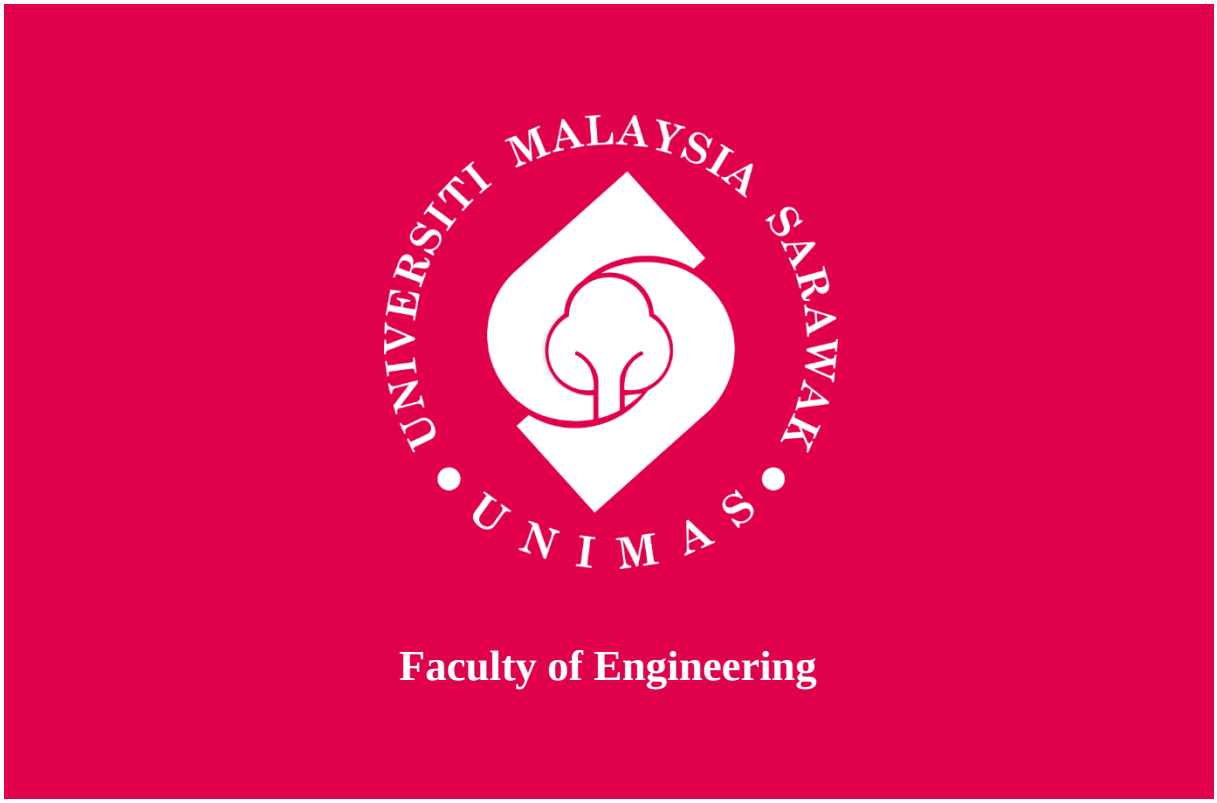

Efficient Hydraulic Flushing Gate System for Managing Sedimentation in Open Drain

Leong Geok Teng

Master of Engineering
2019

Efficient Hydraulic Flushing Gate System for Managing Sedimentation in Open Drain

Leong Geok Teng

A thesis submitted

In fulfillment of the requirements for the degree of Master of Engineering

(Civil Engineering)

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Dedicated to my family and friends.

DECLARATION

I declare that the work in thesis was carried out in accordance with the regulations of Universiti Malaysia Sarawak. Except where due acknowledgements have been made, the work is that of the author done alone. The thesis has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

Signature

Name: Leong Geok Teng

Matrix No.: 17020137

Faculty of Engineering

Universiti Malaysia Sarawak

Date: 20/8/2019

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ABSTRACT

The efficiency of hydraulic flushing gate system for managing sedimentation in open drain was evaluated in this study. The aims of this study include the investigation on the factors that influence sediment removal efficiency, identify the potential failure mode, effect and root cause in using hydraulic flushing, applying FMEA with FIS_RPN model and obtain FRPN on mechanical failure of hydraulic flushing gate system, and to establish a general guideline and management plan for active sedimentation control in open drain. Some experimental works were conducted and proven that number of flush, duration of flushing and sediment bed length are the important parameter in affecting sediment flushing efficiency. Besides that, field investigation shows that environment factor contribute to the failure mode of flush gate during on-site operation. FMEA results show that the size of hinge has the highest FRPN value of 269.4 which is the most critical component affecting the flush gate design. In addition, the gate holder has the highest FRPN value of 266.1 which mean to pay extra attention in the flush gate installation process. Overall, the risk associated with the current design to the flushing operation was considered moderate. In short, the experimental data provides a clear direction in designing the dimensions of flush gate and the selection of site in planning stage. The proposed techniques for the failure analysis will help to understand the failure behavior of the components during construction, installation and operation stage. A general design guideline and management were presented to provide better understanding and precaution on the use of flush gate system for open drain.

Keywords: Flushing gate, flushing efficiency, risk assessment, sedimentation, uncertainty

Kecekapan Sistem Pintu Simbah Hidraulik Bagi Pengurusan Pemendapan Di Saliran Terbuka

ABSTRAK

Kecekapan sistem pintu simbah hidraulik bagi pengurusan pemendapan di saliran terbukan telah dinilaikan dalam kajian ini. Tujuan kajian ini termasuk penyiasatan menegenai faktor-faktor yang mengpengaruhi kecekapan peningkiran isipadu mendapan, penilaian potensi mod kegagalan dan risiko yang berkaitan dengan reka bentuk pintu simbah, menggunakan FMEA *dengan model* FIS_RPN *untuk menentukan* FRPN *bagi penilaian risiko pemendekan hidraulik serta mewujudkan satu garis panduan dan pelan pengurusan bagi penggunaan pintu simbah dalam saliran terbuka. Hasil eksperimen telah membuktikan bahawa bilangan operasi simbahan, jangka masa operasi simbahan dan kepanjangan mendapan mempunyai kesan ke atas yang lehih ke atas prestasi simbahan. Kajian lapangan menunjukkan bahawa faktor persekitaran menyumbang kepada mod kegagalan pintu simbah mendapan semasa operasi. Di samping itu, keputusan* FMEA *menunjukkan bahawa engsel pintu merupakan komponen yang paling kritikal kerana ia memiliki nilai* FRPN *tertinggi iaitu sebanyak 269.4. Selain itu, pemegang pintu (*FRPN = *266.1) harus diberi perhatian tambahan semasa process pemasangan. Secara keseluruhan, risiko yang berkaitan dengan reka bentuk semasa untuk operasi pembersihan itu dianggap sederhana. Hasil eksperiment memberikan arah yang jelas dalam merancangkan dimensi pintu simbah dan pemilihan tapak dalam peringkat perancangan. Teknik yang dicadangkan untuk analisis kegagalan akan membantu dalam pemahaman tingkah laku kegagalan komponen di peringkat pembinaan, pemasangan dan operasi. Garis panduan dan pelan pengurusan telah disediakan untuk memberi permahaman serta langkah-*

langkah pencegahan yang mengenai penggunaan sistem pintu simbah dalam saliran bandaran air ribut konkrit terbuka.

Kata kunci: *Pintu simbah, kecepakan peningkiran, penilainan risiko, pemendapan, ketidakpastian*

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b	Width of the gate [m]
C	Center of membership function
d_{50}	Particle median diameter size [mm]
h_1	Distance of the water surface to the centre of the hinge [m]
h_2	Distance of the water surface to the bottom of the pressure prism [m]
l_s	Sediment bed length [m]
N	Number of flush
P	Probability
R	Correlation coefficient
R^2	Coefficient of determination for regression model
t_f	Flushing duration [mins]
γ_g	Specific weight of the gate [N/m^2]
h_g	Total height of the gate [m]
t_g	Thickness of the gate [m]
γ_w	Specific weight of water [N/m^2]
η_e	Sediment flushing efficiency [%]
θ	Gate opening angle [°]
σ	Width of membership function
$\mu_x^{n_x}(x)$	Membership function for $x \in$ [*Sev, Occ, Det*]
$A_x^{n_x}$	Linguistic term for $x \in$ [*Sev, Occ, Det*]
m_x	Number of membership function for $x \in$ [*Sev, Occ, Det*]

p_x	$p_x \in [1,2,3, \ldots, m_x - 1]$
x	Input for RPN model, $x \in$ [*Sev, Occ, Det*]

LIST OF ABBREVIATIONS

ART	Adaptive Resonance Theory
AIAG	Automotive Industry Action Group
C	Cost
CIDB	Construction Industry Development Board
CN	Control number
Det	Detection
FIS	Fuzzy Inference System
FMEA	Failure Mode Effect Analysis
FRPN	Fuzzy Risk Priority Number
MCDA	Multi-Criteria Decision Analysis
Occ	Occurrence
RCN	Risk Critical Number
REDAC	River Engineering and Urban Drainage Research Center
RPN	Risk Priority Number
Sev	Severity
SSO	Sanitary Sewer Overflow
UNIMAS	Universiti Malaysia Sarawak
USM	Universiti Sains Malaysia

CHAPTER 1

INTRODUCTION

1.1 Background

Storm sewer is designed to convey excess runoff from impervious surface. However, sewer systems are commonly affected by the deposition of solids. The accumulation of deposits is known to generate hydraulic and environmental problems of the sewer channels, reduce the design flow capacity; increase the risk of surcharges or local flooding during intense rain events and operational difficulties (Gent, Crabtree & Ashley, 1996; Arthur & Ashley, 1997; Fan, Field, & Lai, 2003; Bertrand-Krajewski, 2008). Hence, reactive maintenances are taken to remove sewer sediment deposits (Williams, Tait, & Ashley, 2009). Various techniques and tools are used especially in European countries to clean sediments, based on both mechanical and hydraulic principles (Bertrand-Krajewski, Bardin, Gibello, & Laplace, 2003). The applied techniques include the use of rodding, balling, flushing, poly pigs and bucket machines (Dinkelacker, 1991). Among the strategies and techniques, active flow by using hydraulic flush gate is widely used to solve sedimentation problem due to no limitation of flushway length; and no external water supply required.

Popularity of sediment flushing devices lies mainly with their performance, which stem from their efficiency, reduced cost, and their ability to remove deposits in the sewer system. Storm water is used as flushing media for automated sediment flushing device. It operates by storing enough water behind the gate and releases the wave by a sudden opening of the gate cleaning the entire sewer channel (Schaffner & Steinhardt, 2011). Numerous experimental and numerical studies are found in the literature on the mechanism

of sediment flushing devices and their capability of sediment removal such as vacuum flushing (Guo et al., 2004), Hydrass gate (Bertrand-Krajewski et al., 2005), sluice gate (Campisano, Creaco, & Modica, 2007) and tipping flush gate (Bong, Lau, & Ab. Ghani, 2013). These devices produce successive flushing wave at high velocity sufficient to scour and flush out the sediment accumulated in sewer (Bong et al., 2013). As the automated sediment flushing device has been applied in closed conduit, it also has potential for sediment removal in open drain (Bong, Lau, & Ab. Ghani, 2016).

Generally, there are many studies focus on the use of hydraulic flushing devices. Hydraulic performances of flush devices are assessed by assuming perfect technical functioning of all objects during operation. However, only limited data and work are available in the literature for the reliability and risk assessment for sediment flushing device. Although some data on the flushing gate product such as Hydroself exists in unpublished literature, these data are difficult to obtain. There are some uncertainties and ambiguous situation when the system was being used on-site such as environmental factor, technical failure of flush gate, clogging etc. The uncertainty in a system must be considered and required an integrated approach with comprehensive assessment to reduce the failure risk and predict the system performance. Control plan needs to be provided because a system which used in real life application may usually have some failures and causes which need to be assessed and prioritized in terms of their risk so that high risk failure modes can be corrected with top priorities (Wang et al., 2009).

Failure Mode and Effect Analysis (FMEA) have been proven a best method to evaluate the risk and assess the potential failure of a system and the technique was extensively used in wide range of industries. This technique also helps to provide early

preventative plans in design, avoid known failure and errors from happening (Wang et al., 2009). FMEA for a product also provides framework of information for risk management decision making. In the FMEA method, three risk factors (severity, occurrence, and detection) are used to depict each failure mode of a product (McDermott, Mikulak, & Beauregard, 2008). Severity reflects the seriousness of a failure. Occurrence reflects probability of the failure. Detection is the likelihood of detecting the failure. Each parameter is evaluated using rating from 1 to 10. Risk priority number (RPN) is the multiplication of the three ranked rating, severity (*Sev*), occurrence (*Occ*), and detection (*Det*) (McDermott et al., 2008). The critics of each failure mode can be generated by the calculation of RPN. The failure mode with higher scores of RPNs shows greater risk and needs priorization for corrective action or preventive measure (Liu et al., 2013).

However, there are some serious weaknesses when traditional FMEA is applied in the real world cases. Hence, a number of alternatives such as multi-criteria decision making (MCDM), mathematical programming (MP) and artificial intelligent (AI) have been recommended to solve some of the defect of the traditional RPN method and to apply FMEA more effectively (Liu et al., 2013). Among the methods, fuzzy rule base system was found to be the most popular approach (approximately 40%) in FMEA (Liu et al., 2013). Fuzzy transform complicates interpretation of the outcome and the models of the decision making process have become more realistic (Prodanovic & Simonovic, 2002). Fuzzy expert system provides the following advantages: (1) indistinct, qualitative or imprecise information and qualitative data can be used in consistent manner; (2) it allows combining the failure mode of severity, occurrence and detection in more flexible and realistic manner; (3) it provides the failure risk function to be customized based on the product identity, (4)

the system can completely combine engineers' knowledge and expertise in the FMEA analysis (Liu et al., 2013).

To conclude, fuzzy FMEA is suitable to evaluate the risk on the failure of flushing gate system as this study involve data collections from previous study, experimental works and field works. The analysis required both data analysis and human judgment. The scope of the investigation covered the construction process and installation of flush gate in open drain. The aim of this study is to analyze tipping flush gate with a new framework incorporating FMEA with FIS_RPN model to improve the device design, performance efficiency and management control. This study is important because it contributes towards improving the quality and reliability issues of potential use of tipping flush gate in open drain. The results from this study could solve the conceptual design problems by considering on-site uncertainty issue as well as filling the gap in the literature on risk assessment of hydraulic flushing device.

1.2 Problem Statement

In this thesis, the focus is on three shortcomings relating to hydraulic flushing gate. Firstly, risk assessment in active control of sediment by using tipping flush gate in open drain is still lacking. The concept of tipping flush gate for sediment management in open drain was proposed in Malaysia since year 2013 (Ab. Ghani et al., 2013). Based on the feasibility study, the device was efficient in deposit removal but some problems were found in the usage of the gate onsite. Hence, in the current study, fuzzy FMEA framework with FIS_RPN model is used in the risk assessment of active control of sediment via hydraulic flushing for open drain.

Besides, experimental work on the factors that may influence the efficiency of hydraulic flushing for sediment removal are also done so as to provide better understanding on the hydraulic flush gate characteristics and the component that could contribute to the management of sedimentation in open drain. Lastly, there is also lacking of the practical design with managing gate flushing for local condition. General rules on gate sizing, gate hinge positioning, gate opening angle, material for gate, and maintenance of the gate can still be improved (Bong et al., 2016). A general design guidelines and management plan was established for sedimentation control in open drain. This study contributes towards improving quality and reliability issues on the potential use of hydraulic flushing in managing sedimentation in open drain.

1.3 Objectives

The objectives of this thesis are as follows:

a) To determine the factors that influenced the sediment removal efficiency of hydraulic flushing;
b) To identify the potential failure mode, effect and root cause in using hydraulic flushing;
c) To apply FMEA with FIS_PRN model and obtain FRPN for mechanical failure of hydraulic flushing gate system in managing sedimentation in open drain; and
d) To establish a general guideline and management plan for active sedimentation control in open drain.

1.4 Scopes of Study

In this thesis, the risk assessment of tipping flush gate is studied by using fuzzy FMEA procedure. The scopes of study cover the design system of flushing gate, as well as

on-site installation of the device. Some experimental works are conducted to study the hydraulic characteristics of the flushing gate on sediment removal efficiency by using sand with size d_{50} of 0.71 mm, 1.18 mm and 2 mm. The experimental works are conducted at the hydraulic lab, River Engineering and Urban Drainage Research Center (REDAC), Universiti Sains Malaysia. A site monitoring work is conducted to investigate the flushing gate performance as real case study. The field work is conducted at a 0.6 m × 0.8 m rectangular open drain which is located in the campus of Universiti Malaysia Sarawak starting from 2nd March 2017 to 30th April 2017. Then, scale tables for *Sev*, *Occ* and *Det* are developed based on the discussion with an expert of the field and existing studies on the field history on tipping flush gate.

1.5 Thesis Outline

The introduction and discussion on the issue of sediment deposition removal by using active control, verification the product reliability by using fuzzy FMEA, the objectives and scope of study are presented in Chapter 1.

Literature relating to failure mode and effect analysis and related works are presented in Chapter 2. Besides, flushing of sediment in sewer system and the flushing device application in flush cleaning are discussed in the chapter.

Chapter 3 gives the methodology used in the current study which is the application of fuzzy FMEA to tipping flush gate design. The device components are further described. The use of the FIS_RPN model methodology in tipping flush gate design is demonstrated.

Chapter 4 shows some findings on the experimental work on the factors affecting sediment flushing efficiency which contribute to the design guideline of sediment flush

gate system. Besides, Chapter 4 also includes the results from on-site monitoring work, including the problem on site and actions that need to be taken. This chapter also shows the results and discussions on the fuzzy FMEA on the tipping flush gate design and the risk evaluation on the tipping flush gate subsystems and installation.

Chapter 5 provides a general guideline on the use of flush gate system in open drain which covers the design procedures for method of site surveying, flushing gate design, selection of material, construction and assembly process, installation process; monitoring and maintenance process.

Lastly, Chapter 6 concludes the results and findings from the conducted analysis and achievement of the objectives. Besides that, the chapter also includes some recommendations for future studies.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

In Chapter 1, the overview, problem statements, objectives, project's scope and thesis organization have been detailed. In this chapter, the background and literature relating to fuzzy FMEA, sediment flushing and flushing devices are described. This chapter is organized as follows. In Section 2.2, flushing of sediment in the sewer system is presented. The section covers the history background of flushing, principle and effect of flushing cleaning, flushing device application in flush cleaning and factors affecting flushing efficiency. In Section 2.3, FMEA methodology is presented. The used of FMEA, various types of FMEA and FMEA procedure are detailed. The limitation and improvement of FMEA are discussed in Section 2.4. In Section 2.5, an FMEA procedure with an FIS_RPN model is presented. Literatures relating fuzzy FMEA in civil engineering application are presented in Section 2.6. Finally, concluding remarks are presented.

2.2 Flushing of Sediment in Sewer System

2.2.1 History Background of Flushing

The utilization of flushing is one of the most seasoned strategies to clean sewers from stores. The primary confirmation of sewer flushing dated from Roman period. General Marcus Vipsanius Agrippa (63-12 BC) had requested the Cloaca Maxima to be flushed by releasing all the while the water from seven reservoir conduits (Bertrand-Krajewski, 2008). After the fall of Rome and amid the medieval times, the Roman learning was not kept. Amid this period, flushing did not have all the earmarks of being regular

strategy and sewer upkeep predominantly done physically. The exemptions were in the German city of Bunzlau, where the sewer framework worked from 1531 to 1565 was intermittently cleaned of stores by flushing with drinking water (Bertrand-Krajewski, 2008). In 1963, the primary sewers cleaning administration was set up in Paris while in England, the main thought on general sewer cleaning were found in 1687 (Shaffner, 2008).

Before the end of nineteenth century, flushing tanks were utilized as a part of numerous European urban communities. Paris had 3500 flushing tank in 1899 while Berlin had 1220 flushing tanks in 1906. Memphis in the United States utilized 180 flushing tanks as a part of 1879 (Bertrand-Krajewski, 2003). The successful separations of these flushing tanks were assessed to between 150 m and 300 m (Schaffner, 2008). Amidst nineteenth century, the main flushing doors were introduced in sewers to initiate stockpiling volume for flushing. The English specialist John Roe developed the flushing entryways and actualized it in the sewers arrangement of Holborn and Finsbury, England in 1842 (Schaffener, 2008). Similar flushing doors were executed in Hamburg, Germany by William Lindley and in Paris (Bertrand-Krajewski, 2008).

With the change of sewer plan in the late 1950s together with the headway of intense purifying apparatuses like high-influenced water flies, the flushing cleaning was ousted. This is due to the hindrances of streaming with freshwater; before the end of twentieth century, the flushing cleaning was reiterated with new innovations created (Schaffener, 2008).

2.2.2 Principle of Flushing Cleaning

Schaffer (2008) stated that flushing cleaning is the same mode of action as the first flush in sewer network in the course of a storm event in an urbanized area. The sudden runoff of a large volume of water leads a flush wave with highly followed turbulent wave heads. The necessary precondition for the function of flush wave is a dry run off region downstream of the flushing device. Indeed, even a low water level downstream slows the flush wave down and influences the cleaning effectiveness negatively. The flow has to act with high shear stress on the deposits at the sewer base to enable a lift and transport them with the current.

The flush waves are translation waves, which move a volume of flow towards the direction of their propagation. They are produced by discontinuous change of the runoff cause by the opening of a sluice or the break of a reservoir dam that lets out a large amount of water. They are also called shock waves. This implies that the principle of a flush wave is based on the changing transient flow.

In term of flushing duration, high turbulence levels are expected to cause adequate lift force on the residue particles. This force is only being found in the head of the flush. The short duration flush has the similar sediment transport effect as flush of longer duration. Although flush cleaning bring beneficial outcome on sediment deposit removal, there are critics in terms of abrasion of sewer which caused by flush wave (Shaffner, 2008).

2.2.3 Effect of Flushing Cleaning

The flush cleaning, aside from its positive cleaning results, underlies the feedback of the abrasion of the sewer pipes caused by the transport of water and solids mixture. Sand, gravel or metal parts might harm the surface of the sewer pipes. However, limited literature describes the demonstrable damages caused by flush waves. The same applies for the forming of deposit directly upstream of a flushing device.

