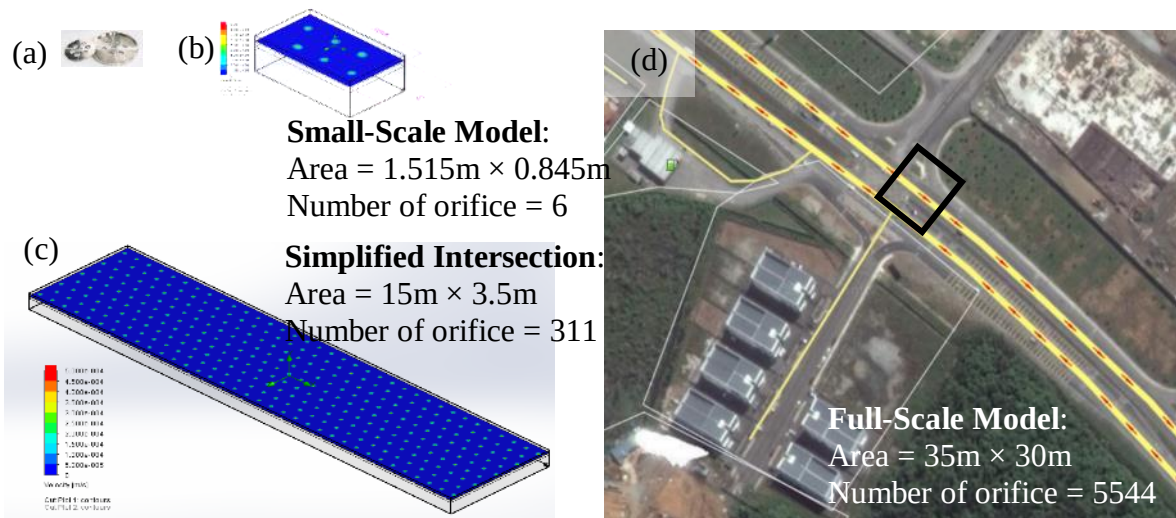


**Figure 4.15:** Comparison of (a) Industrial-Scale Orifice Plate, (b) Small-Scale, (c) Simplified Intersection, and (d) Full-Scale Models

To analyse the modelling results, the author has resorted to use the fundamental of pipeline flow (following the CFD), in which flow rate in a full pipeline is equalled to the velocity over its cross-sectional area, namely  $Q = VA$ . From now on, it is taken as general flow rate equation from this point onwards. This formula implies that the  $Q$  before the orifice plate and the  $Q$  after the orifice plate are constant. In the case of StormPav system, the surface area  $A$  is found to be increasing; therefore,  $V$  shall be decreasing to maintain the continuity of  $Q$ . As reported in Table 4.7, the velocity of the stormwater passing through a single orifice is decreasing when the surface runoff is subjected to a larger catchment area.

The author further analyses a single orifice. Volumetric flow of a single orifice could be calculated using the same formula  $Q_{\text{orifice}} = A_{\text{orifice}} \times V_{\text{orifice}}$ . Adding up the flows from all the orifices, the total volumetric flow of the entire system is found to increase with the number of orifice. It means the larger the pavement area ( $L^2$ ), the faster the flow ( $L^3/T$ ) passing through, the slower the velocity ( $L/T$ ); thus, the slower the surface infiltration that is measured as mm/hr ( $L/T$ ) by converting the m/s ( $L/T$ ).

**Table 4.7:** Comparison of Flows in StormPav System

| Model                                                                                                                                                                                                                                      | Rainfall Intensity (mm/hr) | Surface Runoff <sup>1</sup> (m <sup>3</sup> /s) | Single Orifice <sup>2</sup> |                                  | Total Volumetric Flow <sup>3</sup> (m <sup>3</sup> /s) | Difference (%) |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------|-------------------------------------------------|-----------------------------|----------------------------------|--------------------------------------------------------|----------------|
|                                                                                                                                                                                                                                            |                            |                                                 | Average Velocity (m/s)      | Average Flow (m <sup>3</sup> /s) |                                                        |                |
| Modelling 1 (6 orifices)                                                                                                                                                                                                                   | 32.4                       | $1.20 \times 10^{-5}$                           | 0.0021                      | $2.64 \times 10^{-6}$            | $1.58 \times 10^{-5}$                                  | 24.05          |
|                                                                                                                                                                                                                                            | 57.6                       | $2.13 \times 10^{-5}$                           | 0.0038                      | $4.78 \times 10^{-6}$            | $2.87 \times 10^{-5}$                                  | 25.78          |
|                                                                                                                                                                                                                                            | 90.0                       | $3.33 \times 10^{-5}$                           | 0.0057                      | $6.46 \times 10^{-6}$            | $3.87 \times 10^{-5}$                                  | 13.95          |
| Modelling 2 (311 orifices)                                                                                                                                                                                                                 | 32.4                       | $4.73 \times 10^{-4}$                           | 0.0014                      | $1.76 \times 10^{-6}$            | $5.47 \times 10^{-4}$                                  | 13.53          |
|                                                                                                                                                                                                                                            | 57.6                       | $8.40 \times 10^{-4}$                           | 0.0025                      | $3.14 \times 10^{-6}$            | $9.77 \times 10^{-4}$                                  | 14.02          |
|                                                                                                                                                                                                                                            | 90.0                       | $1.31 \times 10^{-3}$                           | 0.0040                      | $5.03 \times 10^{-6}$            | $1.56 \times 10^{-3}$                                  | 16.03          |
| Note:<br><sup>1</sup> Surface runoff is computed based on Rational Method ( $Q = CIA/360$ )<br><sup>2</sup> Velocity and flow through a single orifice are computed by CFD<br><sup>3</sup> Volumetric flows are computed based on $Q = VA$ |                            |                                                 |                             |                                  |                                                        |                |

There are significant differences between the theoretical flow rates (surface runoffs that are inputted into the model) and calculated volumetric flow rates in the StormPav system, as high as 26% (refer to Table 4.7). As illustrated in Figures 4.7 and 4.13, a general observation can be seen in the contour plots where the stormwater forms a jet when it infiltrates through the service inlets by gravity. Note that CFD is a detailed simulation, in which a range of velocity values are computed and highlighted in the mentioned two figures. On the other hand, the general flow rate equation relies on an average velocity times the cross-sectional area of an orifice ( $A = \pi d^2/4$ ) (see the calculation steps in Appendix G). In this regard, the calculated volumetric flow rates are understandably larger with  $\pm 30\%$ . The author reinstates that StormPav system is an unprecedented case; and in the absence of other similar cases for comparison, the author finds this analyses method is at best at the moment.

Subsequently, surface infiltration of the StormPav system in full scale is explored extending the concept of general flow rate equation. Total volumetric flow rates for 6 orifices and 311 orifices subjected to three rainfall intensities are plotted. As demonstrated in Figure 4.16, with a larger surface area of the road catchment, total volumetric flow rate of the entire

system increases with the number of service inlets, with an allowance of  $\pm 30\%$ . Then, the graphs in Figure 4.16 are extrapolated to determine the surface infiltration rate of service inlet in the full-scale road intersection (see the calculation steps in Appendix H). As tabulated in Table 4.8, the full-scale StormPav system is able to infiltrate 5732 mm/hr, 8600 mm/hr and 14329 mm/hr of stormwater when the intersection is subjected to 32.4 mm/hr, 57.6 mm/hr and 90.0 mm/hr of rainfall intensities respectively.