The investigation by Lorenzen, Ristenpart and Pfuhl (1996) indicated that a complete cleaning of a sewer from its deposits by flushing is not possible. Besides, Ristenpart (1998) stated that it is possible to keep a sewer channel free of deposits for long space of time with the aid of flushing once it is cleaned with high pressured water jet before flushing campaign started. Subsequently the amount of work is restricted to the maintained of the flushing device. The effect of flushing cleaning in sewer channels can be summarized as follows by the results of Lorenzen et al. (1996):-

a) Deposits are detached and transported;

b) The cleaning can be effective for long distance;

c) A backwater effect in connected sewers could be possible;

d) The high flow velocity of the flush waves, which have to be released periodically, reduces the formation of new deposits;

e) The first flush during a storm event will contain only low pollution load which caused by the reducing of deposits, when the sewer is flushed and therefore cleaned continuously.

2.2.4 Flushing Device Application in Flush Cleaning

Various types of flushing devices have been installed in urban drainage network for sewer and basin cleaning for years. Among the devices, tipping bucket, chambers with gate, vacuum flushing systems and flushing drums are more popular. Dip weirs and rotating bends are utilized largely for cleaning main sewers. The various flushing devices for sewers and basin cleaning are shown in Figure 2.1.

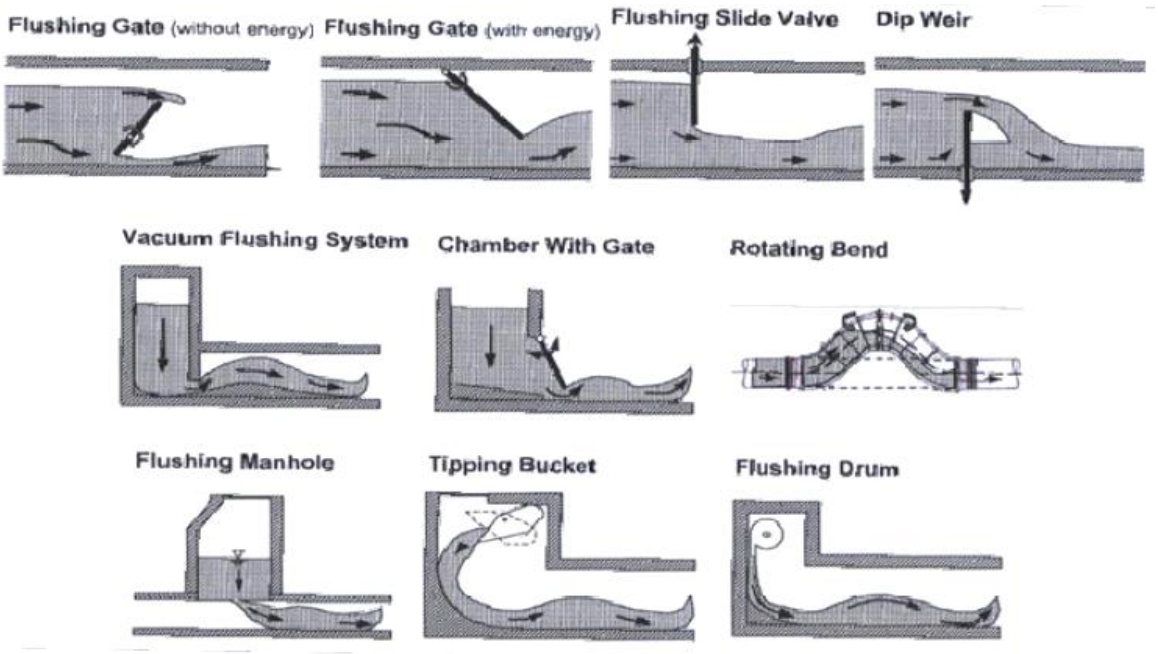


Figure 2.1: Flushing devices implemented for sewer and basin cleaning (Dettmar et al., 2002)

Hydrass gate and tipping flush gate are examples of in-line flushing devices. These types of devices require flushing volume for cleaning the sewer line, by build up a system component, i.e., a gate through completely or partially blocking the sewer cross section.

Hydrass Gate

The Hydrass flushing system is developed and patented in France. It is a sewer cleaning device which automatically stores and releases dry weather effluent applying a concept of hydrostatic rotational system. This system operates by periodically releasing a stored dry-weather flow volume behind the gate from a fixed point in the network (Laplace et al., 2002). The Hydrass system is comprised of a balanced hinged gate with the same shape of the sewer cross section, and obstructs the flow in the section where it is located. The Hydrass gate has a lower part (below the gate hinge/axis) with a smaller but heavier area than the upper part. This result in high water level to provide more force to open the gate with a heavier lower part; a condition which closed conduit sewer could allow without overflowing.

During the low flow period, the gate is held upright by its own weight and the sewer flow builds up behind it. The depth of the sewer flow continues to rise behind the gate until it reaches a critical depth and the gate is tilted by the horizontal force by the retained water. In this way, the gate is forced to pivot about the hinge to a near horizontal position, which suddenly leashes the blocked water volume and this creates a flushing wave. After that, the gate returns to the vertical position and the cycling process is repeated. Figure 2.2 shows the Hydrass gate in storage phase and flushing phase, and Figure 2.3 presents a schematic operation of the Hydrass gate. Generally, the Hydrass gate is used in closed-conduit sewers under pressurized flow.

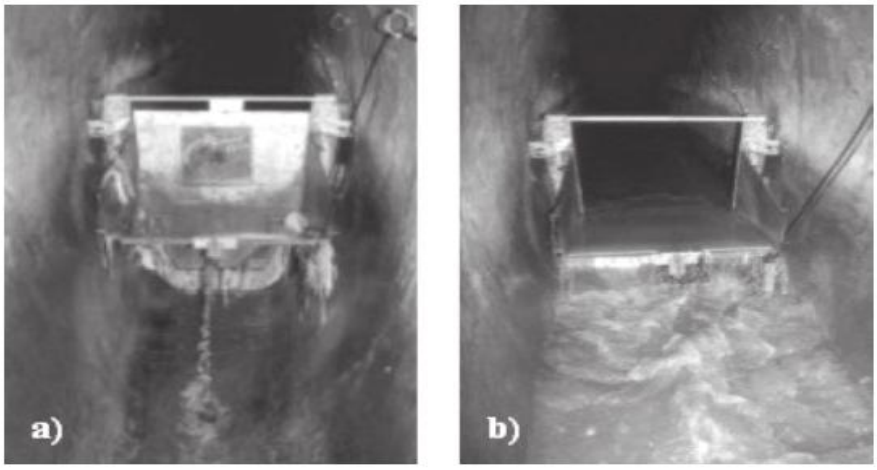


Figure 2.2: Hydrass gate (a) storage phase (b) flushing phase (Bertrand-Krajewski et al., 2005)

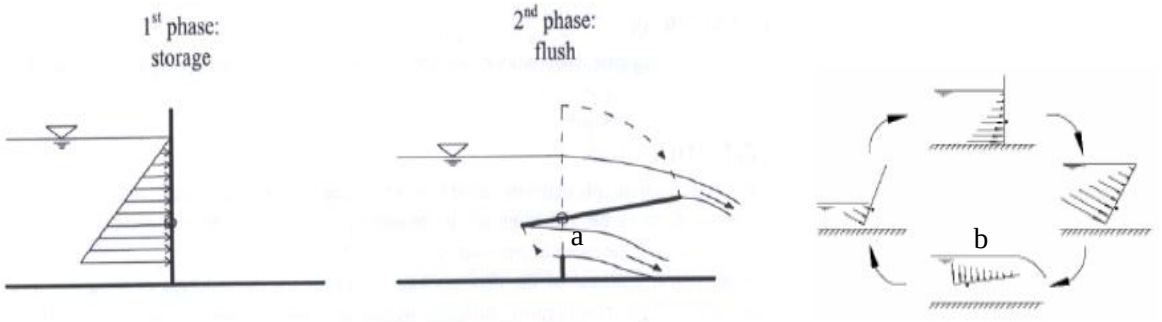


Figure 2.3: Sequences of Hydrass gate operation (Campisano et al., 2006)

Tipping Sediment Flush Gate

The tipping sediment flush gate has a similar concept with Hydrass gate. However, the tipping flush gate is designed to suit the open drain. Figure 2.4 depicts the views of the tipping flush gate model.

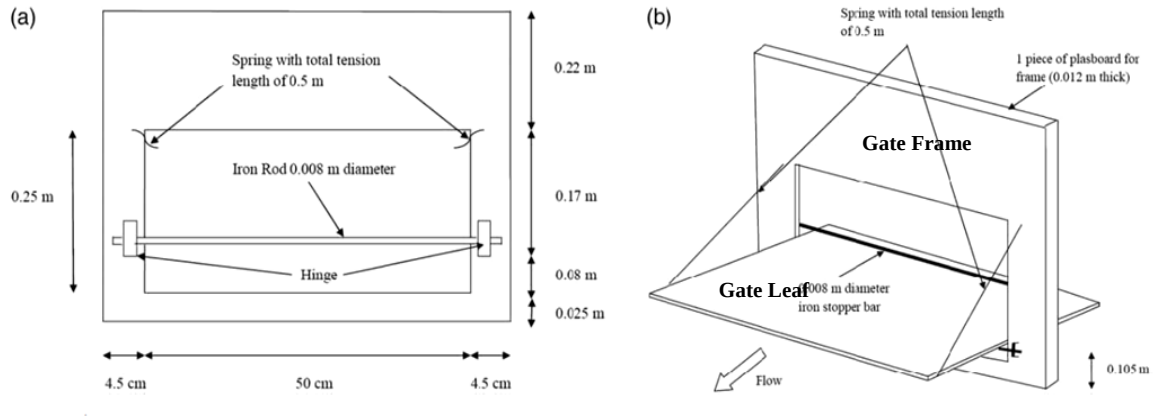


Figure 2.4: Views of the tipping flush gate model
(a) front view; and (b) isometric view (not to scale) (Bong, Lau, & Ab. Ghani, 2013)

The flush gate is made up by double layer GCV Plasboard. This material is produced by Green Cycle Vision (Malaysia) Sdn Bhd. It is one of the IBS component which certified by CIDB Malaysia. The plasboard has a density of 1092 kg/m^3 with a thickness of 12 mm. Figure 2.5 shows the panels of plasboard. This material is used because it is 100% waterproof in both salt and freshwater.

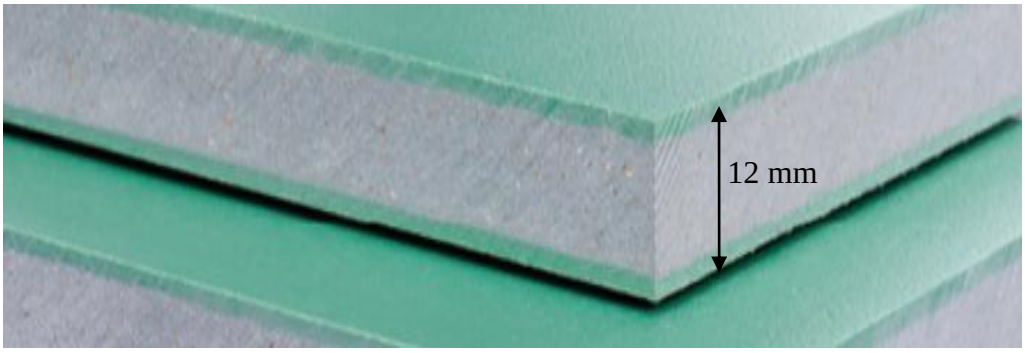


Figure 2.5: Thickness of double layer GCV Plasboard

The performance of the flushing gate is mainly depended on its design and operation mechanism. The operation mechanism of the gate includes the opening angle, upstream water capacity and; opening and closing water levels. The tipping flush gate can be divided

into two major subsystems namely, gate-opening subsystem and gate frame subsystem as shown in Figure 2.6.

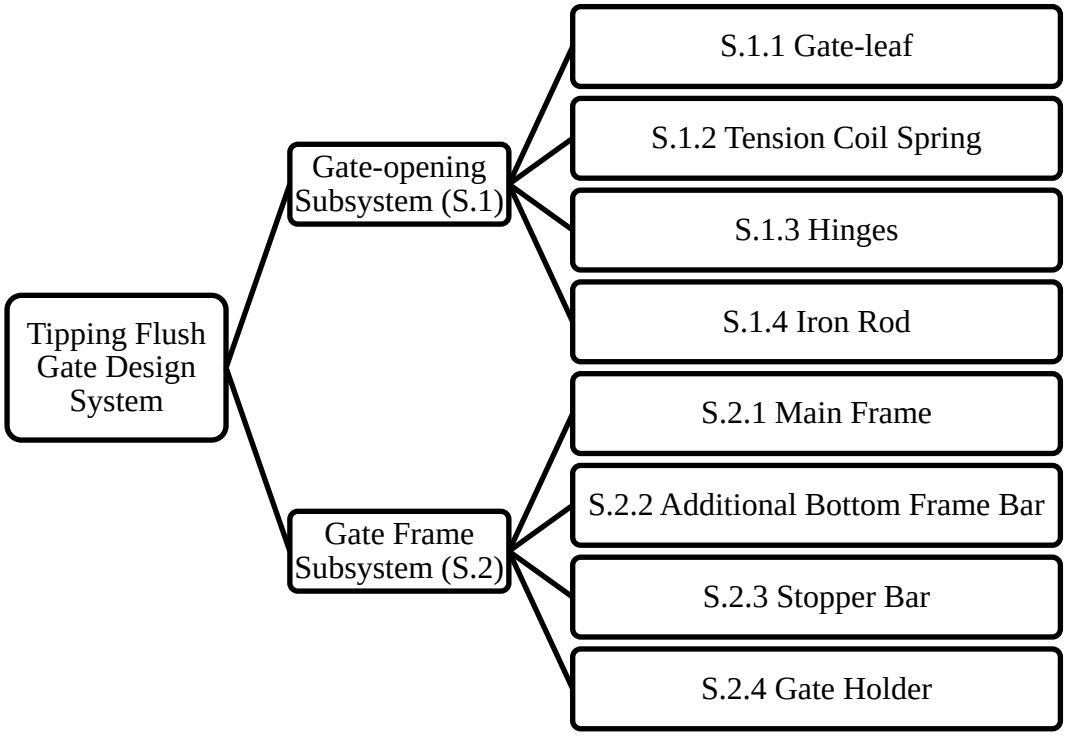


Figure 2.6: Hierarchy structure of tipping flush gate

Gate-opening Subsystem

Gate-opening subsystem is used to store water at storage phase and release water when flushing. The bottom part of the gate is designed lighter than the upper part to allow smooth and easier tipping of the gate during opening phase. This is done by adjusting the gate hinge so that the bottom part of the gate has smaller area as compared to the upper part of the gate. The subsystem consists of the following components i.e., gate-leaf, tension coil spring, hinges and iron rod as shown in Figure 2.7. The functions of the subsystem components are summarized in Table 2.1.

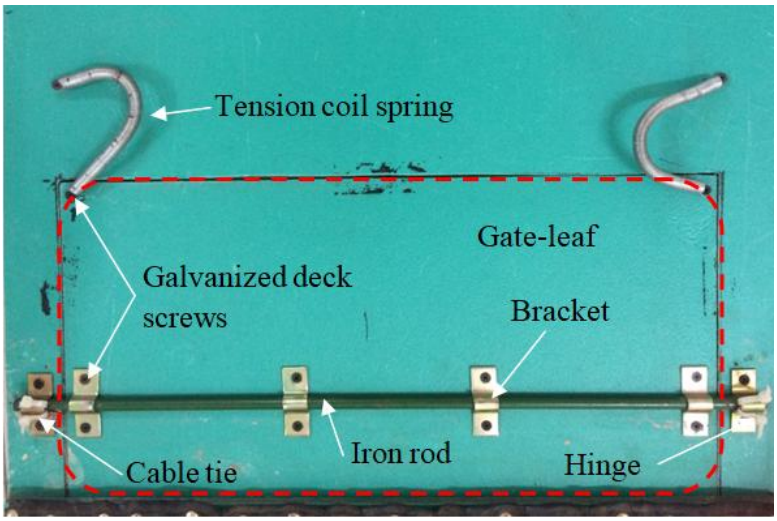


Figure 2.7: Components of gate-opening subsystem

Table 2.1: Function of the gate-opening subsystem components

Component (Location)	**Function**
Tension coil spring (Front edge of the gate, connected to gate frame)	The spring compresses upon by a force that restores the gate tipping to rest or equilibrium position to ensure proper closing of the gate. It is used to ensure the gate close tightly.
Hinge (Side of the gate frame)	It is installed to enable the gate to perform rotation during flushing operation.
Cable tie (Tie around the hinge)	It provides a void and spacing between the iron rod and hinge to ensure smooth rotation. It helps to avoid stuck at the hinge during flushing operation.
Iron rod (Attached to hinges)	It acts as a link to connect the gate-leaf and gate frame.

Table 2.1 continued

Component (Location)	Function
Galvanized deck screws (Brackets, hinge opening and spring opening)	It acts as a fastener to pin the hinge to plasboard so that the iron rod can be attached to the gate properly. It also holds the spring to the gate and gate frame tightly.

Gate Frame Subsystem

Gate frame subsystem is the main supporting structure of the tipping flush gate. All the components are attached to it to form a complete design. To design the gate frame of tipping flush gate, the on-site condition needs to be investigated first such as the drainage geometry (size, shape, length) and the invert level of the inlet pipes to the drain. This is to prevent backwater through the inlet pipe and ponding on the road. In addition, freeboard must be provided between the height of the gate and with the total depth of the sewer to allow the storm water to flow over if the flush gate is stuck or cannot be opened.

The gate dimensions need to follow the dimensions of the selected open drain. After that, plasboard is cut-to-size accordingly. The gate frame consists of the following components i.e., main frame, rubber sheet, additional bottom frame bar, and stopper bar as shown in Figure 2.8. The functions of the components are summarized in Table 2.2.

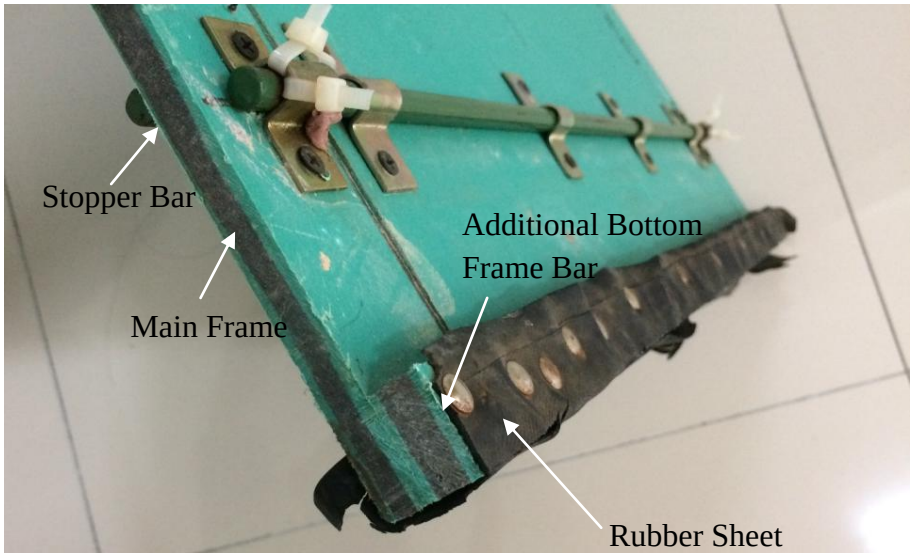


Figure 2.8: Components of gate frame subsystem

Table 2.2: Function of the gate frame subsystem components

Component (Location)	**Functions**
Main Frame	To hold the whole designed system.
Galvanized Deck Screw (Along site the additional bottom frame bar)	It acts as a fastener to pin the main frame and the additional bottom frame bar together.
Stopper Bar (Behind the gate)	It is used to prevent the gate from tipping further from the desired angle of opening (during opening) and also to avoid the gate tipping further when closing.
Additional Bottom Frame Bar (Bottom of main frame, same side with iron rod)	To increase the base of the gate frame and reduce the risk of bending of gate.
Rubber Sheet (Optional: Below the gate frame)	It is used to prevent water slip through the bottom of the gate during flushing operation.

Bong et al. (2016) designed the bottom part (below the gate hinge) lighter than the upper part of the gate by positioning the gate hinge so that the bottom part of the gate has smaller area as compare to the upper part of the gate as shown in Figure 2.9. This allows easier tipping of the gate during opening phase which requires a lower water level as compared to a gate with heavier lower part so as to prevent overflow from the open drain. If the sum of the upper portion force, F_1 and the weight of the gate W_g are larger than the force at the lower portion F_2, then the gate tips to open.

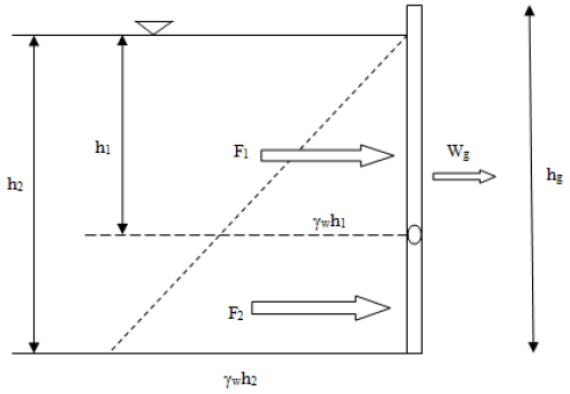


Figure 2.9: Forces acting on tipping flush gate before opening (Bong et al., 2016)

The water force/thrust at the upper portion of the gate is given as follow:

$$F_1 = \frac{1}{2}\gamma_w b {h_1}^2 \quad (2.1)$$

Where γ_w is the specific weight of water [N/m^2]; b is the width of the gate [m] and h_1 is the distance of the water surface to the centre of the hinge [m]. The force at the lower portion of the gate is given by:

$$F_2 = \frac{1}{2}\gamma_w b {h_2}^2 - \frac{1}{2}\gamma_w b {h_1}^2 = \frac{1}{2}\gamma_w b({h_2}^2 - {h_1}^2) \quad (2.2)$$

Where h_2 is the distance of the water surface to the bottom of the pressure prism [m].