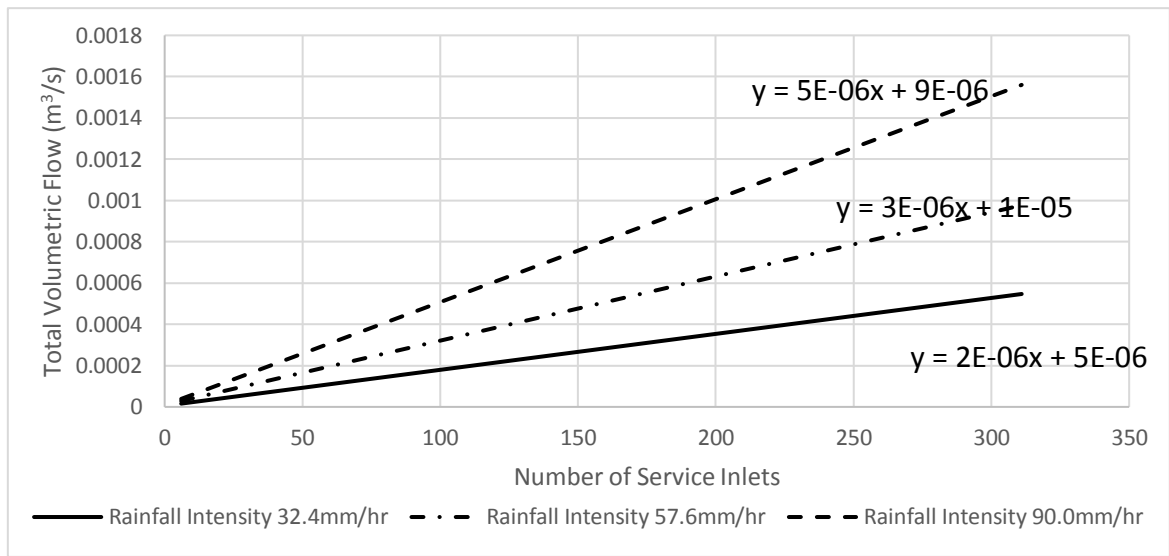


**Figure 4.16:** Graph of Total Volumetric Flow versus Number of Orifice

**Table 4.8:** Extrapolation of Surface Infiltration in StormPav System

| Storm Duration (minutes) | Rainfall Intensity (mm/hr) | Surface Infiltration of Single Orifice (mm/hr) |                                              |                                     |
|--------------------------|----------------------------|------------------------------------------------|----------------------------------------------|-------------------------------------|
|                          |                            | Small-Scale Model (6 Orifices)                 | Simplified Intersection Model (311 Orifices) | Actual Intersection (5544 Orifices) |
| 5                        | 32.4                       | 7560                                           | 5040                                         | 5732 $\pm 30\%$                     |
| 5                        | 57.6                       | 13822                                          | 9000                                         | 8600 $\pm 30\%$                     |
| 5                        | 90.0                       | 20520                                          | 14400                                        | 14329 $\pm 30\%$                    |

## CHAPTER 5

### CONCLUSIONS AND RECOMMENDATION

#### 5.1 Conclusions

This project has demonstrated that StormPav system offers a solution to improve the existing road drainage system. In order to have a good collaboration of road intersection with underground OSD, attempts were made to provide a large number of orifices on the road pavement to infiltrate surface runoff. Through this, a multi-purpose road intersection is envisioned in urban roads to enhance the traffic movement, especially under the wet and humid climate. As embarked by this study, major findings are noted below:

- a) Service inlet on each StormPav cover is successfully tested with both small-scale model ( $0.875\text{ m} \times 1.515\text{ m}$ ) and simplified road intersection model ( $3.5\text{ m} \times 15\text{ m}$ ) by using CFD tool. Extending from the two models, a full-scale road intersection with StormPav system is deduced to have characteristics of:
  - i. Surface infiltration rate changes with the volume of stormwater being infiltrated that reasonably matched between CFD simulation and laboratory testing;
  - ii. For 5-minute of 32.4 mm/hr rainfall intensity, its infiltration rate is found at 5732 mm/hr;
  - iii. For 5-minute of 57.6 mm/hr rainfall intensity, its infiltration rate is found at 8600 mm/hr; and
  - iv. For 5-minute of 90.0 mm/hr rainfall intensity, its infiltration rate is found at 14329 mm/hr.
- b) Through the laboratory testing and CFD analysis, the drainage capability of service inlets is evaluated, in which:

- i. Surface runoff is infiltrated through the edges of service inlets in the real StormPav system which is an unprecedented case;
- ii. Total volumetric flow of StormPav system increases with the number of service inlets for quick surface infiltration of storm runoff; and
- iii. Velocity of surface infiltration reduces as the surface area increases.
- iv. Both CFD and laboratory modelling efforts have deduced that the StormPav green pavement system has superior quality in surface infiltration and an estimation of 14,000 – 24,000 mm/hr has been derived to conquer the formation of water ponding and flash floods on roads.

## **5.2 Recommendation**

Regarding to the improvement of this research, as an unprecedented case, different scales of laboratory testing should be carried out to collect the flow mechanism data. A modified or improved Equation 2.2 could be computed specific to multiple orifice plate of StormPav system.

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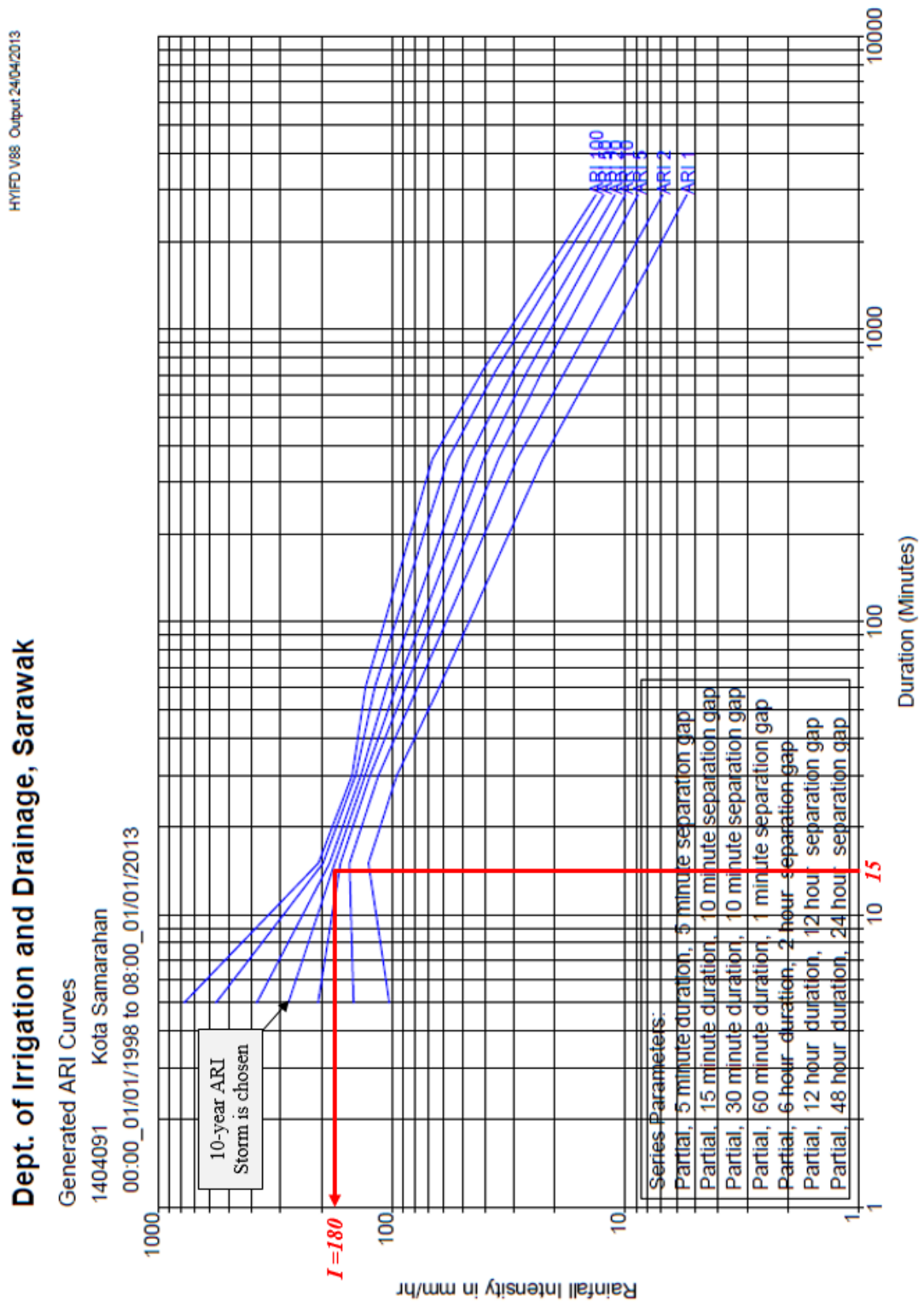
## APPENDICES

### Appendix A: Determination of StormPav Units in the Study Site

For the laboratory setup which involves a physical model size of  $1.326 \text{ m}^2$ , a total of 7 full units of StormPav are required to be fitted into a  $1.50 \text{ m} \times 1.00 \text{ m} \times 0.24 \text{ m}$  water tank. Then, it is compared with a real system to estimate the number of modular units that might require at the proposed study area.

|                                        |                                                                                                                                                                                                                                                                                                                                                                                  |
|----------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>Laboratory Setup</b>                | <p>Model size = <math>1.515 \text{ m} \times 0.875 \text{ m} = 1.326 \text{ m}^2</math></p> <p>Required StormPav units = 6 full units and 2 half units<br/>(In overall, it can be said as 7 full units)</p>                                                                                                                                                                      |
| <b>Riveria Signalised Intersection</b> | <p>Site area = <math>30 \text{ m} \times 35 \text{ m} = 1050 \text{ m}^2</math></p> <p>Ratio = <math>\frac{\text{Site Area}}{\text{Model size in laboratory}} = \frac{1050 \text{ m}^2}{1.326 \text{ m}^2} \approx 792</math></p> <p>Number of StormPav required = Ratio <math>\times</math> 7 units<br/> <math>= 792 \times 7</math><br/> <math>= 5544 \text{ units}</math></p> |

## Appendix B: Intensity-Duration-Frequency Curve for Kota Samarahan



### Appendix C: Computation for Surface Runoff

From Appendix B, the design rainfall of 15-minute 10-year ARI is obtained to be 180mm/hr. Then, a method for design temporal pattern (extracted from MSMA 1 Chapter 13) is adopted in flow calculation. By taking 15-minute storm for example, it can be divided into three number of time periods (refer to Appendix C-1). Based on this method, the rainfall intensity of:

Time Period 1/ 5 minutes:  $180 \text{ mm/ hr} \times 0.32 = 57.6 \text{ mm/ hr}$

Time Period 2/ 10 minutes:  $180 \text{ mm/ hr} \times 0.50 = 90.0 \text{ mm/ hr}$

Time Period 3/ 15 minutes:  $180 \text{ mm/ hr} \times 0.18 = 32.4 \text{ mm/ hr}$