The weight of the gate [N] is given as

$$W_g = \gamma_g b h_g t_g \tag{2.3}$$

Where γ_g is the specific weight of the gate [N/m^2]; h_g is the total height of the gate [m] and t_g is the thickness of the gate [m]. Taking the moment at the hinge which is off the centre, the gate opens if the sum of the force at the top portion and the gate weight is larger than the force at the bottom portion. Thus:

$$\left(F_1 \times \frac{h_1}{3}\right) + \left(W_g \times \frac{h_g}{2}\right) > F_2 \times \frac{2}{3}(h_2 - h_1)\left(\frac{h_2+2h_1}{h_2+h_1}\right) \tag{2.4}$$

Or

$$\left(\frac{1}{2}\gamma_w b {h_1}^2\right)\left(\frac{h_1}{3}\right) + \left(\gamma_g \times t_g \times b \times h_g\right)\left(\frac{h_g}{2}\right) > \frac{1}{2}\gamma_w b\left({h_2}^2 - {h_1}^2\right)\frac{2}{3}(h_2 - h_1)\left(\frac{h_2+2h_1}{h_2+h_1}\right) \tag{2.5}$$

Equation 2.5 could be simplified by taking the thickness of the gate as 0.012 m and the specific weight of the gate (assuming the material is plasboard such as the one used for the gate on site) γ_g = 10712.5 N/m^2 and γ_w = 9810 N/m^2. The simplified version of the Equation 2.5 is as follow:

$$h_1 > \left[2\left({h_2}^2 - {h_1}^2\right)(h_2 - h_1)\left(\frac{h_2+2h_1}{h_2+h_1}\right) - 0.0393{h_g}^2\right]^{1/3} \tag{2.6}$$

By using trial and error, the position of the hinge for the tipping flushing gate design could be calculated by fulfilling Equation 2.4 provided the allowable water level upstream of the gate just before the gate tilts to open and the gate height h_g are predetermined from the

condition on site. The height of the hinge h_{hng} from the bottom of the pressure prism is given by:

$$h_{hng} = h_2 - h_1 \tag{2.7}$$

After the gate has tilted to open, it closes if the force at the lower portion F_2 is larger than the sum of the force at the upper portion F_1 and the weight of the gate W_g as shown Figure 2.10. This happens when the water starts to recede after opening.

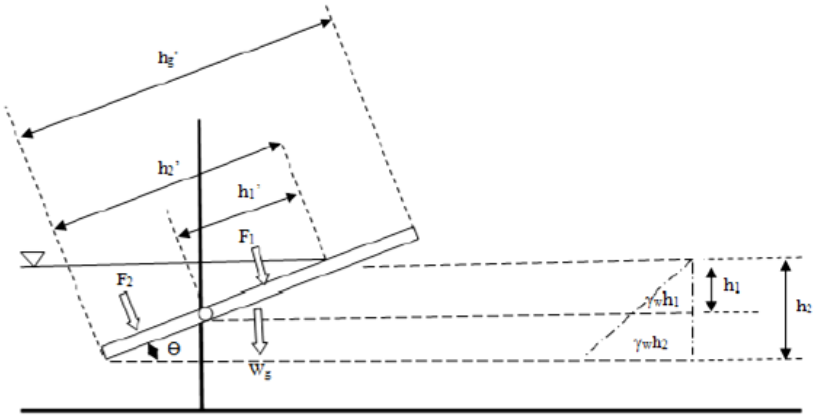


Figure 2.10: Forces acting on tipping flushing gate when open (Bong et al., 2016).

In Figure 2.5, h_1 and h_2 is related to h'_1 and h'_2 respectively as:

$$h_1 = h'_1 \sin\theta \tag{2.8}$$

$$h_2 = h'_2 \sin\theta \tag{2.9}$$

Where h_1 is the distance of the water surface to the centre of the hinge; h_2 is the distance of the water surface to the bottom of the pressure prism and θ is the angle of the opening from the horizontal axis. The water force/thrust at the upper portion of the gate when the gate tilted is given as follow:

$$F_1 = \frac{1}{2}\gamma_w b {h_1}^2 \tag{2.10}$$

Where γ_w is the specific weight of water [N/m^2]; b is the width of the gate [m] and h_1 is the distance of the water surface to the centre of the hinge [m]. The force at the lower portion of the gate is given by:

$$F_2 = \frac{1}{2}\gamma_w b {h_2}^2 - \frac{1}{2}\gamma_w b {h_1}^2 = \frac{1}{2}\gamma_w b({h_2}^2 - {h_1}^2) \tag{2.11}$$

Where h_2 is the distance of the water surface to the bottom of the pressure prism [m].

The weight of the gate [N] is given as

$$W_g = \gamma_g b h_g t_g \tag{2.12}$$

Where γ_g is the specific weight of the gate [N/m^2]; h_g is the total height of the gate [m] and t_g is the thickness of the gate [m]. Taking the moment at the hinge which is off the centre, the gate opens if the sum of the force at the top portion and the gate weight is larger than the force at the bottom portion. Thus:

$$\left(F_1 \times \frac{h_1}{3}\right) + \left(\frac{W_g\left(\frac{h'g \sin\theta}{2}\right)}{\cos\theta}\right) < F_2 \times \frac{2}{3}(h_2 - h_1)\left(\frac{h_2 + 2h_1}{h_2 + h_1}\right) \tag{2.13}$$

Or

$$\left(\frac{1}{2}\gamma_w b {h_1}^2\right)\left(\frac{h_1}{3}\right) + \left(\gamma_g \times t_g \times b \times h_g\right)\left(\frac{h'g \sin\theta}{2}\right) < \frac{1}{2}\gamma_w b\left({h_2}^2 - {h_1}^2\right)\frac{2}{3}(h_2 - h_1)\left(\frac{h_2 + 2h_1}{h_2 + h_1}\right)$$

(2.14)

Equation 2.14 could be simplified by taking the thickness of the gate as 0.012 m and the specific weight of the gate (assuming the material is plasboard such as the one used for the gate on site) γ_g = 10712.5 N/m^2 and γ_w = 9810 N/m^2. The simplified version of the Equation 2.14 is as follow:

$$h_1{}^3 - \frac{0.0393 h_g{}^2 \sin\theta}{\cos\theta} < 2\left(h_2{}^2 - h_1{}^2\right)(h_2 - h_1)\left(\frac{h_2+2h_1}{h_2+h_1}\right) \quad (2.15)$$

By using trial and error to solve Equation 2.14, the water level h_2 when the gate closes could be determined provided the height of the hinge, the angle of the gate opening and gate height have been predetermined.

In this thesis, fuzzy FMEA is applied on tipping flush gate. Thus, the parameters used for equations (from Equation 2.1 to Equation 2.15) in the design tipping flush gate are key factors in the analysis.

2.2.5 Factors Affecting Flushing Efficiency

This section provides a review of the factors affecting the efficiency of flush gate system by classifying the factors into four main system components: (1) sewer characteristics, (2) sediment characteristics, (3) flush gate characteristics and (4) environment factor.

2.2.5.1 Sewer Characteristics

Sediments appear regularly at the section where almost mild slope sewer, bends of the sewer and widening of the cross-sectional diameter (Lorenzen et al., 1996). Boundary conditions of sewer such as initial downstream water level and bottom roughness of sewer

have a major influence on the movement of flush waves. These factors must be considered when designing a flush gate device in practical application.

Type of sewer system

The type of flush system applied varies on the type of sewer system. In European country, the flush system is applied in closed conduit sewer that flows under pressurized conditions during full flow. On the other hand, open channel sewer systems are frequently used in developing and less developed countries which flow under atmospheric pressure. This difference in pressure can affect the efficiency of the flush wave generated (Bong et al., 2016).

Type of sewer cross section

The erosion and deposition processes depend upon the geometry of the channel cross section (Safari et al., 2014). U-shape and V-shape channels have center cross-fall. Flushing for these sewers requires higher shear stress and velocity due to higher incipient motion shear stress are required compared to other types of cross-section. Rectangular channel requires lowest incipient deposition velocity; thus sediment traps easily in rectangular channel (Safari et al., 2014). Besides, sediment particles start moving from a narrow section, as it connects towards the point of sewer with maximum depth in cross section. Sewer with larger cross section is subjected to more sediment deposition and thus higher flushing velocity is required for sediment removal.

Longitudinal sewer slope

An increase in channel slope determines more effective flushes despite the corresponding reduction in water volume stored upstream of the gate (Campisano et al.,

2007). This scenario is due to water flows faster and thus enhancing the erosion of sedimentary deposit. Besides, bottom slope variability also affects the grain size distribution and organic fraction of sediment particles usually before flushing event where they build up during dry weather condition. More bed materials are entrained at higher slope during the flush regardless of the distance from the gate (Shahsavari et al., 2015).

Initial downstream water level

The amount of the flushed sediment decreases with increasing water level depth in the sewer section. A larger initial water depth in the flume provided the bottom sediment a better sheltering against the advancing flush wave. When the initial after depth above the sediment layer increase from zero (i.e., saturated, water level exactly at the top of the sediment layer), the weight of the flush decreased by 51% (Guo et al., 2004). Schaffner and Steinhardt (2013) observed that even at a low downstream water level of only 0.10 m can lead to a loss of effective flushing distance of 75% due to dissipation of some of the upcoming surges energy.

Bottom roughness

The shear stresses generally increase with a higher roughness while the velocity drops. The flush wave running on smooth surface reaches the end of the sewer faster at a lower shear stress (Schaffner & Steinhardt, 2013). An increase of bottom roughness lends to an increase of the shear stress but the flow velocity slows down which indicates a loss of cleaning efficiency (Schaffner & Steinhardt, 2013). A numerical investigation was carried out by Schaffner and Steinhardt (2013) found that the flush wave running on a smooth surface, M = 0.01 $s/m^{1/3}$, reaches the sewer end at a wave running time of 1446 s at a maximum shear stress of = 2.29 N/m^2. The flush wave with the roughest surface, M =

0.025 $s/m^{1/3}$, reaches the sewer end at a wave running time of 3538 s at a maximum shear stress of = 4.21 N/m^2.

2.2.5.2 Sediment Characteristics

In order to forecast the sediment flushing efficiency, it is important to understand the erosion process of sediment in sewer channel. The shear stress required for sediment erosion process highly depends on the characteristics of the sediment deposit and the local hydraulic condition. A higher flow velocity gradient means higher bed shear stress, which characterizes the ability of the flow to keep the solid in motion and to avoid deposition (Lorenzen et al., 1996).

Level of consolidation and cohesiveness

Consolidation process exerts a significant influence on the erosion behavior of sewer sediments. Post changes (consolidation, biological reaction) lead to the development of "dirty" cohesive sediment bed. Crabtree (1989) stated that there are five categories of sediment deposit can be found in the nature of combined sewer sediment as shown in Table 2.3. In real sewer sediments, for example loose deposit (Type A), contains significant amounts of organic material which may give cohesion to the deposit. Such deposit may have higher critical yield stress, and hence requires a higher bed shear stress to initiate the erosion (Crabtree 1989).

Table 2.3: Categories of sediment deposit (Crabtree, 1989)

Type	Characteristics
A	Coarse, loose, granular, predominantly mineral, material found in the inverts of pipes
B	As Type A but concreted by the addition of fat, bitumen, cement, etc into a solid mass
C	Mobile, fine grained deposits found in slack flow zones, either in isolation or above Type A material
D	Organic pipe wall slimes and zoogloeal biofilms around the mean flow level
E	Fine-grained mineral and organic deposits found in sanitary sewer overflow (SSO) storage tank

Sediment void ratio and porosity

Campisano et al. (2007) stated that scouring effects increase as sediment porosity increases. Length of flushed sediment increases with increasing void ratio. Flushed water more easily penetrates sediment with high void ratio. For larger cohesive sediments, the sediment void ratio increases and flushed water easily penetrates into the sediment and more sediment particles are suspended by incoming surge and transported to downstream end (Shafai-Bejestan et al., 2012).

Grain size and relative density of deposited sediment

Grain size and relative density of deposited sediment affect the resistance of particles against mobility by the flow. Smaller gain size of sediment causes higher scouring effect when flushing (Campisano et al., 2007). Shahsavari et al. (2015) reported that grains smaller than 2 mm are easier to be flushed downstream. For coarser sediments, the flushing

efficiency decreases. Single flush by a flush gate with sharp crested weir can only break down mainly the particles with diameter smaller than 2 mm (Shahsavari et al., 2015). Besides, structure of sediment bed is crucial for the removal effectiveness of the flush. Gross sediment consists of silts; construction and street asphalt debris have high relative density. This type of sediment has the tendency to be “armoured” bed structure, causing it hard to be removed (Shahsavari et al., 2015).

Sediment thickness

Ab Ghani (1993) stated that the sediment deposits’ thickness affect the incipient motion of the particles and sewer ability to erode the sediment deposit. Bong et al. (2013) observed that as the thickness of sediment deposit increases, the critical velocity required for incipient motion also increases. Thicker sediment deposit might cause formation of micro-bed forms leading to additional resistance and friction between sediment particles leading to higher critical velocity to move the particles. Thus, number of flush needed for particle removal increases as the sediment bed deposit thickness increases (Bong, 2013).

2.2.5.3 Flush Gate Characteristics

In particular, the operations of the flush gate involve two stages: (1) store water behind a flush shield in the sewer channel to a predetermined level with no external reservoirs, (2) open the shield to release the water and generate flush wave to flush out accumulated sediment at downstream.

Location of flush gate device

Location of flush device affects the wave velocity that contributes to scour the sediment. Lorenzen et al. (1996) observed that the sediment level in the section

downstream further from the flush device remains almost unaltered after flushing. The greatest cleaning effects with complete bed erosion are observed close to the flush device due to the maximum wave energy in that area (Ristenpart, 1998). The influence of flushing is restricted to a limited distance.

Upstream water level

The initial water head and store volume available for the flush affect the magnitude of the shear stress generated by the flush, as it is a measure of the initial energy held by the water behind the gate (Lorenzen et al., 1996; Guo et al., 2004). Higher upstream water level results in higher potential energy per unit weight of water for flushing, creating bigger scouring effect, increasing weight of flushed sediment (Guo et al., 2004). Flush wave moves further to downstream as upstream water level increases. Besides, this factor plays the key role on the duration of the erosion process (Campisano et al., 2007). Longer single flush duration is observed as stored water increases.

Duration and frequency of flushing

The frequency of flush events and the time of arrival of a flush are important qualities (Lorenzen et al., 1996; Ristenpart, 1998). Single flush might significantly modify sediments composition and structures depending on the type of the flow (Shahsavari et al., 2015). Bong et al. (2017) suggested that short flushing duration is more efficient in term of total volume of sediment being removed from the sewer as compared to long flushing duration. However, in term of mean sediment bed advancement, longer flushing duration moves the sediment bed front further as compared to short duration flush. This is because high turbulence levels, which cause sufficient lift forces onto sediment particles, are found

in the head of the flush. Hence, flushing devices with short flushing duration with higher flushing frequency are efficient (Bong et al., 2017).

2.2.5.4 Environment Factor

Rainfall

Rainfall is an active factor that impacts erosion and transport of sediment in sewer flushing system as stormwater is the media for flushing device. Frequency and intensity of rainfall in tropical climate tend to be higher than those in temperate climate. Thus, frequent rainfall increases the number of hydraulic flushing operation of flush gate. Besides, the intensity of rainfall affects the downstream water level in open storm sewer. It is probable, that the flush has not the same effect, as if there is a low water level in sewer (Lorenzen et al., 1996).

Debris

Debris transported by the flow might disturb the flush gate operation (Bertrand-Krajewski et al., 2003). During rain event, domestic waste such as solid waste and garbage will easily carried by water into the open drain (Zakaria et al., 2004). Thus, the garbage or litter might cause the gate stuck or fail to operate. Bong at al. (2016) suggested that maintenance of the gate and cleaning of litter caught at the gate need to be done when necessary to maintain the system performance and avoid backflow or overflow of water.

2.3 FMEA Methodology

2.3.1 Background

FMEA is a systematic approach to evaluate the risk associated with a complex engineered technological entity (Liu et al., 2013). FMEA is a forward logic (bottom-up), tabular technique which used as an improvement and risk assessment tool (Shammas & Wang, 2016). This technique is useful in identifying and eliminating known or potential failure to provide information for making risk management decisions (Liu et al., 2013). It has been proven to be a useful and powerful tool in assessing potential failures and preventing them from occurring (Sankar & Prabhu, 2001).

FMEA techniques are focused on preventing defects, enhancing safety, and improving customer satisfaction (McDermott et al., 2008). This technique gathers the knowledge and experience of experts to analyze the potential impacts failures of a design, system, or a process. They rank the priorities for attention as indicated by the particular impact of failure, and eliminate the chances of the negative effect before they occur (Yeh & Hsieh, 2007). The practice of FMEA is associated with different approaches are proposed by different organizations and researches from one application to another.

2.3.2 Use of FMEA

Historically, FMEA was formalized by the US Armed Forced Military by the introduction of Military Procedures document (MIL–P) -1629 in the 1940s, to classify failures according to their impact on mission success and personnel or equipment safety. Then, it was later applied by the contractor for the National Aeronautic and Space Administration (NASA) during Apollo mission in the early 1960s to find and mitigate risk

due to an unanticipated design problem. The use of FMEA gained momentum during the 1960s, with the push to put a man on the moon and return him safely to earth. In 1967, civil aviation industry started to use FMEA and related techniques, and a standard of ARP926 (ARP4761 revised) for performing FMEA was published.

In year 1973, the U.S. Environment Protection Agency provided a report describing the application of FMEA to wastewater treatment plants. Then, the used of FMEA in the automotive industry began in the mid-1970s. It was adopted by Ford Motor Company for safety and regulatory consideration after the Pinto affair. Besides, the company also used this technique to enhance the production and design. Furthermore, Toyota conducted the FMEA technique on the catalytic converter which was used in the 1975 Toyota models. In the 1980s, FMEA was prominently actualized in the automotive industry by standardizing the structure and routines through the Automotive Industry Action Group (AIAG).

Today, FMEA has become a standard practice in various manufacturing companies from Japan, America, and Europe. Despite the fact that the FMEA technique was initially proposed by the military, this technique is now generally utilized in various industries which including semiconductor processing, foodservice, plastics, software, automotive, and medical technologies (Carlson, 2012).

2.3.3 Types of FMEA

Generally, there are three common types of FMEAs, i.e. system FMEA, design FMEA, and process FMEA. All these types of FMEA produce a list of failure modes ranked by RPN and list of failure modes ranked by RPN and list of corrective actions to reduce failure or to improve detection.

System FMEA

System FMEA is the highest level analysis of an entire system, constructed dependent upon various subsystems in the conceptual and design phase (Stamatis, 2015). This analysis concentrates on the failure mode related to the system-related deficiencies, including system safety, system integration, interfaces, or interactions between subsystems or with other systems, connections with encompassing environment, human interaction, service, and other issues that might cause the overall system not to work intended (Carlson, 2012). The significant output of system FMEA is to provide a list of potential system functions that could detect potential failure mode.

Design FMEA

The design FMEA is also known as product FMEA. This technique is used to uncover issues with the product that result in safety hazards, product malfunctions, or a shortened product life (McDermott et al., 2008). This analysis concentrates on the product design at the subsystem or component level, which related to the design deficiencies, emphasis on improving the design and ensuring product operation is safe and reliable during the useful life of the equipment (Carlson, 2012). The scopes of the design FMEA incorporate the subsystem or component itself and the interfaces between adjacent components. Design FMEA generally assumes the product is manufactured according to specifications (Carlson, 2012). The significant output of the design FMEA is to establish a list of product design improvement and actions with priority and thus the safety and reliability of product operating during the useful life of the equipment.

Process FMEA

The process FMEA is used to investigate the risks related to the manufacturing process (McDermott et al., 2008). This analysis concentrates on the manufacturing or assembly process to ensure that a product is built to design requirements in a safe manner with minimal failures (Carlson, 2012). The scopes of a Process FMEA include the manufacturing and assembly operations, shipping, incoming parts, transporting of materials, storage, conveyors, tool maintenance, and labeling. The significant output of process FMEA is to provide a list of critical and significant characteristics of the process. The potential recommended actions have to be provided based on the significant characteristics of the process.

2.3.4 FMEA Procedure

FMEA is performed in several steps. The first step is describing the product or process on which FMEA is conducted. Then, functions of the product or process are defined so that potential failure modes could be defined. Once all possible failure modes are obtained, occurrence rating is assigned to the cause of the failure mode to reflect the probability of the cause and immediate failure mode, severity rating is assigned to the effect of the failure mode to reflect the seriousness of the end effect, and detection rating is assigned to the cause of the failure mode to reflect the difficulty of detecting the cause or failure mode. All the three ratings are quantified by integer values ranging from 1 to 10 and then multiplied together to obtain the RPN, which is used to determine the risk priority of a failure mode (Wang et al., 2009).

$$RPN = Sev \times Occ \times Det \tag{2.16}$$

2.4 Limitation and Improvement of FMEA

2.4.1 Limitation of FMEA

FMEA is an effective problem counteractive action procedure which is interfaced with many engineering and reliability approach. However, it is important to understand the limitations of FMEA. Over the years, investigations to enhance the FMEA methodology and to overcome the shortcoming have been directed. Based on the study by Liu et al. (2013), the researchers had concluded that there are 11 major shortcomings of the traditional RPN Model i.e.,

a) The relative importance among the three risk factors (severity, occurrence and detection) are not taken into consideration;

b) The diverse combinations of *Sev*, *Occ* and *Det* might produce exactly the same RPN value. However, their hidden risk implications may be completely distinctive;

c) The three risk factors are difficult to be assessed decisively;

d) The use of multiplication method in the calculation of RPN value may be flawed;

e) The conversion of scores is different for the three risk factors;

f) The RPN value cannot be used to measure the effectiveness of the corrective and preventive measure;

g) The risk priority numbers are not continuous with many hole;

h) Interdependencies among different potential failure modes and effects are not taken under account;

i) The mathematical form used for calculating the RPN value is determinedly sensitive to the changes in the risk factors evaluations;

j) The elements of RPN have different duplicated number;

k) The RPN considers only three risk factors mainly in term of safety.

The use of multiplication method in the calculation of RPN value (Equation 2.16) is questionable (Chin, Chan, & Yang, 2008). Different combinations of *Sev*, *Occ*, and *Det* factors might result precisely the same value of RPN, even the hidden risk implications might be totally different. For example, two different events with the values of 4, 3, 1 and 3, 2, 2 for *Sev, Occ* and *Det* respectively, have the same RPN value of 12. This may cause a waste of resources and time or in some case a high risk event unable to be noticed (Pillay & Wang, 2003).

Besides, Bowles and Peláez (1995) stated that, the evaluation for RPN is quantitative, without considering the relationships between the output RPN and inputs *Sev*, *Occ* and *Det* depending on qualitative assessment. The traditional FMEA framework does not consider linguistic variables that come from experts. When the *Sev*, *Occ*, and *Det* are multiplied together for the RPN calculation, the ratings are treated as if they represent numeric quantities. Furthermore, the relative importance among *Sev*, *Occ*, and *Det* is neglected in conventional RPN model (Pillay and Wang, 2003). The three risk factors are expected to have the same importance; significantly, it might not be the case for practical application of FMEA.