After that, Rational Method is qualified to be used for determining the surface runoff since the road catchment involved in this project is less than 80 hectare. The equation of Rational Method is expressed as the following:

$$Q = \frac{CIA_c}{360}$$

where

$Q$  = Peak Runoff ( $\text{m}^3/\text{s}$ );

$C$  = Runoff coefficient (considered as 1.0 for impervious surface);

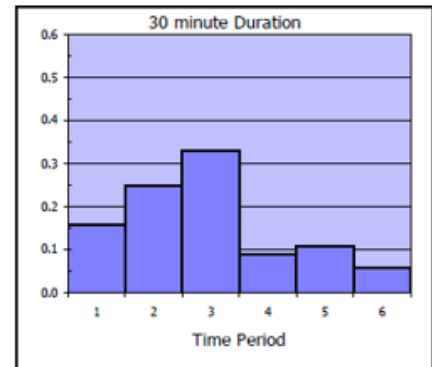
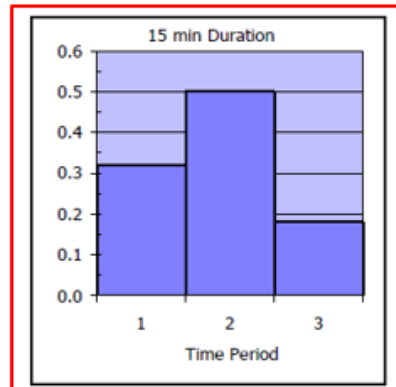
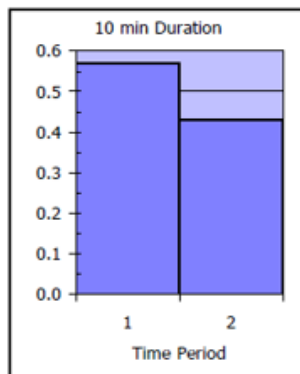
$I$  = Rainfall Intensity ( $\text{mm/ hr}$ ); and

$A_c$  = Catchment area (ha).

| Road Catchment                                           |            | Storm Duration, t (min) | C   | I (mm/ hr) | Q ( $\text{m}^3/\text{s}$ ) |
|----------------------------------------------------------|------------|-------------------------|-----|------------|-----------------------------|
| Length $\times$ Width                                    | $A_c$ (ha) |                         |     |            |                             |
| Small-Scale Model<br>(0.875 m $\times$ 1.515 m)          | 0.00013    | 5                       | 1.0 | 57.6       | $2.13 \times 10^{-5}$       |
|                                                          |            | 5                       | 1.0 | 90.0       | $3.33 \times 10^{-5}$       |
|                                                          |            | 5                       | 1.0 | 32.4       | $1.20 \times 10^{-5}$       |
| Simplified Intersection Model<br>(3.5 m $\times$ 15.0 m) | 0.00525    | 5                       | 1.0 | 57.6       | $8.40 \times 10^{-4}$       |
|                                                          |            | 5                       | 1.0 | 90.0       | $1.31 \times 10^{-3}$       |
|                                                          |            | 5                       | 1.0 | 32.4       | $4.73 \times 10^{-4}$       |

### Appendix C-1: Temporal Patterns – East Coast of Peninsular Malaysia (DID, 2002)

| Duration (min) | No. of Time Periods | Fraction of Rainfall in Each Time Period |       |       |       |       |       |       |       |       |       |       |       |   |
|----------------|---------------------|------------------------------------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|---|
| 10             | 2                   | 0.570                                    | 0.430 | -     | -     | -     | -     | -     | -     | -     | -     | -     | -     | - |
| 15             | 3                   | 0.320                                    | 0.500 | 0.180 | -     | -     | -     | -     | -     | -     | -     | -     | -     | - |
| 30             | 6                   | 0.160                                    | 0.250 | 0.330 | 0.090 | 0.110 | 0.060 | -     | -     | -     | -     | -     | -     | - |
| 60             | 12                  | 0.039                                    | 0.070 | 0.168 | 0.120 | 0.232 | 0.101 | 0.089 | 0.057 | 0.048 | 0.031 | 0.028 | 0.017 | - |
| 120            | 8                   | 0.030                                    | 0.119 | 0.310 | 0.208 | 0.090 | 0.119 | 0.094 | 0.030 | -     | -     | -     | -     | - |
| 180            | 6                   | 0.190                                    | 0.230 | 0.190 | 0.160 | 0.130 | 0.100 | -     | -     | -     | -     | -     | -     | - |
| 360            | 6                   | 0.290                                    | 0.200 | 0.160 | 0.120 | 0.140 | 0.090 | -     | -     | -     | -     | -     | -     | - |