FMEA has many-to-many relationships between the failure modes, effects, causes, controls, and corrective actions (Bluvband & Zilberberg, 1998). Thus, FMEA analysis is time-consuming (Montgomery et al., 1996). Besides, the traditional brainstorming process for FMEA is tedious, time-consuming, error-prone, and causing conflict and deficiency (Montgomery et al., 1996), thereby causing difficulty in understanding and maintaining the FMEA table.

2.4.2 Improvement of FMEA by Using Artificial Intelligence Approaches

Different computing techniques have been recommended to solve the weaknesses of the conventional FMEA methodology. Generally, those existing risk evaluation methods could be grouped under five categories, i.e., MCDM methods, mathematical programming methods, artificial intelligence methods, integrated methods, and other methods. In this thesis, the centering is on the AI methods. Fuzzy cognitive map was implemented in FMEA to show the cause-and-effect relationships in FMEA (Bowles & Peláez, 1996). The opinions from various experts were merged with the utilized of fuzzy cognitive map in FMEA (Bowles & Peláez, 1996). A fuzzy rule-base system was then implemented in FMEA, which utilized the linguistic variables to describe the input risk factors, i.e., *Sev*, *Occ*, and *Det*, and the output RPN score (Bowles & Peláez, 1995). The relationships between the *Sev, Occ*, *Det* and RPN score were characterized by a set of fuzzy If-Then rules from experts. Besides, fuzzy ART neural network was also applied in FMEA to assess the risk outcomes (Keskin & Özkan, 2009). The inputs *Sev, Occ*, and *Det* values which constitute the output RPN scores were evaluated independently for each input.

Wang et al. (2009) stated that the evidential reasoning approach was suggested to express FMEA users' assessments in multiple attribute decision analysis that held

imprecision and uncertainty. In addition, visualization technique had been incorporated into FMEA in Chang, Tay, and Lim (2015). The proposed visualization serves as a communication means between FMEA and its users by providing the users an overview of all failure modes and corrective actions in a structure that is easy to understand. As a result, this method gives more efficient processes for users to access and analyze the FMEA worksheet for performing risk prioritization and corrective actions (Chang et al., 2015).

2.5 An FMEA Procedure with an FIS_RPN Model

The FIS, which is classified as an AI-based method (Liu et al., 2013) is used to replace the conventional RPN model in aggregating the *Sev*, *Occ*, and *Det* ratings, resulting in an FIS_RPN model. Specifically, the relationships between the inputs (*Sev, Occ,* and *Det* ratings) and the output (FIS_RPN score) are formulated as a set of fuzzy rules. Examples of successful industrial applications of FIS_RPN models include agriculture (Jong et al., 2013), marine (Pillay & Wang, 2003), and automotive (Xu et al., 2002).

The framework of an FIS_RPN is illustrated in Figure 2.11. In general, an FIS_RPN model is more preferred to the conventional RPN model for the following reasons: (1) it allows customization of the RPN model based on expert's knowledge provided in the form of fuzzy "IF-Then" rules (Jong et al., 2013; Yang, Bonsall, & Wang, 2008); (2) it allows a nonlinear relationship between the FIS_RPN score and the input risk factors to be formulated (Bowles & Peláez, 1995); (3) it is robust against uncertainty and vagueness due to fuzzy information processing (Pillay & Wang, 2003; Yang et al., 2008); (4) it captures the three input risk factors qualitatively, instead of quantitatively, by using fuzzy logic (Bowles & Peláez, 1995).

In an FIS_RPN model, the product function in Equation 2.16 is replaced by an FIS model. The FIS model is used to aggregate three risk factors, i.e. *Sev*, *Occ*, and *Det* and produces an FIS_RPN score. In contrast to the conventional RPN model, each *Sev*, *Occ*, and *Det* rating is defined using a scale table with a number of partitions.

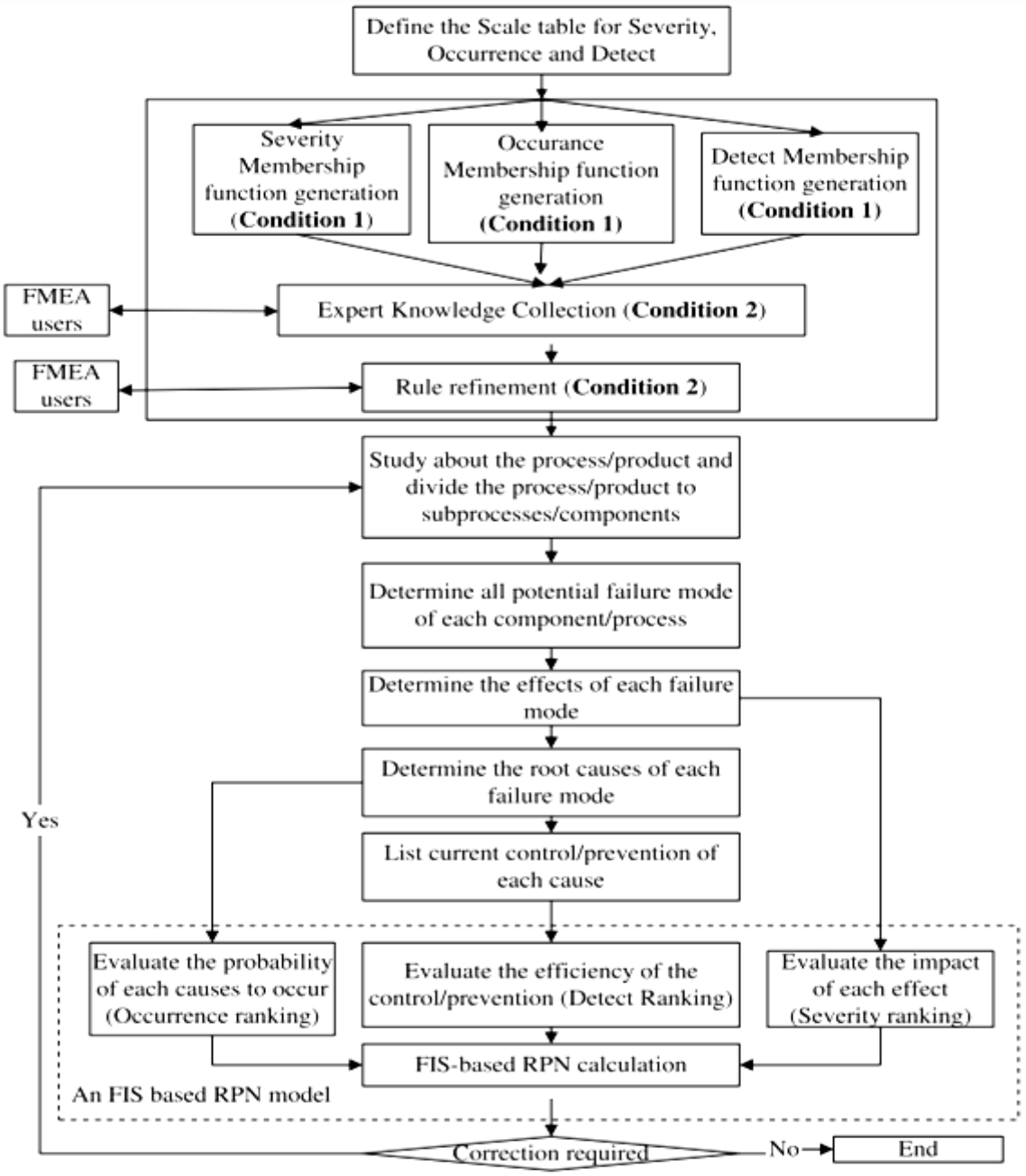


Figure 2.11: Enhancement of FMEA methodology with the FIS_RPN model (Tay & Lim, 2010)

2.5.1 Fuzzy Inference System

The zero-order Sugeno FIS model is effective in modeling the nonlinear relationship between the inputs and output (Wang, Tanaka, & Griffin, 1996) as well as its universal approximation property (Buckley, 1993). Each fuzzy IF-Then rule is represented as follows:

$R^{n_{sev},n_{occ},n_{det}}: If\ Severity\ is\ A_{sev}^{n_{sev}}\ and\ Occurence\ is A_{occ}^{n_{occ}}\ and\ Detection\ is\ A_{det}^{n_{det}},$

$Then\ RPN\ is\ B^{n_{sev},n_{occ},n_{det}}$

Where $B^{n_{sev},n_{occ,}n_{det}}$ denote the fuzzy consequence in the RPN space. Note that $b^{n_{sev},n_{occ},n_{det}}$ is the fuzzy singleton of $B^{n_{sev},n_{occ},n_{det}}$.

To simplified the notation, the fuzzy rule is written as

$R^{n_{sev},n_{occ},n_{det}}: A^{n_{sev,}n_{occ},n_{det}} \rightarrow\ b^{n_{sev,}n_{occ},n_{det}},$

where $A^{n_{sev,}n_{occ},n_{det}} = A_{sev}^{n_{sev}} \wedge A_{occ}^{n_{occ}} \wedge A_{det}^{n_{det}}$. Using the zero-order Sugeno FIS model, the FIS_RPN score is obtained with Equation 2.2 (Kerk, Tay, & Lim, 2015), hereafter denoted as classical FIS_RPN. The lower and upper bounds for $b^{n_{sev},n_{occ},n_{det}}$ are denoted as $\underline{b}$ and $\bar{b}$, respectively.

$FIS_{RPN}(sev, occ, det)$

$$= \frac{\sum_{n_{Sev=1}}^{m_{Sev}} \sum_{n_{Occ=1}}^{m_{Occ}} \sum_{n_{Det=1}}^{m_{Det}} \left(\mu_{Sev}^{n_{Sev}}(sev) \times \mu_{Occ}^{n_{Occ}}(occ) \times \mu_{Det}^{n_{Det}}(det) \times b^{n_{sev},n_{occ},n_{det}}\right)}{\sum_{n_{Sev=1}}^{m_{Sev}} \sum_{n_{Occ=1}}^{m_{Occ}} \sum_{n_{Det=1}}^{m_{Det}} \left(\mu_{Sev}^{n_{Sev}}(sev) \times \mu_{Occ}^{n_{Occ}}(occ) \times \mu_{Det}^{n_{Det}}(det)\right)} \quad (2.17)$$

Where each *Sev*, *Occ*, and *Det* domain is defined using a scale table, with m_{Sev}, m_{Occ}, and m_{Det} partitions, respectively. Each partition is represented by a fuzzy membership function, i.e., $\mu_x^{n_x}(x)$, and is associated with a linguistic term, $A_x^{n_x}$,where n_x = 1, 2, 3, . . .,m_x, $x \in$ [*sev*, *occ*, *det*], and $x \in$ [*Sev*, *Occ*, *Det*].

2.5.2 Monotonicity Property of FIS_RPN Model

Based on the findings in Jee, Tay, and Lim (2015), fulfillment of the monotonicity property is determined according to Definition 2.9. A sequence, $\bar{s}$, denotes a subset of $[Sev, Occ, Det]$ where x is excluded, i.e., $\bar{s} \subset [Sev, Occ, Det]; x \notin \bar{s}$, is considered.

Definition 2.9: (Jee et al., 2015). The classical FIS_RPN model is said to fulfill the monotonicity property if the FIS_RPN score increases or remains unchanged, as x increases, i.e., $FIS\_RPN\ (\bar{s}, x_2) \geq FIS\_RPN\ (\bar{s}, x_1)$, where $x_2 > x_1$.

Theorem 2.1: (Jee et al., 2015). The classical FIS_RPN model (i.e., Equation (2.2)) is said to fulfill the monotonicity property between Sev, Occ, Det and FIS_RPN, if the following conditions are satisfied.

Condition 2.1: At the rule antecedent part, $\frac{\left(\frac{d\mu_x^{p_x+1}(x)}{dx}\right)}{\mu_x^{p_x+1}(x)} \geq \frac{\left(\frac{d\mu_x^{p_x}(x)}{dx}\right)}{\mu_x^{p_x}(x)}$. Note that $\frac{\left(\frac{d\mu_x^{p_x}(x)}{dx}\right)}{\mu_x^{p_x}(x)}$ is the ratio between the rate of change of the membership function and the membership function itself.

Condition 2.2: At the rule consequent part, $b^{p_x+1,p\bar{s}} \geq b^{p_x,p\bar{s}}$, where $p_x \in [1,2,3, \ldots, m_x - 1]$.

Condition 2.2 implies that the fuzzy rule base should be completed; all ($m_{Sev} \times m_{Occ} \times m_{Det}$) fuzzy rules should be available. In this thesis, the Gaussian membership function is used, and Corollary 2.1, which is an extension of Condition 2.1, applies.

Corollary 2.1 (Jee, Tay, & Lim, 2015). Let $\mu_x^{n_x}(x)$ be a Gaussian membership function, i.e., $\mu_x^{n_x}(x)\left(x: c_x^{n_x}, \sigma_x^{n_x}\right) = e^{-\left[x_i - c_x^{n_x}\right]^2 / 2\sigma_x^{n_x}}$, where $c_x^{n_x}$ and $\sigma_x^{n_x}$ are the centre and width of the membership function, respectively. The ratio $\frac{\left(\frac{d\mu_x^{p_x}(x)}{dx}\right)}{\mu_x^{p_x}(x)}$ of a Gaussian membership function returns a linear function, as follows.

$$E_x^{p_x}(x) = -(1/{\sigma_x^{p_x}}^2)x_i + (c_x^{p_x}/{\sigma_x^{p_x}}^2) \tag{2.18}$$

Condition 2.1 of Theorem 2.1 is satisfied if $\left(E_x^{p_x+1}(x) \geq E_x^{p_x}(x)\right)$ and $\left(E_x^{p_x+1}(\bar{x}) \geq E_x^{p_x}(\bar{x})\right)$ are valid.

2.6 Previous Studies of Fuzzy FMEA in Civil Engineering

2.6.1 The Application of Fuzzy Performance Measures to a Regional Water Supply System

Based on the study by Simonović (2009), a fuzzy performance measures was applied to the regional water supply at City of London (Ontario, Canada). Fuzzy performance system measures aim to identify the critical system components for the Lake Huron Primary Water Supply (LHPWSS) and the Elgin Area Primary Water Supply System (EAPWSS). A summary list of LHPWSS and EAPWSS and treatment process were listed to identify the scope of analysis. Then, fuzzy reliability analysis was used to

quantify the uncertainty through the use of appropriate fuzzy membership functions to describe the system's state of safety and the fuzzy failure events. Besides, the change in the system-state membership function was used to identify critical system component. For example, in the case of the LHPWSS, the system-state membership function changes significantly with the addition of transfer pump. The improvement of the system components helps to improve the overall system performance. The procedures also extended to find out the optimum improvement of the critical components. Generally, the analysed results show that there was a 20% increase in the maximum capacity of the transfer pump; results in a 30% increase in the combined reliability-vulnerable measure and an increase of 24% in the robustness measures. As a conclusion, fuzzy is an effective tools in carrying out risk assessment in water resources system under uncertain condition.

2.6.2 Application of Fuzzy FMEA in The Case of Sewerage Treatment Plan

Based on the study by Yeh and Hsieh (2007), fuzzy theory approach was applied to the analysis of a sewage treatment system (STS). The sewerage treatment plant is located near by the Taipei-Yilan Expressway's Syueshan Tunnel. The study was categorized as system FMEA. The researchers had proposed a knowledge-based model to make the FMEA assessment method more reasonable. The overall structure of fuzzy FMEA is shown in Figure 2.12. Through collecting the expert's knowledge and engineers' experience, the input and output membership functions and the fuzzy rule base were constructed before implementing the fuzzy FMEA. The inference process of carrying out the fuzzy FMEA included fuzzification, rule evaluation, and defuzzification. The analysis results showed that fuzzy FMEA method gave a more accurate and reasonable ranking. The researchers suggested that this method can be applied in other investigation.

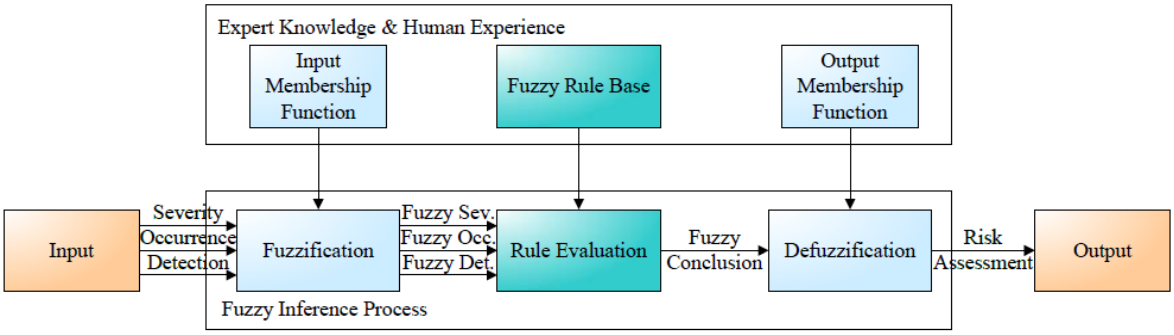


Figure 2.12: The basic structure of FMEA based on fuzzy theory (Yeh & Hsieh, 2007)

2.7 Summary

Generally, although there are many studies focus on the performance and hydraulic aspects of the flushing device, only limited studies are available in the literature on the reliability and risk assessment of hydraulic flushing of hydraulic flushing gate in managing sedimentation in open drain. Furthermore, the use of hydraulic flushing for sedimentation control in open drain can be considered a novelty, just having one literature exploring on the potential of sediment removal in open drain using tipping flush gate (Bong, et al., 2016). Besides, it is applicable to apply of using FMEA with FIS_RPN model in flush gate system as similar method has been applied to civil engineering field, aiming to provide a quality and reliable strategy method to the use of active control using flush gate system in sediment removal.

CHAPTER 3

METHODOLOGY

3.1 Background

The current study is divided into five major parts as depicted in Figure 3.1. The first stage involves the preliminary study of tipping flush gate characteristics to understand its operational mechanism in open drain. Besides, the relationship between the components of automated flushing operation was developed. Then, risk identification was carried out in second stage which involved the sets of experiment. Some experimental works were conducted to study the hydraulic characteristics of flush gate on sediment removal efficiency and the factors that influenced the sediment flushing efficiency. In addition, a field testing was conditioned to collect the failure mode of flush gate system in real life application.

Third stage involved data collection and combination of expert judgment through questionnaire and discussion to identify the potential failure mode, effect and root cause of flushing gate design. The *Sev*, *Occ*, and *Det* ranking were assigned after determining the failure modes of each component and its effect. After the data collection, fourth stage involved the fuzzy FMEA application with included constructing the interval FIS_RPN model and generated the surface plot of FRPN by using Matlab simulation.

Lastly, FMEA tables for flush gate system design were proposed based on the failure risk evaluation and prioritization outcome from FIS_RPN model. Management and preventive control action were included in the FMEA table to improve the device design and reduce the impact of failure mode.

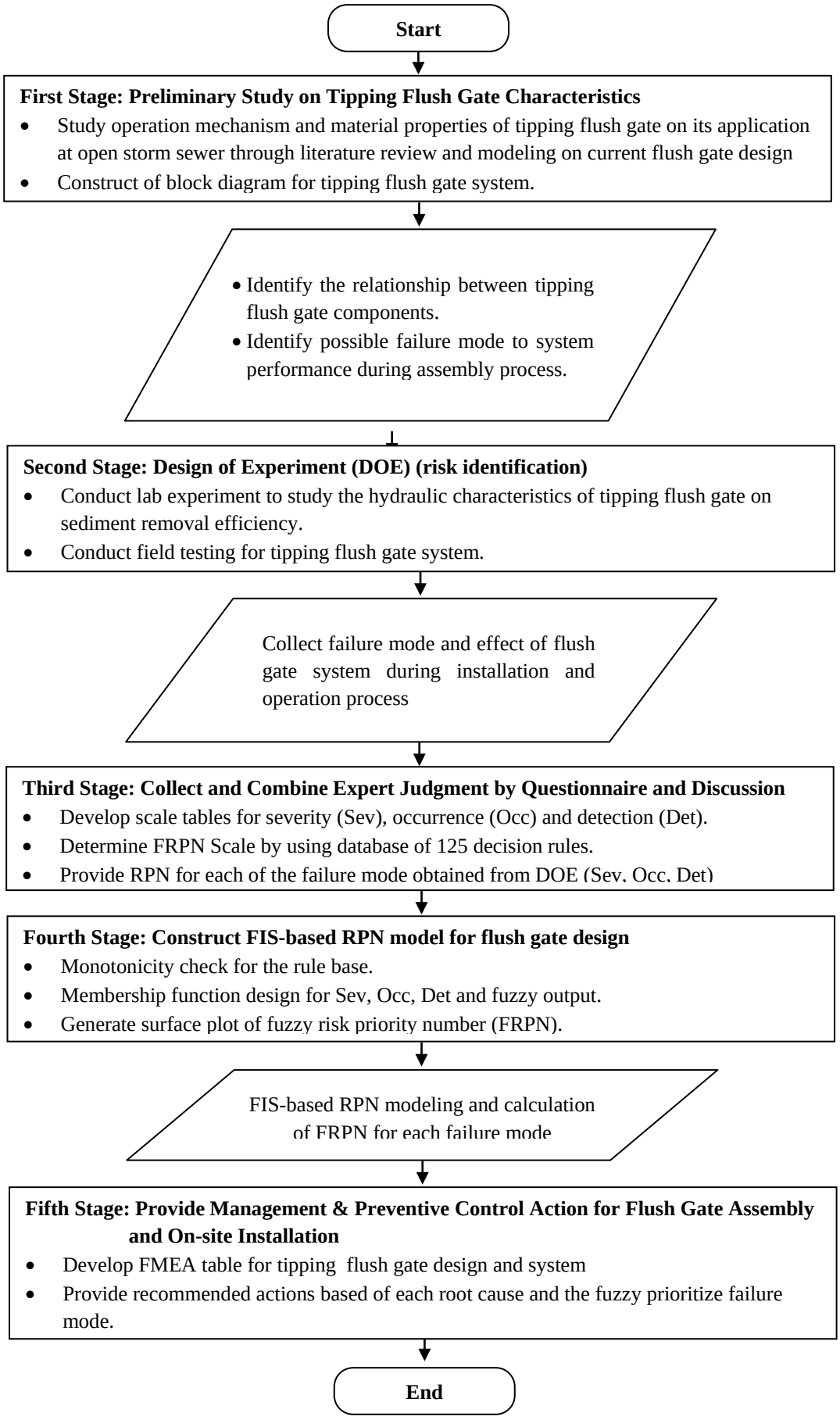


Figure 3.1: Research methodology

3.2 First Stage (Preliminary Study of Tipping Flush Gate Characteristics)

3.2.1 Block Diagram

Tipping flush gate that used in this study is as shown in Figure 2.4 (refer Chapter 2). In order to make this project scope visible and narrowing down the project focus, a FMEA block diagram for automated sediment flushing system was done as shown in Figure 3.2. Rain is the key element to drive the flushing operation. Rain water was stored and accumulated behind the gate. The store water created a kinetic force to push the gate leaf to open. Boundary line was enclosing the tipping flush gate to establish the tipping flush gate design issues that needed to be considered. The FMEA block diagram shows the interface between adjacent components for the flush gate. For examples, water force pushed the gate-leaf to tip; the tension of the spring caused the gate-leaf to return to its original position; a stopper bar was attached to the gate frame by using brackets and screws sets. The gate opening subsystem and gate frame subsystem were used for FMEA analysis.

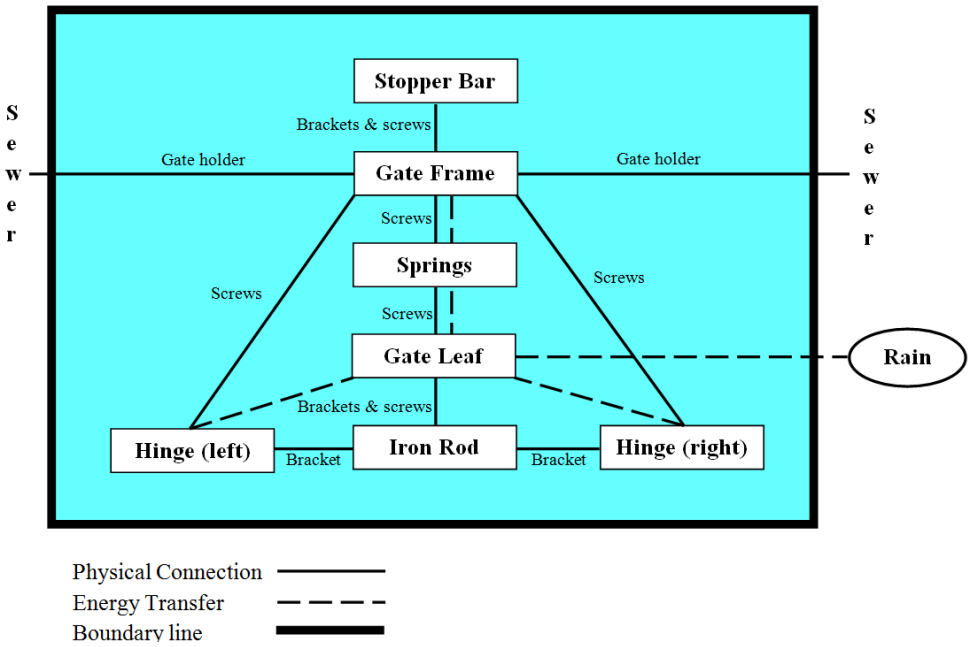


Figure 3.2: FMEA block diagram for tipping flush gate

3.2.2 Assembly of Tipping Flush Gate

The tipping flush gate was designed based on the design calculation (from Equation 2.1 to Equation 2.15). After the design stage, the design drawing was given to the technical assistance for construction of the flush gate as shown in Figure 3.3. The construction and assembly process of flushing gate was done manually. This process consists of ten stages as shown in Figure 3.4. Some failure modes were collected during the flushing gate construction through construction of size 1.5 m (W) × 1 m (H) flushing gate (bigger size flushing gate) as compared to size 0.6 m (W) × 0.5 (H) which was used for sediment flushing experiment (refer Section 3.3.1) and field testing (refer to Section 3.3.2). Each stage consisted of different failure mode that affected the flushing operation system. The collected failure modes and effects were recorded to the FMEA table and evaluated by the expert.

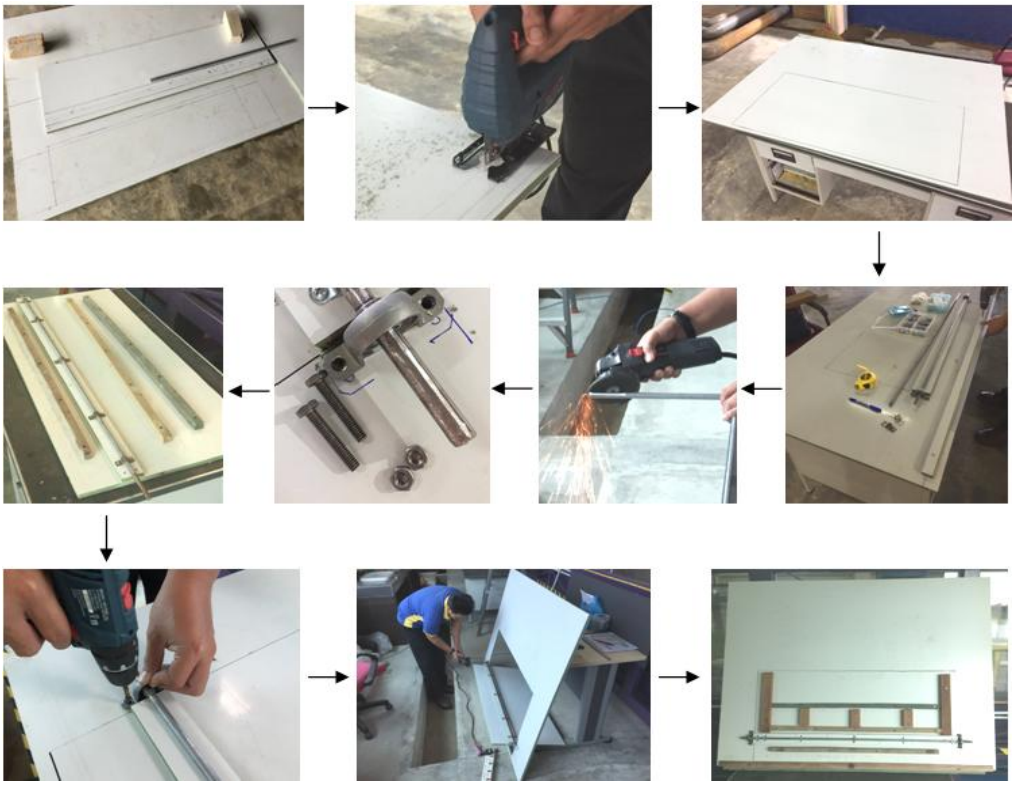


Figure 3.3: Tipping flush gate construction and assembly process

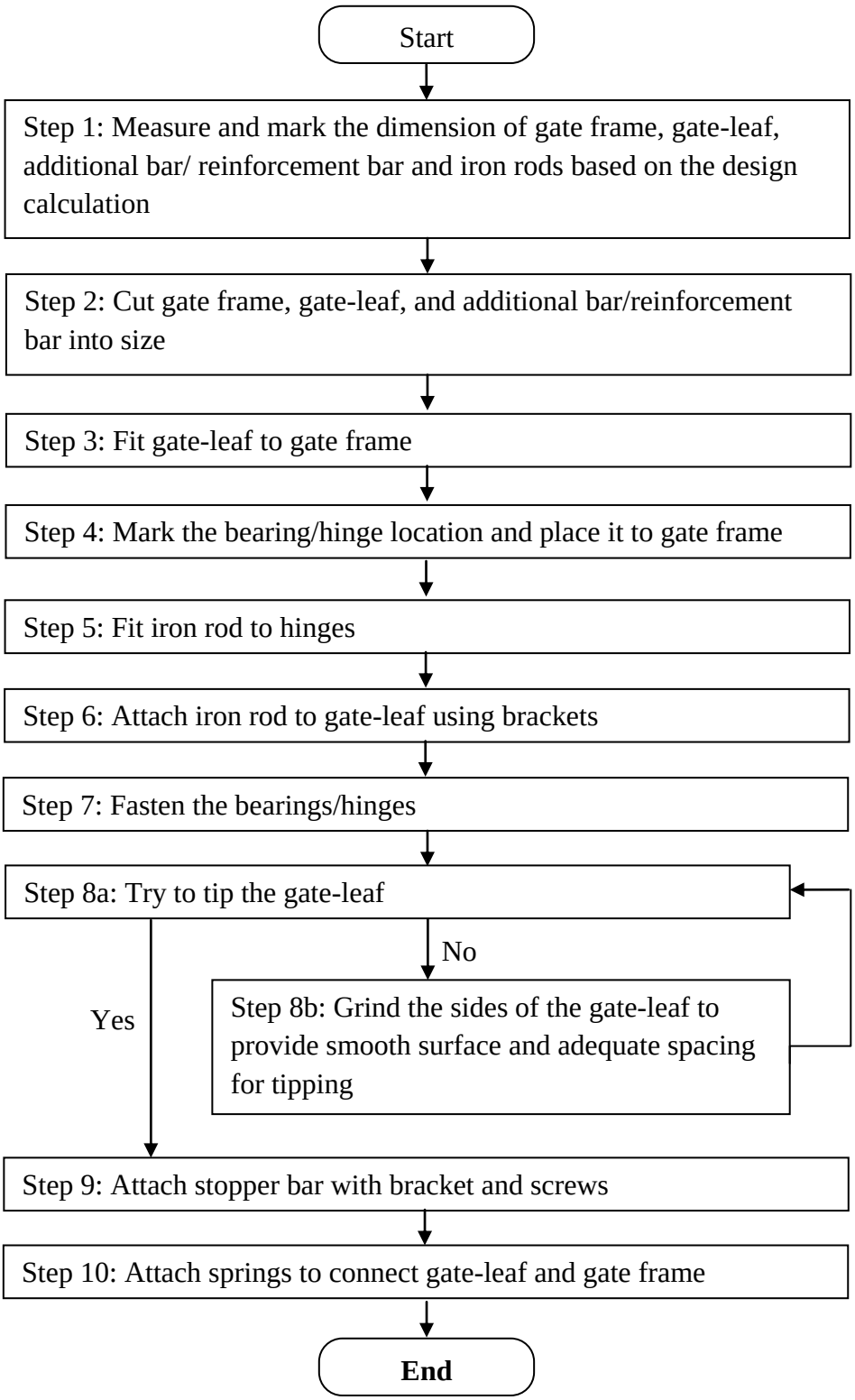


Figure 3.4: Tipping flush gate construction and assembly process chart

3.3 Second Stage (Design of Experiment-Risk Identification)

This stage included some experimental works and field investigation to collect the failure mode for flush gate system during operation. The experimental works focused mainly on the effect of sediment profile change due to flushing effect. Sediment of open drains in Malaysia city such as Alor Setar, Butterworth, Ipoh, Kota Bahru, Johor Bahru has the sediment size, d_{50} in the range of 0.6 mm to 0.9 mm (Ab. Ghani, et al., 2000). Besides, according to Bong et al., (2016), sediment size at Kuching city, d_{50} was 0.62 mm; d_{mode} was 0.47 mm and d_{mean} was 1.81 mm. For sediment outside Kuching city, d_{50} was 1.03 mm, d_{mode} was 0.74 mm, d_{mean} was 2.32 mm. For sediment at Penang, $d_{50}$was 0.79 mm, d_{mode} was 0.52 mm, d_{mean} was 1.73 mm. The sediment was mainly non-cohesive, sand and gravel. In addition, Bong et al., (2014) stated that the sediment thickness for Penang and Kuching was in the range of 20 mm to 100 mm and 10 mm to 100 mm respectively. Thus, sediment d_{50} (0.71, 1.18 and 2 mm) was used and average sediment height for the sediment bed was set at 5.0 cm. On the other hand, the field testing was conducted to observe the performance of the flush gate at on-site condition.

3.3.1 Flushing Experiment in Flume

A flume with dimensions 6.0 m (L) × 0.6 m (W) × 0.39 (D) was used a series of experiments. The flush gate was installed at 2.2m from the inlet of the flume (see Figure 3.5). The series of experiment conducted determined the effect of variation of sediment size, sediment length and angle of opening of the gate on the sediment removal efficiency due to flushing.

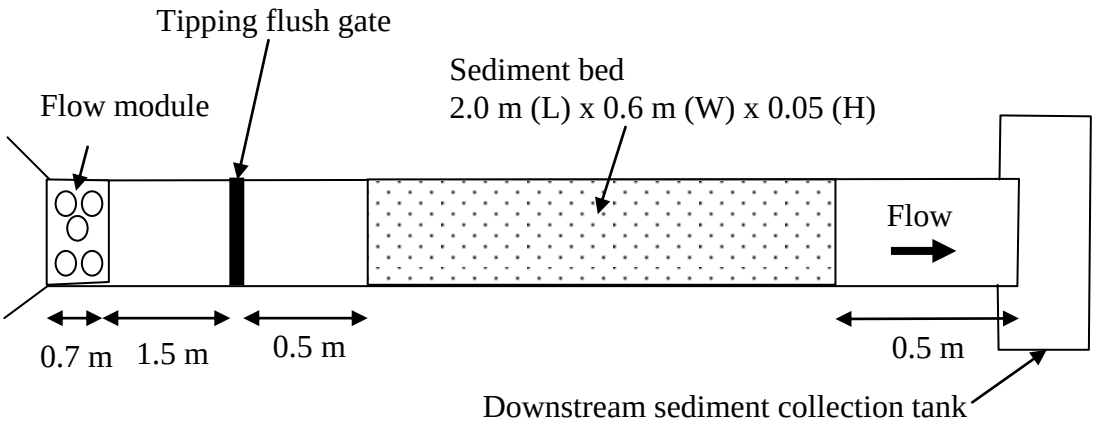


Figure 3.5: Plan view schematic of flushing experiment in flume (not to scale)

Flush Gate Operation Experiment

The flushing gate operation experiment was conducted to test the number of flushes before the tipping flushing gate failed to operate. The method used in this experiment was to determine the probability of failure (occurrence) via calculate the number of cycle of flushing. After the flush gate installation, pump was turned on and the upstream section of the channel behind the gate was filled up until the gate automatically open and flushing begins as shown in Figure 3.6. The number of cycle count started when the water level receded. The result was recorded for a flushing duration of 2.5 hours. The data collected helped to develop the scale table of occurrence (Occ).

Figure 3.6: Flush gate operation experiment

Initial Flushing Experiment (without Sediment Bed)

For initial flushing experiment, velocity of the flush waves during flushing operation was measured using an electromagnetic flow meter at the section (centre line, left and right) at the distance of 0.5 m, 0.75 m, 1.0 m, 1.25 m, 1.5 m, 1.75 m, 2.0 m , 2.25 m and 2.5 m from the gate. The time was set to every 2 seconds to capture the average flow velocity using Fixed Point Average (FPA) option in the flow meter. The reading was taken continuously during flushing operation. The flume slope was set to 0.0012.

Relationship of Sediment Bed Length and the Changes of Sediment Bed Profile for Sediment Size for Sediment D_{50}.

The purpose of this experiment was to determine the effect of the sediment bed length on the changes of the sediment profile. This experiment was designed to simulate closely the onsite condition. The experiment was conducted using three different d_{50} sizes of non-cohesive sediment (0.71 mm, 1.18 mm and 2 mm). Sediment bed length of 0.5 m, 1.0 m and 2.0 m were investigated. The experiment set up is showed in Figure 3.7. Short flush duration was fixed for this experiment. The sediment bed profiles were compared after 5, 10, 15, 20 and 25 flushing. After five cycles of flushing, the heights of sediment bed along the flume were measured at every 0.25 m interval and at every centerline with a ruler with accuracy of 0.5 mm. The total number of run for this experiment was 9 (3 different sediment sizes × 3 different lengths × 1 gate opening angle).

(a) (b)

Figure 3.7: Sediment bed set up for sediment bed length (a) 2 m and (b) 0.5 m

Relationship of Gate Opening Angle and the Changes of Sediment Bed Profile for Sediment Size for Sediment d_{50}.

The gate opening angles from vertical of 90°, 75°, and 60° with 5 cm thickness of sediment were tested in this experiment by adjusting the height of stopper bar at the gate frame. The sediment bed profiles were also being compared after 5, 10, 15, 20 and 25 flushing. The total number of run for this experiment was 9 (3 different sediment sizes × 1 length × 3 different gate opening angle). The angle of 90° and 75° were chosen as no literature was found from previous studies.

Figure 3.8: Gate opening angle of 90◦

Relationship of Flushing Duration and the Changes of Sediment Bed Profile for Sediment Size for Sediment d_{50}.

The purpose of this experiment was conducted to determine the effect of the flushing duration on the changes of the sediment profile. This experiment was designed to simulate closely the onsite conditions for short time flushing and long time flushing. Sediment d_{50} of 2 mm was used and average sediment height for the sediment bed was set at 5.0 cm. The sediment bed profiles were compared after 1.5 minutes, 3 minutes, 4.5 minutes, 6 minutes and 7.5 minutes.

Correlation and Regression Analysis

All the experiment data were then be analysed by correlation and linear regression analysis to evaluate the efficiency of sediment flushing. Before regression analysis was performed, the relationship between the parameters (number of flush, gate opening angle, flushing duration, sediment size) with the sediment flushing efficiency were checked by plotting a scatterplots with regression graph and by computing Pearson's correlation coefficient. The Pearson's correlation coefficient indicated the strength of the linear relationship between the parameters with the sediment flushing efficiency (refer to Table 3.1). The correlation was significant for calculated probability, p-value less than 0.05. The sample correlation r was computed as:

$$r = \frac{\sum_{i=1}^{n}(X_i-\bar{X})(Y_i-\bar{Y})}{\sqrt{\sum_{i=1}^{n}(X_i-\bar{X})\sum_{i=1}^{n}(Y_i-\bar{Y})}} \quad (3.1)$$

Where n is the number of observation; X_i and Y_i are the values of the i th observation and $\bar{X}$ and $\bar{Y}$ are the sample means.

Table 3.1: Interpretation of the size of a correlation coefficient

Size of correlation	Interpretation
0.9 to 1.0 (-0.9 to -1.0)	Very high positive (negative) correlation
0.7 to 0.9 (-0.7 to -0.9)	High positive (negative) correlation
0.5 to 0.7 (-0.5 to -0.7)	Moderate positive (negative) correlation
0.2 to 0.5 (-0.2 to -0.5)	Low positive (negative) correlation
0.0 to 0.2 (0.0 to -0.2)	Negligible correlation

Next, the data for significant parameters were further analysed using fit regression model to identify their relationship on the sediment flushing efficiency using ordinary least square method. Besides, linear regression calculated the equation to minimizes the distance between the fitted lined and all the data points and was in the form of

$$Y = \beta_0 + \beta_1 X_1 + \cdots + \beta_k X_k + \varepsilon \quad (3.2)$$

Where Y is the dependent variable/response; β_0 and β_1 are the regression coefficient; X is the independent variable (s); ε is the random error.

Besides, R-squared, R^2 was also evaluated to measure of how close the input data are to be fitted regression line. It was a coefficient of determination for multiple regressions. In general, the higher the R-squared, the better the model fitted the data. It can be explained by:-

R^2 = Explained variation/ Total variation (3.3)

3.3.2 Field Investigation

Environmental factors such as rainfall duration, rainfall intensity, drainage condition might give an impact to the tipping flush gate operation and affect the subsystem component. Thus, an extension work was done to find the potential failure mode of tipping flush gate for onsite operation, a section of open concrete drain located at Kolej Sakura, Universiti Malaysia Sarawak (UNIMAS), Kota Samarahan, Sarawak, Malaysia was chosen as shown in Figure 3.9. The monitoring period of the sediment tipping flush gate was two months, starting from 2nd March 2017 to 30th April 2017. The operation performance of flush gate with the corresponding rainfall events and the problems on-site were capture using digital camera. The rainfall precipitation data of JPS Samarahan Station were obtained from http://www.ihydro.did.sarawak.gov.my. The conditions of the gate were checked immediately after the rainfall event. Action plan was proposed and readily prepared before the next rainfall event start.

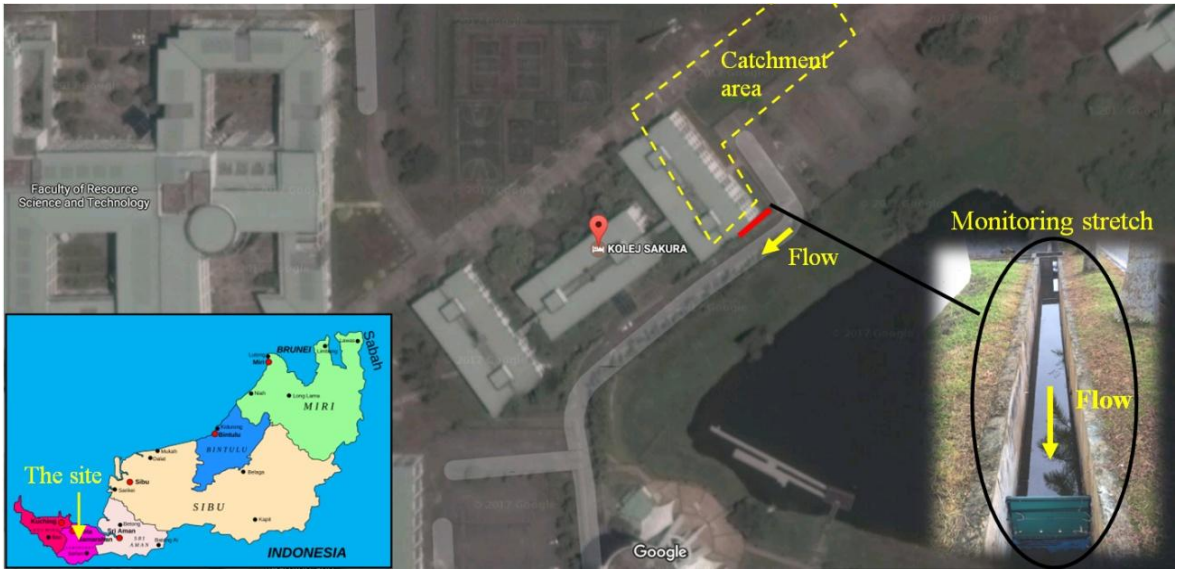


Figure 3.9: Site map of study area in Kolej Sakura UNIMAS, Kota Samarahan, Sarawak, Malaysia with the inset photo showing the sewer section for this study

3.3.3 Site Descriptions

The chosen sewer section was straight with no discontinuity. The total length of the chosen section for monitoring purposes was 40 m (the sewer section with open area) with the cross-section of rectangular drain being 0.6 m (width) × 0.8 m (depth). The catchment that drained into the chosen sewer section had an area of about 0.145 km^2 with a roughly 90% impervious area. The average slope for the sewer was 0.0012 m/m. The flushing gate was installed 12.5 m away after sump.