### Appendix D: Calibration of Rainfall Simulator

To test the rainfall simulator, 5 l of water is poured into the simulator tank, and then the time taken for the water to drain through the perforated plate is determined and recorded for the determination of various rainfall intensities, as shown in the followings.

| Number of Openings | Time Taken (s) |      |      |         | Flow Rate |                     | Rainfall Intensity (mm/hr) |
|--------------------|----------------|------|------|---------|-----------|---------------------|----------------------------|
|                    | 1              | 2    | 3    | Average | (l/s)     | (m <sup>3</sup> /s) |                            |
| 1                  | 4684           | 4649 | 4688 | 4673.67 | 0.001070  | 1.07E-06            | 2.96                       |
| 2                  | 2828           | 2899 | 2844 | 2857.00 | 0.001750  | 1.75E-06            | 4.85                       |
| 3                  | 1941           | 1925 | 1903 | 1923.00 | 0.002600  | 2.60E-06            | 7.20                       |
| 4                  | 1606           | 1578 | 1578 | 1587.33 | 0.003150  | 3.15E-06            | 8.58                       |
| 5                  | 1256           | 1228 | 1257 | 1247.00 | 0.004010  | 4.01E-06            | 11.10                      |
| 6                  | 919            | 935  | 929  | 927.67  | 0.005390  | 5.39E-06            | 14.93                      |
| 7                  | 697            | 738  | 734  | 723.00  | 0.006916  | 6.92E-06            | 19.15                      |
| 8                  | 646            | 659  | 695  | 666.67  | 0.007500  | 7.50E-06            | 20.77                      |
| 9                  | 565            | 541  | 528  | 544.67  | 0.009180  | 9.18E-06            | 25.42                      |
| 10                 | 488            | 466  | 495  | 483.00  | 0.010352  | 1.04E-05            | 28.66                      |
| 12                 | 391            | 381  | 399  | 390.33  | 0.012810  | 1.28E-05            | 35.47                      |
| 14                 | 351            | 332  | 370  | 351.00  | 0.014245  | 1.42E-05            | 29.43                      |
| 16                 | 314            | 329  | 306  | 316.33  | 0.015806  | 1.58E-05            | 43.75                      |
| 18                 | 268            | 288  | 219  | 258.33  | 0.019355  | 1.94E-05            | 53.58                      |
| 20                 | 244            | 213  | 271  | 242.67  | 0.020604  | 2.06E-05            | 57.07                      |
| 22                 | 207            | 231  | 211  | 216.33  | 0.023112  | 2.31E-05            | 63.97                      |
| 24                 | 174            | 195  | 213  | 194.00  | 0.025773  | 2.58E-05            | 71.42                      |
| 26                 | 191            | 174  | 169  | 178.00  | 0.028090  | 2.81E-05            | 77.84                      |
| 28                 | 164            | 161  | 178  | 167.67  | 0.029821  | 2.98E-05            | 82.52                      |
| 30                 | 131            | 155  | 171  | 152.33  | 0.032823  | 3.28E-05            | 90.89                      |

#### Calculation:

As an example, when all of holes of water flow simulator are opened, average time taken for 5 l of water to drain through the perforated plate is 152.33 s.

$$\text{Flow Rate, } Q = \frac{\text{Volume of Water (l)}}{\text{Time Taken (s)}} = \frac{5.0}{152.33} = 0.03282 \text{ l/s}$$

$$\text{Rainfall Intensity, } I = \frac{Q \text{ (m}^3\text{/s)} \times 360}{\text{Area of Catchment (ha)}} = \frac{(3.28 \times 10^{-5}) \times 360}{0.00013} = 90.89 \text{ mm/hr}$$

### Appendix E: Simulation Results for Small-Scale Model

CFD simulation results with an inflow of 0.01 l/s, 0.02 l/s and 0.03 l/s of surface runoffs at different mesh levels are tabulated in the following:

| Mesh Level | Surface Runoff (l/s) |                |                    |                |                    |                |
|------------|----------------------|----------------|--------------------|----------------|--------------------|----------------|
|            | Q = 0.01             |                | Q = 0.02           |                | Q = 0.03           |                |
|            | Orifice Depth (mm)   | Velocity (m/s) | Orifice Depth (mm) | Velocity (m/s) | Orifice Depth (mm) | Velocity (m/s) |
| 1          | 0.00                 | 0.000997       | 0.00               | 0.001847       | 0.00               | 0.002768       |
|            | 5.86                 | 0.001210       | 5.86               | 0.002236       | 5.86               | 0.003390       |
|            | 24.01                | 0.001709       | 24.01              | 0.003132       | 24.01              | 0.004820       |
|            | 42.17                | 0.001708       | 42.17              | 0.003129       | 42.17              | 0.004817       |
|            | 60.33                | 0.001368       | 60.33              | 0.002494       | 60.33              | 0.003849       |
|            | 75.00                | 0.001012       | 75.00              | 0.001855       | 75.00              | 0.002906       |
| 2          | 0.00                 | 0.001344       | 0.00               | 0.002353       | 0.00               | 0.003639       |
|            | 5.86                 | 0.001661       | 5.86               | 0.002913       | 5.86               | 0.004499       |
|            | 17.97                | 0.002019       | 17.97              | 0.003516       | 17.97              | 0.005441       |
|            | 30.08                | 0.002053       | 30.08              | 0.003548       | 30.08              | 0.005481       |
|            | 39.84                | 0.002064       | 39.84              | 0.003561       | 39.84              | 0.005489       |
|            | 42.18                | 0.002067       | 42.18              | 0.003564       | 42.18              | 0.005491       |
|            | 54.29                | 0.002062       | 54.29              | 0.003557       | 54.29              | 0.005477       |
|            | 66.40                | 0.001957       | 66.40              | 0.003385       | 66.40              | 0.005230       |
|            | 75.00                | 0.001848       | 75.00              | 0.003220       | 75.00              | 0.005002       |
| 3          | 0.00                 | 0.001587       | 0.00               | 0.002712       | 0.00               | 0.004102       |
|            | 5.87                 | 0.001980       | 5.87               | 0.003434       | 5.87               | 0.005249       |
|            | 14.95                | 0.002334       | 14.95              | 0.004059       | 14.95              | 0.006240       |
|            | 24.03                | 0.002456       | 24.03              | 0.004268       | 24.03              | 0.006557       |
|            | 33.11                | 0.002492       | 33.11              | 0.004337       | 33.11              | 0.006658       |
|            | 39.85                | 0.002503       | 39.85              | 0.004362       | 39.85              | 0.006693       |
|            | 51.27                | 0.002521       | 51.27              | 0.004400       | 51.27              | 0.006749       |
|            | 60.35                | 0.002527       | 60.35              | 0.004414       | 60.35              | 0.006778       |
|            | 69.43                | 0.002488       | 69.43              | 0.004367       | 69.43              | 0.006726       |
|            | 75.00                | 0.002391       | 75.00              | 0.004225       | 75.00              | 0.006539       |
|            | 75.00                | 0.002653       | 75.00              | 0.004609       |                    |                |

| Mesh Level | Surface Runoff ( $\ell/s$ ) |                |                    |                |                    |                |
|------------|-----------------------------|----------------|--------------------|----------------|--------------------|----------------|
|            | Q = 0.01                    |                | Q = 0.02           |                | Q = 0.03           |                |
|            | Orifice Depth (mm)          | Velocity (m/s) | Orifice Depth (mm) | Velocity (m/s) | Orifice Depth (mm) | Velocity (m/s) |
| 4          | 0.00                        | 0.001542       | 0.00               | 0.002580       | 0.00               | 0.003859       |
|            | 5.87                        | 0.001959       | 5.87               | 0.003306       | 5.87               | 0.005001       |
|            | 11.93                       | 0.002292       | 11.93              | 0.003873       | 11.93              | 0.005877       |
|            | 17.98                       | 0.002488       | 17.98              | 0.004205       | 17.98              | 0.006379       |
|            | 24.04                       | 0.002582       | 24.04              | 0.004366       | 24.04              | 0.006613       |
|            | 30.09                       | 0.002628       | 30.09              | 0.004447       | 30.09              | 0.006725       |
|            | 37.50                       | 0.002662       | 37.50              | 0.004512       | 38.28              | 0.006821       |
|            | 38.28                       | 0.002665       | 38.28              | 0.004518       | 52.57              | 0.006958       |
|            | 45.66                       | 0.002692       | 48.25              | 0.004587       | 61.22              | 0.007024       |
|            | 55.17                       | 0.002718       | 56.90              | 0.004637       | 66.41              | 0.007048       |
|            | 60.36                       | 0.002728       | 61.22              | 0.004657       | 72.47              | 0.007044       |
|            | 66.41                       | 0.002729       | 66.41              | 0.004672       | 75.00              | 0.006953       |
|            | 72.47                       | 0.002704       | 72.47              | 0.004664       |                    |                |
|            | 75.00                       | 0.002653       | 75.00              | 0.004609       |                    |                |