The storm sewer was cleaned before the installation of flush gate and trash trap. Besides, cleaning of sediment and trash behind the trash trap was done regularly to ensure smooth flushing operation. Monitoring of water level and sediment level were done using a measuring tape with an accuracy of ±0.2 mm throughout the monitoring period.

3.3.4 Sediment Sampling

The field sediment samplings were conducted to determine the physical characteristics of the sediment in the selected sewer. Sediment samples were collected during hot day when the flow in the storm sewer was minimum as shown in Figure 3.10. Eight points of samples were scooped from the surface to the bottom of the sediment across the sewer's cross-section at every 2.5 m interval in the chosen sewer section.

Figure 3.10: Collected sediment samples

3.3.5 Sieve Analysis

All the samples were subjected to oven drying for at least 24 hours at a temperature of 105°C – 110°C before sieve analysis. Impurities were removed after oven-dried. Then, sieve analysis was done according to BS 1377-2:1990: clause 9.2.3. The samples were mixed thoroughly and weighted for 1000g for sieving as shown in Figure 3.11. The sieves size used were 10 mm, 6.3 mm, 4.75 mm, 2.36 mm, 1.18 mm, 0.600 mm, 0.300 mm, 0.150 mm and 0.075 mm with a pan at the bottom. The sieves were vibrated mechanically for 10 minutes. The sediments particles retained on each of the sieve was weighted and recorded. Then, the accumulative grain size distribution curve was plotted according to the soil specification by BS 5930:1990.

Figure 3.11: 1000 g oven dried samples

(a) (b)

Figure 3.12: (a) Sieve analysis of samples (b) weighted sample retained in sieve

3.4 Third Stage (Collect and Combine Expert Judgment by Questionnaire and Discussion)

In order to conduct FMEA, a right team of subject matter experts must be formed. The team must have the expertise and knowledge in the hydraulic flush gate design to perform and execute the corresponding FMEA. The leader for the FMEA should be the design engineer (Stamatics, 2015). The team leader was the “expert” of the project to guide the team (Stamatics, 2015). Therefore, Dr Charles Bong Hin Joo was chosen as the expert in this study as he founded and designed tipping flush gate in year 2013. He is a researcher

under the research cluster Hydro-Environmental Engineering Research and Development (HERD). Furthermore, he research focuses on sedimentation mitigation in urban drainage and sediment transport. Besides Dr Charles Bong Hin Joo, another two researchers: Prof. Dr. Aminuddin Ab. Ghani (expert in sediment transport) and Dr. Jorg Schaffner (expert in Hydrass Gate design and hydraulic flushing) were invited to join this study. However, only both of them were not available during the period of study. Thus, only single expert model FMEA was applied in this study.

A questionnaire was prepared by the author to collect the data from the expert. The questionnaire consisted of two parts. The first part was prepared to collect the 125 fuzzy IF-THEN rules (refer to Appendix C) for the FIS_RPN model for flush gate system (refer Section 3.4.2). Besides, the second part of questionnaire was designed to survey the critical factors that might result in the failure of hydraulic flush gate in open drain. The outcomes of the survey contributed to the preventive measure, strategies and the guideline to avoid the failure mode on the system as stated in the FMEA table.

3.4.1 Scale Table Design

The scale tables were design based on the field history data and literature available for the tipping flush gate design and operation. The scale tables for each risk factor *Sev*, *Occ* and *Det* for the tipping flush gate designed. Each scale table was divided into three columns, i.e., Ranking, Linguistic Term, and Description. “Ranking” defined the score intervals for each *Sev*, *Occ*, and *Det*, respectively. These intervals were assigned with a definition, as in column “Linguistic Term”. A detailed description of each interval was summarized in the column “Description”. The lower and upper limits *Sev, Occ,* and *Det* were in the range of 1 to 10, respectively.

3.4.2 Fourth Stage (Construction of FIS_RPN Model)

Generally, a fuzzy expert model, i.e., interval FIS_RPN model was developed in this stage to compute the tipping flush gate design. There were several interface processes of fuzzy FMEA involved in the model, i.e. fuzzification and membership function design, fuzzy rules gathering, monotone rules checking and defuzzification as shown in Figure 3.13.

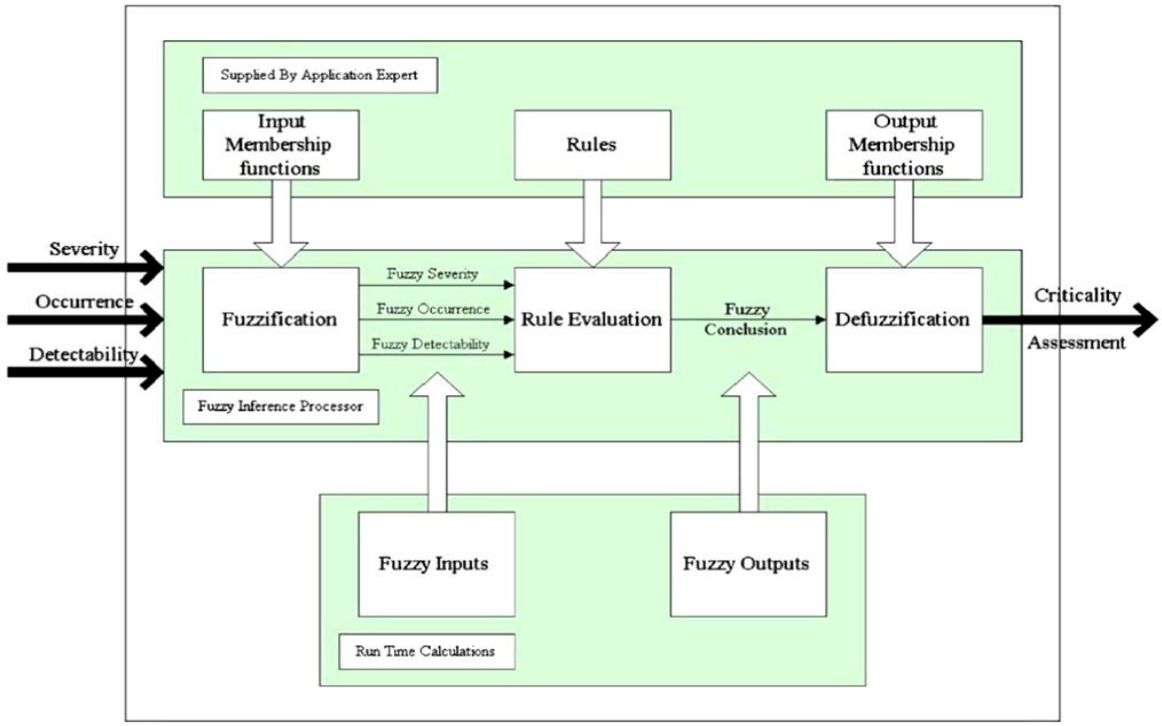


Figure 3.13: Overall view of the fuzzy critical assessment system (Chin et al., 2008)

3.4.3 Membership Function Design for *Sev, Occ* and *Det*

Fuzzification was a process of defining the membership function of input fuzzy set by converting the three risk factors, i.e. *Sev, Occ*, and *Det* rating into fuzzy input. The membership function of *Sev, Occ* and *Det* were designed in such a way that Condition 1 of Theorem 1 (refer to Section 2.4.2) was satisfied. The fuzzy membership function was then

be the input of the FIS_RPN model. The fuzzy RPN score for the FIS_RPN model was range from 1 to 1000. The fuzzy RPN's range was divided into five equal partitions, and each was then presented with a membership function after discussion with expert.

3.4.4 Fuzzy Rule Gathering

Fuzzy rule described the relationships between failure modes and effects in this analysis. For rule evaluation, the *Sev, Occ* and *Det* values of the failures were gathered with the help of expert opinions by using a database of 125 decision rule (refer Appendix C) determined specifically. Then, the gather expert's knowledge was arranged in fuzzy IF-Then format. For example,

If Severity is ***Remote***, Occurrence is ***Remote***, Detection is ***Very High***

then **FRPN** = **Remote**

3.4.5 Monotonicity Check

The collected rule from expert was check using monotonicity test to ensure the validity of a set of fuzzy rules in the monotonic FIS model. The surface plots for FRPN versus *Sev* and *Occ* with *Det* were generated to after FIS_RPN model for the tipping flush gate design. Monotonic surface were observed based on the result generated by Matlab simulation. When using the FIS_RPN model, the *Sev*, *Occ* and *Det* (inputs) and RPN (output) were represented by a membership functions, i.e. RPN=f^{RPN} *(Sev ,Occ*, *Det*). The relationships followed the monotonic relationship, i.e., when *Sev*, *Occ*, and/or *Det* increased then the RPN increased.

3.4.6 Defuzzification

Lastly, the fuzzy risk priority number for each failure mode of tipping flush gate component was then calculated by using the constructed FIS_RPN model which undergoes defuzzification process. Defuzzification was interpreting the membership degree of the fuzzy set into the FRPN value. The model for tipping flush gate design was constructed using Matlab simulation. According to the classical FIS_RPN model in Chapter 2, Equation 2.2 was found to fulfill the monotonicity property between *Sev, Occ* and *Det.*

3.5 Fifth Stage (Provide Management and Preventive Control Action) for Tipping Flush Gate Design

The FMEA tables for tipping flush gate design were presented in this stage. Each of the table consisted of column "Criterion", "Functions and descriptions", "Failure mode", "Cause", "Failure effect", "Failure detection", "*Sev*", "*Occ*" "*Det*", "FRPN" and "Recommendation actions". For the FIS_RPN model, failure risk evaluation and prioritization outcome were explained in the column "FRPN". The "recommendation actions" was included in the FMEA table to improve the design and reduce the impact of a failure mode of the tipping flush gate. By implementing the proposed actions, the potential failure cause can be eliminated and reduced completely.

CHAPTER 4

RESULTS AND DISCUSSIONS

4.1 Introduction

This chapter consists of three sections. Section 4.2 covers results from sediment flushing experiments that show the hydraulic characteristics of the flush gate and the effects of the variations of gate opening angle, sediment size, sediment bed length and duration of flushing. The experimental works on the sediment flushing for the current study were conducted using a flume with the dimensions 6.0 m (L) × 0.6 m (W) × 0.4 m (D) at the physical modeling laboratory, REDAC, USM. Uniform sand particles with d_{50} size of 0.71 mm, 1.18 mm and 2 mm were used for the experiments. The three sediment samples were subjected to one thickness (5 cm) with one flume slopes (0.0012) making altogether 20 runs. In addition, the on-site monitoring results of the operation of tipping flush gate at the rectangular drain in UNIMAS were also presented in this chapter. Then, experimental results and field observations were then be used for FMEA. A FMEA procedure with the interval FIS_RPN model was applied to tipping flush gate design at assembly stage and flush gate system onsite installation. The results were obtained from MATLAB (matrix laboratory) (2015). An extension work on constructing a bigger flushing gate with a size of 1.5 m (W) x 1.0 m (D) was also presented at the last section. The aim of this chapter is to evaluate the risk associated at the tipping flush gate design.

4.2 Flushing Experiment without Sediment Bed

A series of experiment were conducted to determine the flush characteristics produced by the flush gate for short duration flushing with varying gate opening angle. The flow velocities were measured at three sections (center, left, right) of the flume at distance of -0.25 m (upstream), 0.5 m, 0.75 m, 1.0 m, 1.25 m, 1.5 m, 1.75 m, 2.0 m, 2.25 m and 2.5 m from the gate during each flush. Figure 4.1 shows the comparison of flow velocity variation of gate opening angle θ of 60°, 75° and 90° from vertical axis. The gate with bigger opening angle shows higher flow velocity with more water volume flushed during gate operation. Figure 4.1 shows that there were drop of the mean flow velocity at 0.75 m and 1.0 m for gate opening of 75° and 90° respectively. This happened due to hydraulic jump occur when the gate opened. The transition of flow generates the flush wave, converting some flow's initial kinetic energy to potential energy. Some energy irreversibly lost through turbulence during the flow impact on the channel causing the reduction in velocity.

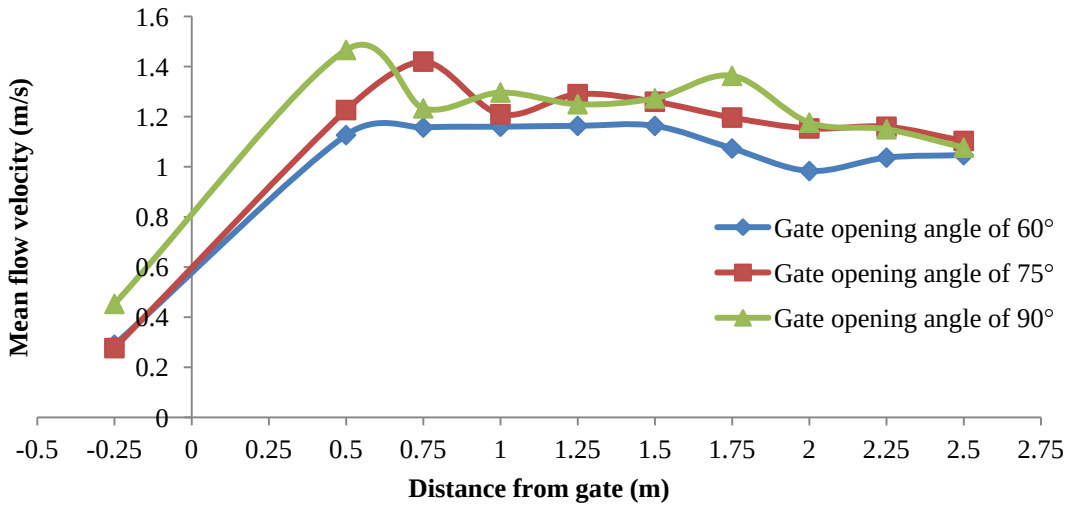
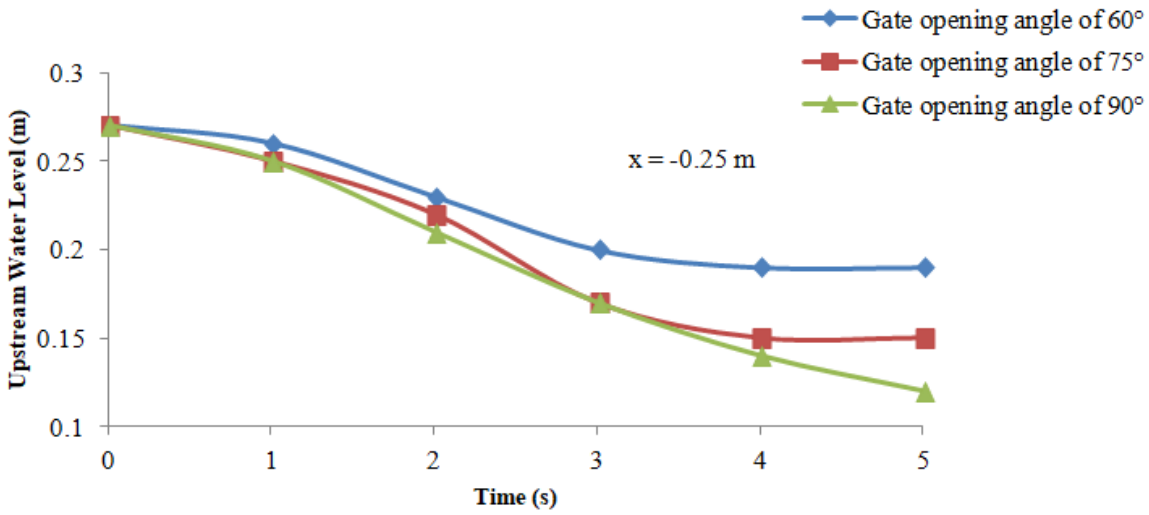
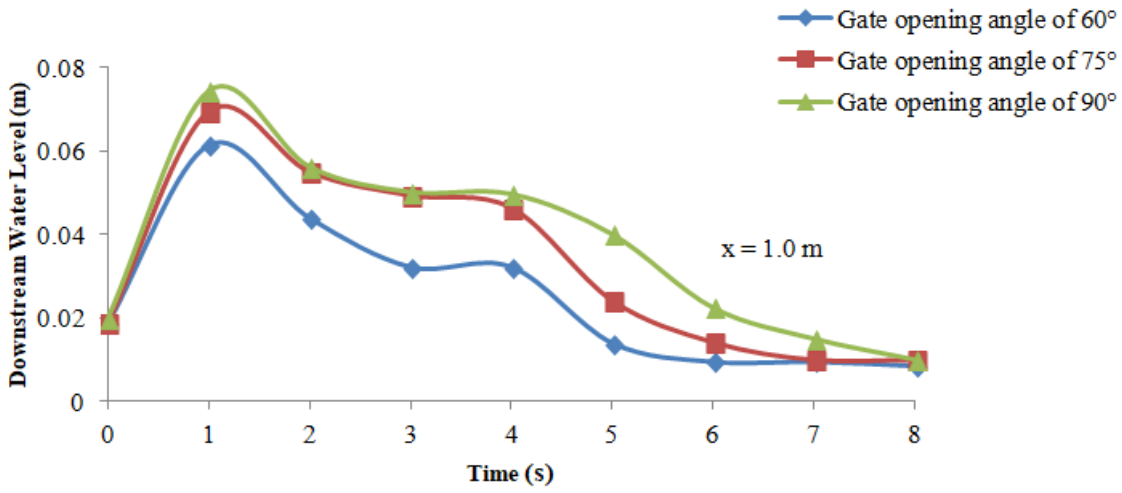


Figure 4.1: Mean flow velocity for θ = 60°

Besides, the variations of water level at 0.25 m upstream of the gate and also at 1 m downstream of the gate were also recorded as shown in Figure 4.2 (a) and (b) respectively for gate opening angle θ of 60°, 75° and 90°. Highest water level was found at 1 m downstream during flushing. Thus, the benchmark for comparison was set at 1 m downstream.



(a)



(b)

Figure 4.2: Water level variations for θ = 60°, 75° and 90°: (a) at 0.25 m upstream of gate; (b) at 1 m downstream of the gate

From the variations of water level, the effects of gate opening angle on the closing water level and the volume of flush can be observed clearly. Figure 4.2 shows the variation of water level at 0.25 m upstream and 1 m downstream of the gate during flushing. For gate opening angle θ = 60°, the gate opened when the upstream water level was at 0.27 m at 0 s (Figure 4.2 (a)). After the gate opened, the water level reduced to 0.19 m when the gate closed. In Figure 4.2 (b), at 1 m downstream of the gate, it took approximately 1 s for the flush to reach this distance. Thus the water level at this point had a sudden peak after 1 s at 0.0615 m. Reaching 4 seconds, the gate had closed and the water level continued to recede until 7 s when the water level maintained at 0.01 m.

For gate opening angle, θ of 75°, the gate also opened at 0.27 m but it closed at 0.15 m at the 4 s. At 1.0 m downstream of the gate, it also took approximately 1 s to reach this distance. Therefore, the water level at this point had a sudden surge after 1 s with 0.0695 m. By 4 s, the gate had closed and the water level continued to recede until 7 s when the water level started to maintain at 0.01 m.

As for gate opening angle, θ of 90°, the gate opened for longer duration which was about 5 s. The gate still opened at the designed water level of 0.27 m but it closed at 0.12 m (refer to Figure 4.2 (a)). At 1.0 m downstream of the gate, it took approximately 1 s for the flush to reach this distance and having a peak flow at 0.743 m (refer to Figure 4.2 (b)). By 5 s, the gate had closed and the water level continued to reduce until at 8 s when the water level started to maintain at 0.01 m.

Table 4.1 summarizes the flush gate characteristics during flushing operation. The gate was designed to open at the same water level (0.27 m). The different of gate opening angle resulted in different water levels when closing. The volume of water flushed was

calculated by multiplying the difference of the water levels between opening and closing with the flume width (0.6 m) and the length of upstream of the gate (2.2 m) which was the storage area behind the gate (refer Figure 3.11). To conclude, for bigger gate opening angle with longer flushing duration, it allowed more volume of water to be discharged during flushing with higher downstream water level and higher flow velocity.

Table 4.1: Flush gate characteristics during flushing

Gate opening angle, θ (°)	Water level during operation (m)		Gate opening duration (s)	Volume of water during flushing (m^3)	Maximum water level at 1 m downstream during flushing (m)	Velocity at 1 m downstream during flushing (m/s)
	Open	Close				
60	0.27	0.19	3.85	0.1056	0.0615	1.127
75	0.27	0.15	4.02	0.1584	0.0695	1.153
90	0.27	0.12	5.02	0.1980	0.0743	1.272

4.3 Sediment Flushing Experiment

The risk identification stage for tipping flush gate system in sediment removal involved both experiment (quantitative) and on-site data (qualitative) collection. The experimental works showed the relationships of number of flush n, gate opening angle θ, sediment size d_{50}, sediment bed length, l_s and flushing duration, t_f on the changes of sediment bed profile during flushing operation. The efficiency of the flush gate system was evaluated based on the percentage of total volume of sediment removal after the flush.

Firstly, the relationship of the gate opening angle on the changes of sediment bed profile after flushing operation is presented. The gate opening angle was measured from the vertical axis. Figure 4.3 to Figure 4.5 show the variations of the sediment bed profiles after flushes for sediment d_{50} size of 0.71 mm with θ = 90°, 75° and 60° for the initial sediment deposition thickness of 5 cm laid starting from 0.5 m downstream of the gate. The total volume of flush through the gate was not the same. The sediment bed volume decreased after each flush as the number of flush increased as shown in Table 4.2. Based on the table, there was a total of 81.5 % to 99.75% sediment volume reduction after 25th flush.

The gate opening angle of 90° showed the best flushing efficiency as the sediment was almost flushed off totally at 25th flush. For all cases, the flushing effect start to decrease significantly at 2.00 m downstream from the gate as sediment profiles were observed nearly the same after 20 flush. The experiments were repeated using sediment d_{50} size of 1.18 mm and 2 mm, which were found to show the similar trend (refer Appendix B, Figure B.1 to Figure B.6). The experiment data were compiled in Appendix B1. Overall, the results show a general trend that as the number of flush increased, the more sediment can be flushed off effectively; bigger gate opening angle provided higher flushing efficiency to remove sediment deposited. However, the flushing efficiency decreased as the sediment size increased.