### Appendix F: Simulation Results for Simplified Road Intersection Model

The surface infiltration rates of the service inlet of simplified road intersection model are computed below:

| Surface Runoff<br>(l/s) | Orifice Depth<br>(mm) | Velocity<br>(m/s) | Surface Infiltration<br>(mm/hr) |
|-------------------------|-----------------------|-------------------|---------------------------------|
| Q = 0.47                | 0.00                  | 0.001072          | 3859.89                         |
|                         | 2.93                  | 0.001195          | 4302.61                         |
|                         | 5.86                  | 0.001316          | 4739.38                         |
|                         | 24.01                 | 0.001659          | 5973.73                         |
|                         | 39.84                 | 0.001668          | 6003.40                         |
|                         | 42.17                 | 0.001669          | 6008.12                         |
|                         | 60.33                 | 0.001568          | 5646.53                         |
|                         | 75.00                 | 0.001235          | 4446.81                         |
| Q = 0.84                | 0.00                  | 0.001608          | 5789.40                         |
|                         | 5.86                  | 0.001969          | 7088.25                         |
|                         | 24.01                 | 0.002541          | 9146.74                         |
|                         | 42.17                 | 0.002547          | 9170.67                         |
|                         | 60.33                 | 0.002309          | 8313.33                         |
|                         | 75.00                 | 0.001811          | 6520.93                         |
| Q = 1.31                | 0.00                  | 0.002755          | 9917.87                         |
|                         | 3.26                  | 0.003132          | 11274.40                        |
|                         | 6.52                  | 0.003478          | 12520.03                        |
|                         | 20.14                 | 0.004141          | 14907.13                        |
|                         | 24.68                 | 0.004364          | 15711.65                        |
|                         | 33.45                 | 0.004368          | 15726.19                        |
|                         | 40.33                 | 0.004369          | 15729.57                        |
|                         | 42.83                 | 0.004373          | 15741.98                        |
|                         | 47.37                 | 0.004311          | 15518.08                        |
|                         | 56.45                 | 0.004213          | 15166.47                        |
|                         | 60.99                 | 0.004151          | 14944.14                        |
|                         | 65.88                 | 0.003886          | 13988.88                        |
|                         | 75.00                 | 0.003330          | 11988.27                        |

## Appendix G: Determination of Total Volumetric Flow Rate

Calculation steps in determining the total volumetric flow rate of StormPav system in Table 4.7 can be referred as below.

### Calculation:

For Modelling 1 (small-scale model with 6 service inlets),  $1.20 \times 10^{-5} \text{ m}^3/\text{s}$  of surface runoff is generated when the rainfall intensity is 32.4 mm/hr. Then, the velocity through an orifice that is found to be 0.0021m/s (CFD results).

Flow rate of a single orifice,  $Q = AV$

$$\begin{aligned} &= \frac{\pi \times 0.04^2}{4} \times 0.0021 \\ &= 2.64 \times 10^{-6} \text{ m}^3/\text{s} \end{aligned}$$

Total Volumetric Flow Rate,  $Q_{\text{total}} = Q_1 + Q_2 + Q_3 + \dots + Q_{n-1} + Q_n$

$$\begin{aligned} &= A_1 V_1 + A_2 V_2 + A_3 V_3 + \dots + A_{n-1} V_{n-1} + A_n V_n \\ &= \sum_{n=1}^6 AV \\ &= n (AV) \\ &= 6 (2.64 \times 10^{-6}) \\ &= 1.58 \times 10^{-5} \text{ m}^3/\text{s} \end{aligned}$$

Differences between  $Q_{\text{total}}$  and the Inputted Q in the model (Surface Runoff)

$$\begin{aligned} &= \frac{1.58 \times 10^{-5} - 1.20 \times 10^{-5}}{1.58 \times 10^{-5}} \times 100\% \\ &= 24.05\% \end{aligned}$$

$\therefore$  Then, the same calculation step is repeated for other scenarios.

## Appendix H: Surface Infiltration of Full-Scale System

Calculation steps in determining the surface infiltration of service inlets in the full-scale system (study site) as shown in Table 4.8 can be referred in the following:

### Calculation:

For rainfall intensity of 90.0 mm/hr, the equation of the graph in Figure 4.16 is:

$$y = (5 \times 10^{-6}) x + (9 \times 10^{-6})$$

Then, substitute the total number of service inlets  $x = 5544$  into the equation:

$$\begin{aligned} Q_{\text{total}} &= (5 \times 10^{-6}) (5544) + (9 \times 10^{-6}) \\ &= 0.02773 \text{ m}^3/\text{s} \end{aligned}$$

$$Q_{\text{total}} = n (AV)$$

$$0.02744 = 5544 \times \left[ \frac{\pi \times 0.04^2}{4} \right] \times V$$

$$V = 0.00398 \text{ m/s or } 14329 \text{ mm/hr}$$

∴ Therefore, the surface infiltration of each service inlet is 14329 mm/hr when the real system is subjected to 90.0 mm/hr of rainfall intensity. Then, the same calculation step is repeated for another two rainfall intensities.