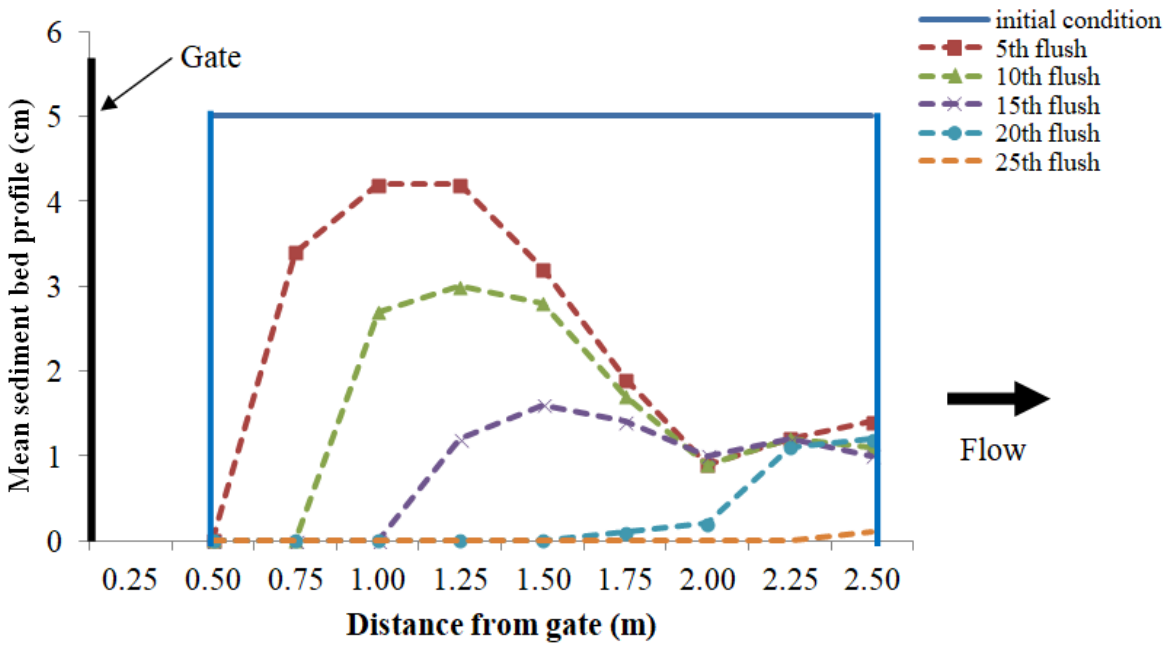


Figure 4.3: Sediment profiles for sediment d_{50} of 0.71 mm laid starting from 0.5 m from the gate with θ = 90° after flushes for 5 cm initial sediment deposition thickness

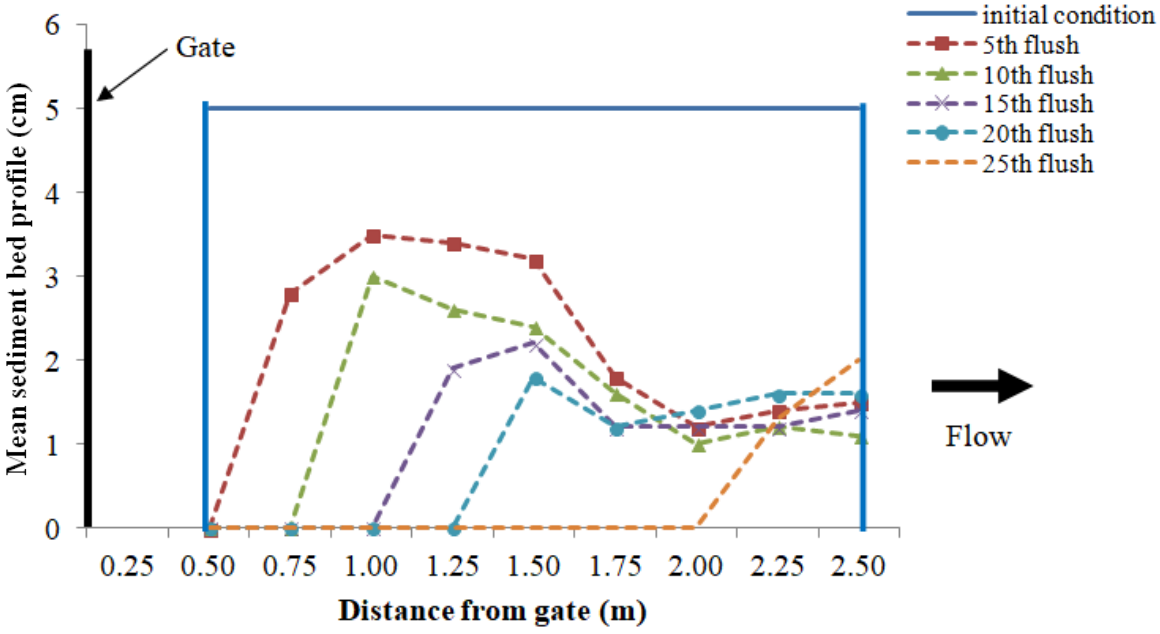


Figure 4.4: Sediment profiles for sediment d_{50} of 0.71 mm laid starting from 0.5 m from the gate with θ = 75° after flushes for 5 cm initial sediment deposition thickness

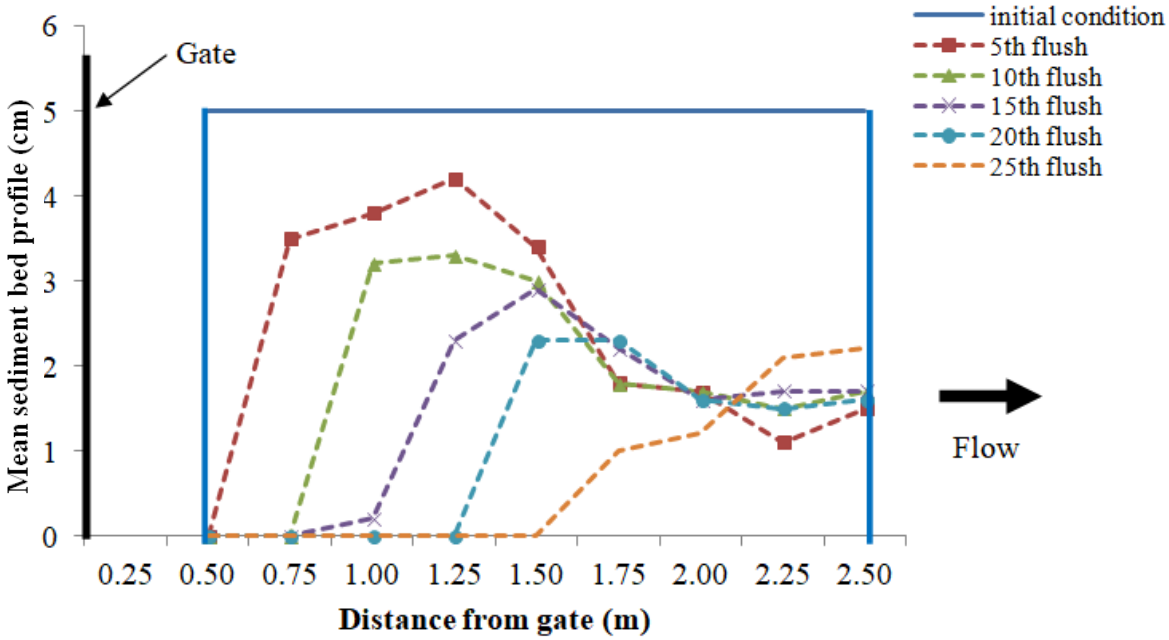


Figure 4.5: Sediment profiles for sediment d_{50} of 0.71 mm laid starting from 0.5 m from the gate with $\theta = 60°$ after flushes for 5 cm initial sediment deposition thickness

Table 4.2: Flush gate characteristics during flushing

No. of Flush	Gate Opening Angle (deg)	Sediment Size (mm)	Volume of Sediment Left After Flushing Operation (m^3)	Percentage of Sediment Volume Reduction after 25 flush (%)
0	90	0.71	0.060	99.75
5	90	0.71	0.031	
10	90	0.71	0.020	
15	90	0.71	0.011	
20	90	0.71	0.004	
25	90	0.71	0.000	
0	75	0.71	0.060	91.75
5	75	0.71	0.028	
10	75	0.71	0.019	
15	75	0.71	0.014	
20	75	0.71	0.011	
25	75	0.71	0.005	
0	50	0.71	0.060	81.50
5	50	0.71	0.031	
10	50	0.71	0.024	
15	50	0.71	0.019	
20	50	0.71	0.014	
25	50	0.71	0.011	

Secondly, the effects of the sediment bed length on sediment flushing using the tipping flush gate were determined using another set of experiments. The data for the sediment bed length flushing are as tabulated in Appendix B2. Figure 4.6 to Figure 4.8 show the variations of the sediment bed profiles after flushes for sediment with d_{50} size of 2 mm with θ = 60° for 5 cm deposition thickness laid starting from 0.5 m to 1.0 m; 0.5 m to 1.5 m; and 0.5 m to 2.5 m downstream of the gate. Gate opening angle, θ of 60° was used in this experiment as the gate can operate smoothly without the use of additional spring. With the sediment bed length of 0.5 m (sediment bed from 0.5 m to 1.0 m), the scouring process was observed significantly that the sediment was removed totally at 25^{th} flush. Overall, the results showed the tipping flush gate had a very good flushing performance in terms of removing shorter sediment bed length. More number of flush needed to be performed to remove longer sediment bed length. Similar trend of sediment bed profiles was observed by repeating the experiment using sediment with d_{50} size of 1.18 mm and 0.71 mm (refer to Appendix B, Figure B.7 to Figure B.12). Besides, the results also showed that the flushing efficiency increased as the sediment size decreased.

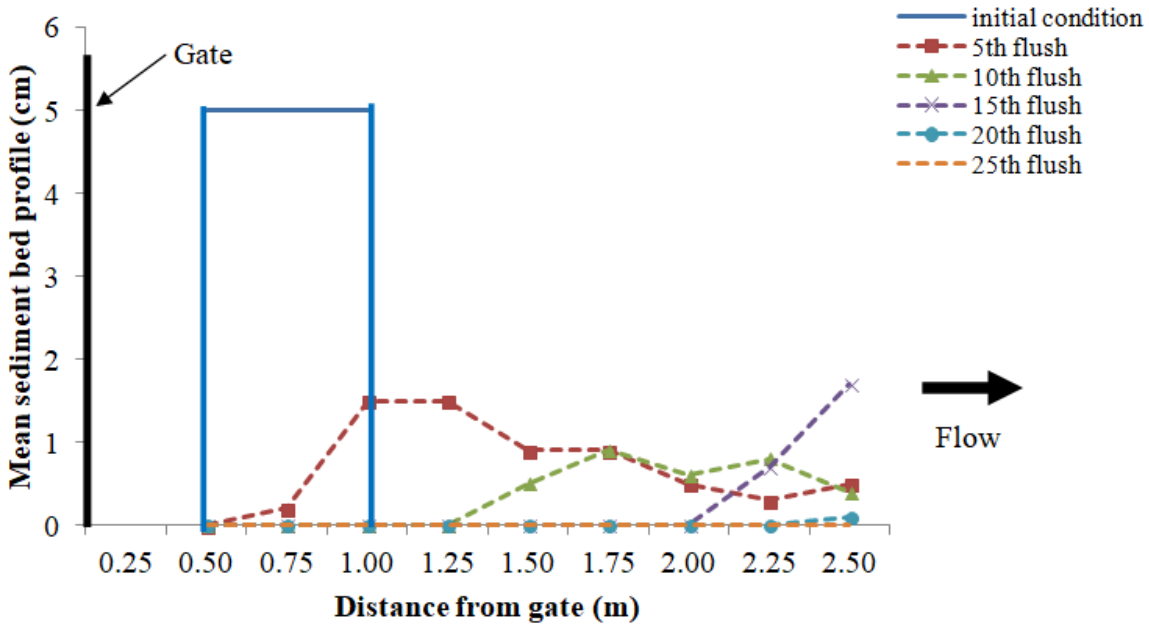


Figure 4.6: Sediment profiles for sediment d_{50} of 2 mm laid starting from 0.5 m to 1.0 m from the gate with $\theta = 60°$ after flushes for 5 cm initial sediment deposition thickness

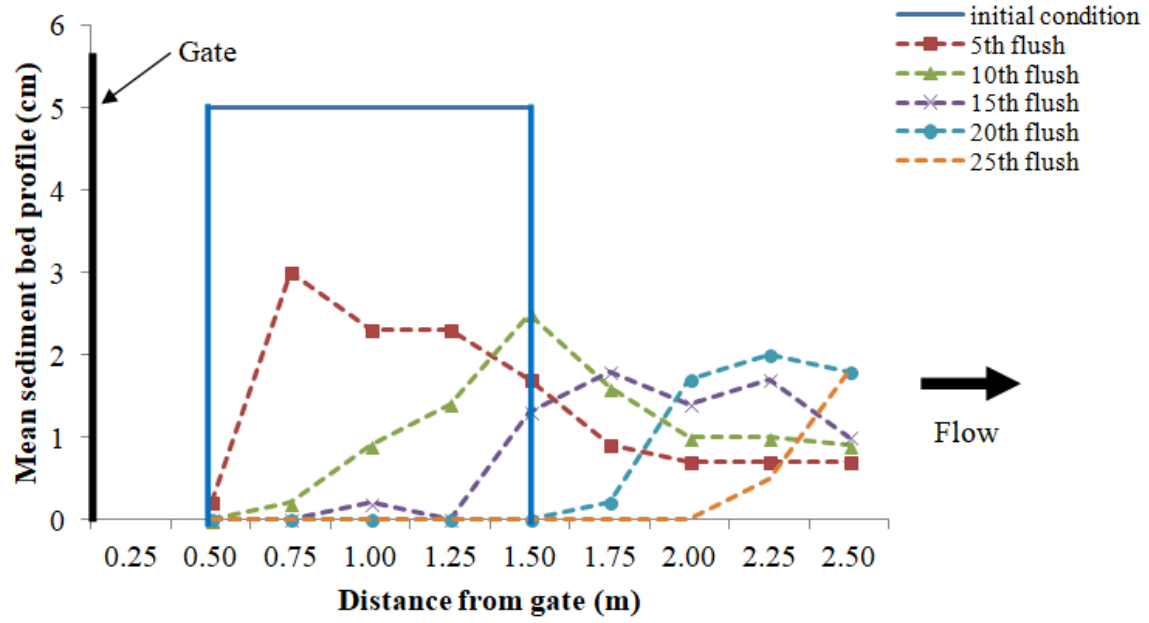


Figure 4.7: Sediment profiles for sediment d_{50} of 2 mm laid starting from 0.5 m to 1.5 m from the gate with $\theta = 60°$ after flushes for 5 cm initial sediment deposition thickness

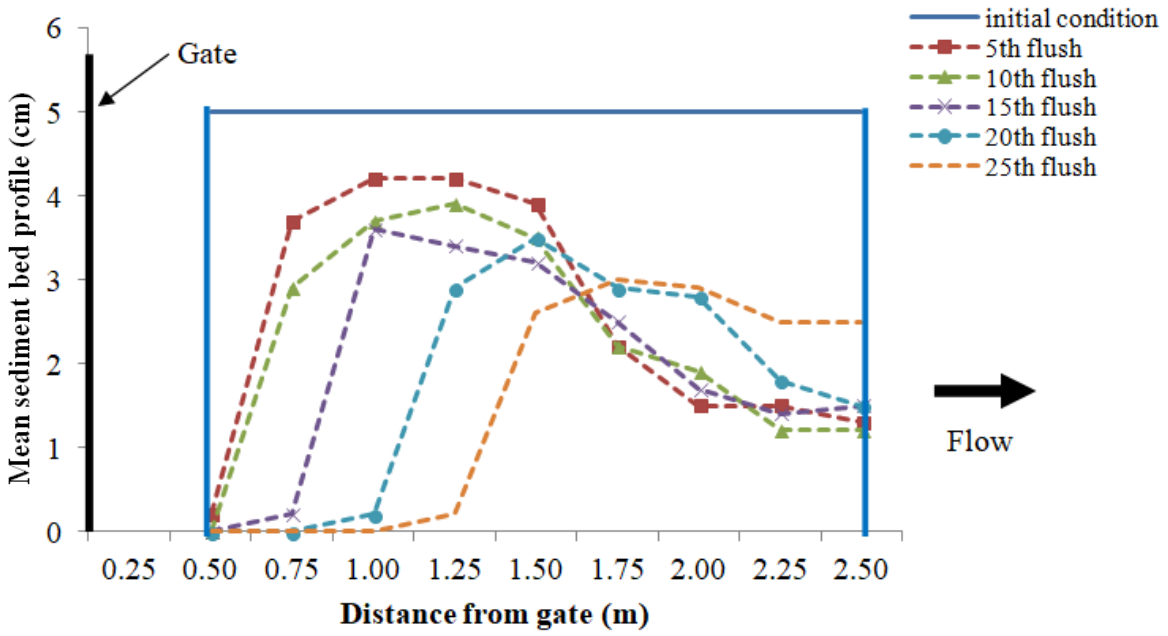


Figure 4.8: Sediment profiles for sediment d_{50} of 2 mm laid starting from 0.5 m to 2.5 m from the gate with $\theta = 60°$ after flushes for 5 cm initial sediment deposition thickness

Lastly, the effects of the flushing duration on the changes of the sediment profile were investigated by only using sediment d_{50} of 2 mm to observe longer effects of flushing duration as compared to sediment d_{50} of 0.71 mm and 1.18 mm. The experiments were conducted up to 7.5 minutes of flushing operation. Figure 4.9 shows the mean flow velocity for long and short flush. The flow velocity was maintained uniformly throughout the short flush. In addition, the flushing velocity at short flush was higher than the velocity during long flush, causing more scouring effect on sediment. In addition, the sediment particles did not have enough time to settle down for short flush operation due to the sudden flow and frequent flush. Figure 4.10 and Figure 4.11 show the changes of the sediment bed profiles for long flush and short flush respectively. Figure 4.11 shows that the 2 mm can be totally removed after 7.5 minutes of flush. Thus, short flushing operation was having a better efficiency as compared to long flush.

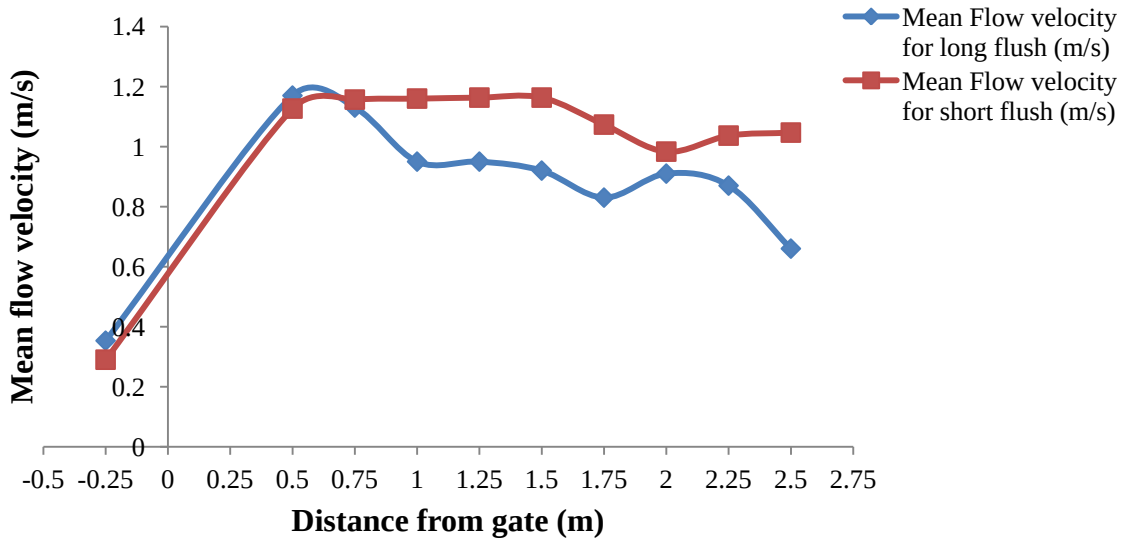


Figure 4.9: Mean flow velocity for long flush and short at $\theta = 60°$

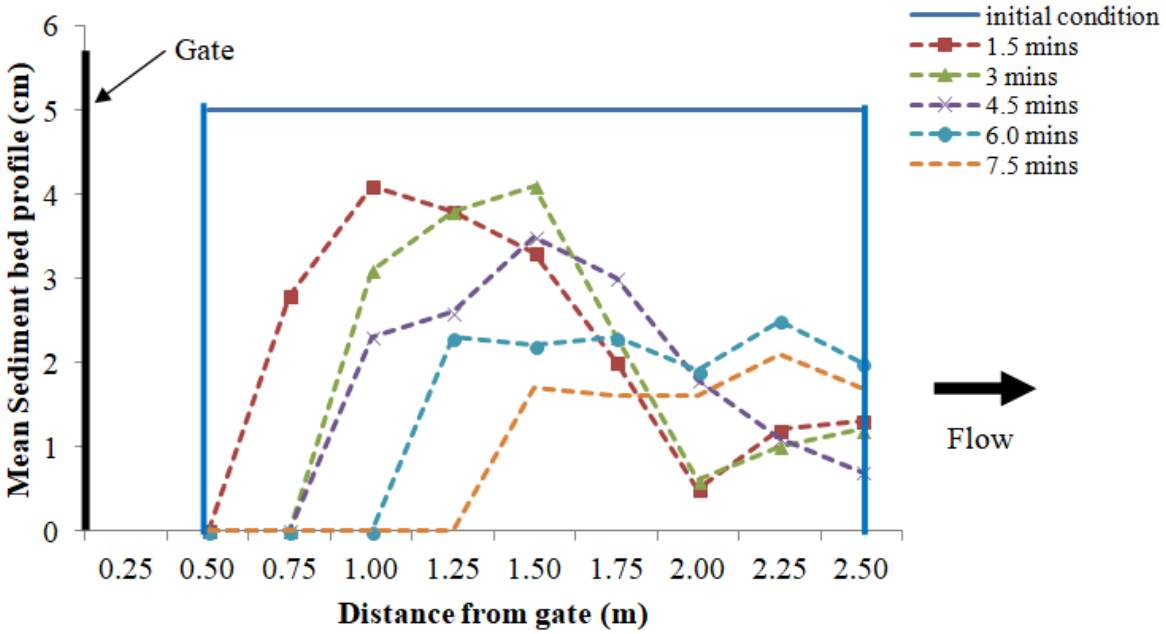


Figure 4.10: Sediment profiles for sediment d_{50} of 2 mm laid starting from 0.5 m from the gate with $\theta = 60°$ after flushes for 5 cm initial sediment deposition thickness for long flush operation

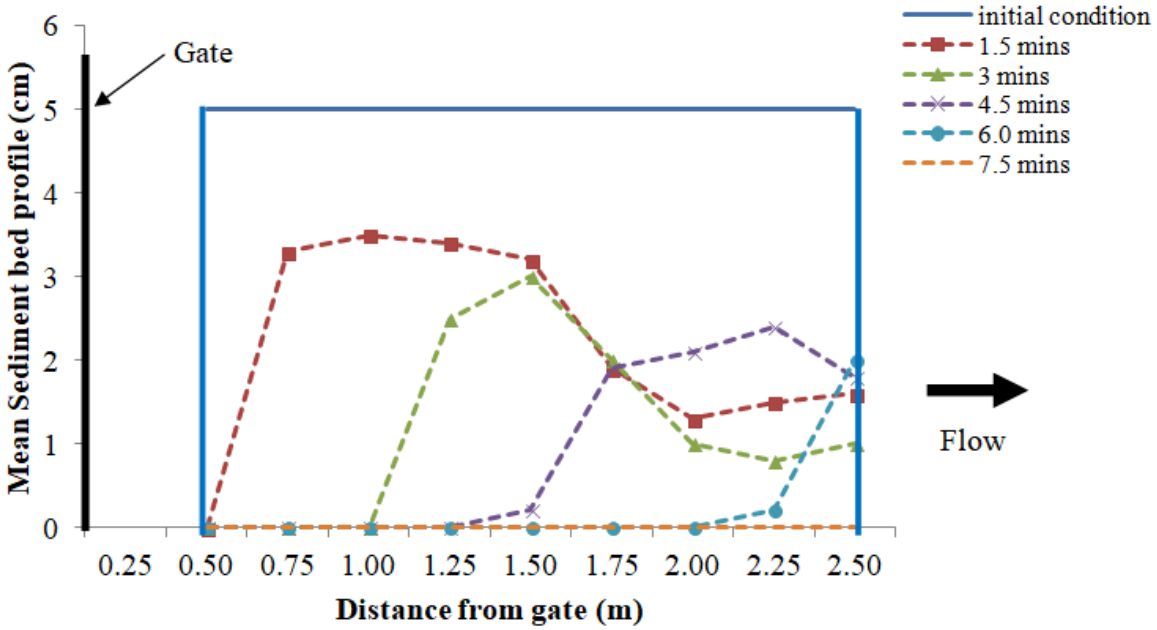


Figure 4.11: Sediment profiles for sediment d_{50} of 2 mm laid starting from 0.5 m from the gate with θ = 60° after flushes for 5 cm initial sediment deposition thickness for short flush operation (more frequent flush)

4.3.1 Correlation and Regression Analysis

A correlation analysis was performed to investigate the strength of the relationships between sediment flushing efficiency with the variables, i.e., number of flush n, gate opening angle θ, sediment bed length l_s, sediment size, d_{50} and flushing duration t_f. The correlation analysis was performed using Minitab software. The information on with number of flush n, gate opening angle θ, sediment bed length l_s, sediment size, d_{50} and flushing duration t_f were obtained from the experiment data in Sections 4.3.1 or refer to Table 4.3. The results of correlation analysis were calculated and summarized in Table 4.4.

The Pearson correlation, between sediment flushing efficiency and number of flush was about 0.478 (p-value = 0.000) which indicated that there was a moderate positive relationship between the variables. The p-value was less than 0.05, thus the correlation is statistically significant. The experimental results had proven that the more flush cycles can

remove the sediment more effectively. Besides, the flushing duration also had a positive moderation correlation (r = 0.594; p-value = 0.00) with the sediment flushing efficiency. This showed that the short flush with longer flushing duration produced more frequent flush and enhanced the flushing efficiency. However, the sediment bed length had a negative weak correlation with the sediment flushing efficiency. The total volume of sediment removed reduced when the longer the sediment bed being laid on the flume. On the other hand, sediment flushing efficiency had no correlation with gate opening angle θ, (r = 0.064; p-value = 0.606) and sediment size, d_{50} (r = -0.122; p-value = 0.327). This showed that the small changes on the gate opening angle and sediment size did not influence much on sediment flushing efficiency as compared to number of flush, flushing duration and sediment bed length.

Using multiple linear regressions, an equation relating the evaluation of flushing gate efficiency, η_e in removing sediment bed length l_s, with a number of flush, n within a flushing duration t_f was developed for the current study and as shown in Equation 4.1. Equation 4.1 has a R^2 value of 74.17%.

$$\eta_e = 84.29 + 0.805n + 6.868t_f - 22.38l_s \quad (4.1)$$

Table 4.3: Compiled data for sediment flushing experiment

No. of Flush	Duration of flushing (mins)	Sediment bed length (m)	Gate opening angle (deg)	Sediment size (mm)	Sediment flushing efficiency (%)
5	0.917	2.0	90	2.00	47.75
10	1.750	2.0	90	2.00	57.13
15	2.583	2.0	90	2.00	71.50
20	3.417	2.0	90	2.00	83.13
25	4.250	2.0	90	2.00	96.50
5	0.846	2.0	75	2.00	47.00
10	1.679	2.0	75	2.00	55.13

Table 4.3 continued

No. of Flush	Duration of flushing (mins)	Sediment bed length (m)	Gate opening angle (deg)	Sediment size (mm)	Sediment flushing efficiency (%)
15	2.513	2.0	75	2.00	64.13
20	3.333	2.0	75	2.00	72.13
25	4.179	2.0	75	2.00	82.88
5	0.833	2.0	60	2.00	45.13
10	1.667	2.0	60	2.00	50.25
15	2.500	2.0	60	2.00	58.13
20	3.333	2.0	60	2.00	62.88
25	4.167	2.0	60	2.00	68.88
5	0.833	2.0	90	1.18	48.75
10	1.667	2.0	90	1.18	65.25
15	2.500	2.0	90	1.18	77.38
20	3.333	2.0	90	1.18	90.50
25	4.167	2.0	90	1.18	99.88
5	0.846	2.0	75	1.18	49.50
10	1.679	2.0	75	1.18	54.25
15	2.513	2.0	75	1.18	67.38
20	3.333	2.0	75	1.18	75.38
25	4.179	2.0	75	1.18	81.38
5	0.833	2.0	60	1.18	45.88
10	1.667	2.0	60	1.18	52.88
15	2.500	2.0	60	1.18	61.25
20	3.333	2.0	60	1.18	64.38
25	4.167	2.0	60	1.18	75.25
5	0.833	2.0	90	0.71	50.75
10	1.667	2.0	90	0.71	67.88
15	2.500	2.0	90	0.71	82.75
20	3.333	2.0	90	0.71	95.00
25	4.167	2.0	90	0.71	99.88
5	0.846	2.0	75	0.71	54.88
10	1.679	2.0	75	0.71	69.13
15	2.513	2.0	75	0.71	79.00
20	3.333	2.0	75	0.71	83.00
25	4.179	2.0	75	0.71	94.25
5	0.833	2.0	60	0.71	49.38
10	1.667	2.0	60	0.71	61.63
15	2.500	2.0	60	0.71	70.63

Table 4.3 continued

No. of Flush	Duration of flushing (mins)	Sediment bed length (m)	Gate opening angle (deg)	Sediment size (mm)	Sediment flushing efficiency (%)
20	3.333	2.0	60	0.71	78.75
25	4.167	2.0	60	0.71	86.50
5	0.833	0.5	60	2.00	90.50
5	0.833	1.0	60	2.00	57.25
10	1.667	1.0	60	2.00	81.25
15	2.500	1.0	60	2.00	92.25
5	0.833	0.5	60	1.18	94.00
5	0.833	1.0	60	1.18	56.50
10	1.667	1.0	60	1.18	70.00
15	2.500	1.0	60	1.18	96.00
5	0.833	0.5	60	0.71	94.50
5	0.833	1.0	60	0.71	60.00
10	1.667	1.0	60	0.71	77.50
15	2.500	1.0	60	0.71	96.25
1	1.500	2.0	60	2.00	61.77
1	3.000	2.0	60	2.00	67.71
1	4.500	2.0	60	2.00	69.48
1	6.000	2.0	60	2.00	74.58
1	7.500	2.0	60	2.00	83.65
9	1.500	2.0	60	2.00	52.75
9	3.000	2.0	60	2.00	75.50
9	4.500	2.0	60	2.00	81.25
9	6.000	2.0	60	2.00	97.00
9	7.500	2.0	60	2.00	100.00

Table 4.4: Correlation analysis on the factor affecting the sediment flushing efficiency

Factor	Sediment flushing efficiency (%)
No of flush, n	0.478 (p-value = 0.000)
Gate opening angle, θ	0.064 (p-value = 0.606)
Sediment bed length, l_s	- 0.279 (p-value = 0.022)
Sediment size, d_{50}	-0.122 (p-value = 0.327)
Flushing duration, t_f	0.594 (p-value = 0.000)

4.4 Tipping Flush Gate Monitoring On-Site

A field work was conducted to obtain more qualitative information for the tipping flush gate. This section included the data and information collected from the field work during daytime. The characteristics of the sediment accumulated in the sewer were investigated. Furthermore, the relationships between precipitation and flushing operation were study. Site monitoring of tipping flush gate provided basis information needed to develop a guideline for the design. Better design of tipping flush gate system was proposed with a better understanding of the potential failure cause of flush gate performance on-site.

4.4.1 Sedimentation Characteristics On-Site and Sieve Analysis Result

Sediment samplings from the site had provided understanding in terms of the sediment physical characteristics and sediment sizes. Table 4.5 shows the results from sieve analysis in the determination of sediment size distribution. 1000 g of sample was used for each sieve. The accumulative grain size distribution curve from the sieve analysis was plotted according to the soil specification by BS 5930:1990 as shown in Figure 4.12.

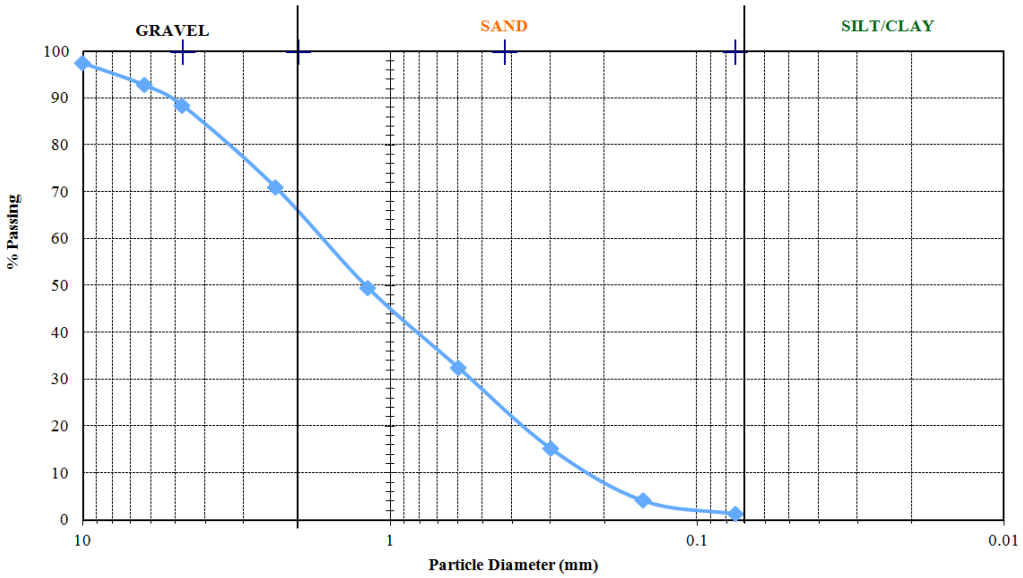


Figure 4.12: Sediment size distributions for the selected open storm sewer

Table 4.5: Sieve analysis result for the sewer sediment

Sieve Size (mm)	Weight of Sediment Retained (g)				Percent Retaining (%)	Cumulative Percent Retained (%)	Percent Passing (%)
	Test 1	Test 2	Test 3	Average			
10	21	30	24	25.00	2.50	2.50	97.50
6.3	54	39	48	47.00	4.70	7.20	92.80
4.75	43	40	46	43.00	4.30	11.51	88.49
2.36	184	170	171	175.00	17.51	29.02	70.98
1.18	212	202	229	214.33	21.45	50.47	49.53
0.600	155	195	159	169.67	16.98	67.44	32.56
0.300	175	170	173	172.67	17.28	84.72	15.28
0.150	113	112	109	111.33	11.14	95.86	4.14
0.075	29	28	28	28.33	2.84	98.70	1.30
Pan	13	14	12	13.00	1.30	100.00	0.00
Total	999	1000	999	999.33	100		

Results from the sediment sampling had shown that the grain sizes of the sediment sample were d_{50}= 1.3 mm, d_{10}= 0.24 mm, d_{30}= 0.55 mm and d_{60}= 1.8 mm. Besides, the sediment also had the following physical characteristics: geometric standard deviation σ_g= 3.65, uniformity coefficient, C_u= 7.5 and coefficient of gradation, C_k= 0.70. Thus, the sediment sample was categorized as well-graded gravelly sand with predominantly sand at 64.7%, gravel at 34%, and silt and clay at 1.3%.

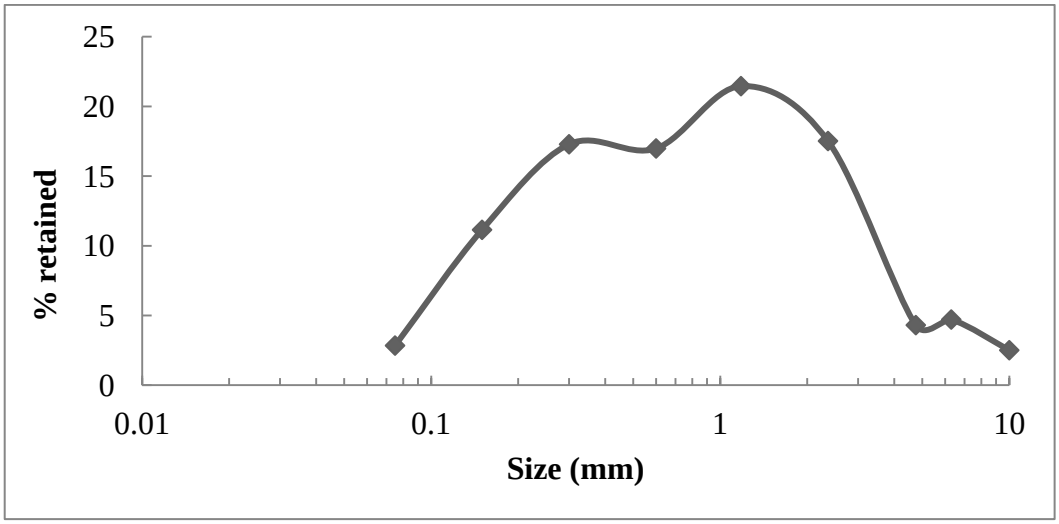


Figure 4.13: Unimodal sediment distributions for sample from site

The unimodal samples had the tendency to skew to the right as shown in Figure 4.13. The results showed that the sample was similar to sediment samples of surrounding towns outside the Kuching City as the sand component ranged from 43.9% to 96.9%, gravel constituents 3% to 56 % and silt and clay constituents from 0.1 % to 2.4 % (Bong et al., 2016). The sediment samples collected were mainly inorganic and non-cohesive. The sediments were categorized as Type A according to the categories proposed by Crabtree (1989) which the sediments deposited were coarse, loose, granular, predominantly mineral and material.

4.4.2 Tipping Flush Gate Operation Performances

Flushing operations of the tipping flush gate only performed during rainfall events. The tipping flush gate operated for 15 rainfall events during the monitoring period with the durations of flushing (gate opening) ranging from 10 minutes to 79 minutes before the gate automatically closed (refer Table 4.6). The rainfall precipitation data were obtained from http://www.ihydro.did.sarawak.gov.my.

Table 4.6: Gate operations with the corresponding rainfall duration and precipitation

Date	Rainfall time (hr)	Rainfall duration (min)	Operation performance during rainfall	Rainfall precipitation (mm)	Rainfall intensity (mm/hr)
12/3/17	11:37-12:56	79	Gate cannot close, leafs caught at the gate. Operate well after immediate cleaning on site.	42	31.90
14/3/17	18:15-18:42	27	Gate open partially, leafs caught at the gate	38	84.44
2/4/17	18:05-18:27	22	Operate well, consistently open and close	29	79.09
4/4/17	16:10-16:24	14	Gate cannot close, leafs caught at the gate. Operate well after immediate cleaning on site.	11	47.14
6/4/17	16:07-16:17	10	Gate operate well, consistently open and close	N/A	N/A
6/4/17	16:55-17:05	10	Gate keep open due to heavy rain, water level higher than 0.28 m.	16	96.00
13/4/17	12:07-12:29	22	Gate cannot close. Trash trap burst, causing leafs caught at the gate. Operate well after immediate cleaning on site.	N/A	N/A
16/4/17	13:23-14:17	54	Operate partially, gate can open but partially close, flow rate of water was affected by trash trap.	18	20.00
21/4/17	13:00-13:39	39	Operate well, consistently open and close	44	67.69
22/4/17	14:15-14:36	21	Operate well, consistently open and close	N/A	N/A
23/4/17	14:00-14:30	30	Operate well, consistently open and close	14	28

Table 4.6 continued

Date	Rainfall time (hr)	Rainfall duration (min)	Operation performance during rainfall	Rainfall precipitation (mm)	Rainfall intensity (mm/hr)
24/4/17	14:45-15:33	48	Operate well, consistently open and close	N/A	N/A
27/4/17	16:20-16:42	22	Operate well, consistently open and close	44	120
28/4/17	17:15-1730	15	Operate well, however the trash trap break	31	124
29/4/17	16:55-1720	25	Operate well, consistently open and close	29	69.60
Average rainfall intensity (mm/hr)		63.99			

Based on the field observations, the flushing gate opened when the rainfall intensity was more than 20 mm/hr for 54 min rainfall event. The gate still operated although there was some water leaking through the gate frame. Besides, the leaf-gate opened partially when the flow was affected by rubbish on trash trap. Sometimes, the water builds up too slow and affects the flushing performance. On the other hand, the flushing gate was performed well when the rainfall was more than 40 mm/hr because the water was stored behind the gate at a consistence rate and built up to the desired water level, i.e., 27 cm in height.

4.4.3 Problems on Site Operation

There were some problems detected during the flushing operations during the field monitoring period. The problems vary with the scenario and condition on site.

a) Scenario 1: Tipping flush gate system without trash trap

Scenario 1 happened after the first installation (3rd March 2017) of the gate at the selected open drain. One of the major problems found was that the leaf-gate cannot be closed tightly after one cycle of flushing operation (close, open and close). This failure caused the system failed to operate because water cannot be stored behind the gate. Flushing operation cannot be performed. There were several factors causing this failure mode and some actions were proposed to overcome the failure as listed in Table 4.7.

Table 4.7: Cause of failures and proposed actions on site

Cause of Failure	Proposed Actions
1.1 Leaves falling from trees and wind blowing and trapped at the leaf-gate during flushing.  **Figure 4.14:** Leaves trapped at the gate-leaf	**Immediate Action:** 1. Remove the trapped leave at the leaf-gate manually. **Preventive Actions:** 1. Trash trap needs to be installed behind the gate to block the trash. 2. Avoid install the gate near trees

Table 4.7 continued

Cause of Failure	Proposed Actions
1.2 Plasticine installed at the bottom of gate frame was being flushed up and stucked at the bottom internal gate frame area.  **Figure 4.15:** Blockage material was found at the bottom edge gate frame area	**Immediate Action:** 1. Remove the blockage manually. **Prevention Action:** 1. Plasticizer, rubber tube or any blockage materials need to be installed properly and tightly to avoid to be flushed up during flushing operation.
1.3 Insufficient water level behind the gate  **Figure 4.16:** Incomplete flushing performance where water only discharge through the bottom of the gate	**Immediate Action:** 1. Push the leaf-gate to open so that the spring can pull the leaf-gate up by the sudden compression force and close the leaf-gate tightly. Then, the water level can be stored again. **Prevention Action:** 1. Control the flow rate of the discharge water behind the gate. No preventive action found yet. Action undefined.

Scenario 2: Tipping flush gate system with trash trap (Fix one end)

After two flushing operations (12th March 2017 and 14th March 2017), a trash trap was installed at 0.6 m behind the gate to block leaves and rubbish in the sewer. The trash trap was made by using an extension rod and one steel mesh. The steel mesh was only fixed with one end as shown in Figure 4.17. The trap was installed on 27th March 2017.

Figure 4.17: A trash trap with one end fixed was installed

However, leaves were again found trapped between the gate frame and leaf-gate during flushing operation. The trap design was unable to hold the large amount of leaves and the accumulated sediments behind the gate. The leaf-gate was stucked and cannot function as shown in Figure 4.18. The immediate action was to clean all the leaves to provide clearances and unblocking the tipping flush gate. The trash trap was then reinstalled at a distance 2.5m behind the gate with two ends fixed as shown in Figure 4.19.

Figure 4.18: The leaf-gate was stuck due to large amount of leaves passing through the trash trap

Figure 4.19: The trash trap was installed 2.5m away behind the gate

Scenario 3: Tipping flush gate system with trash trap (Fix two end-vertically)

The new trash trap was reinstalled on 4nd April 2017. The trash trap was installed vertically by fixing the two ends with extension rod. The sediment and leaves behind the trap were not cleaned. The trash was managed to catch the leaves and rubbish as shown in Figure 4.20.

Figure 4.20: Trash trap was functioning well

However, the trash trap was then flushed off during a heavy rain on 6th April 2017. The trap was flushed off and fully submerged in the water as shown in Figure 4.21. The water level was 0.36 m. The failure of the trash trap caused the leaves being trapped in the internal gate frame causing the leaf-gate failed to close during the decreasing of water level (refer to Figure 4.22).

Figure 4.21: Trash trap was flushed off and fully submerged in water

Figure 4.22: Leaves get stucked at the gate frame

No immediate action can be taken when the water level was high and flowed at high speed. The preventive action suggested was to reinstall the trash trap when the water level was below 5 cm height. Secondly, the leaves and rubbish that accumulated behind the trash trap needed to be cleaned before the installation of the trap.

Scenario 4: Tipping flush gate system with trash trap (Fix two end-incline)

The trash trap was reinstalled on 8th April 2017. The trap design was different with the previous design. The new design trap was installed incline (the bottom extension rod is 8 cm in front from the top extension rod) increased the storage capacity of the trap. The schematic diagrams of the trash trap are shown in Figure 4.23.

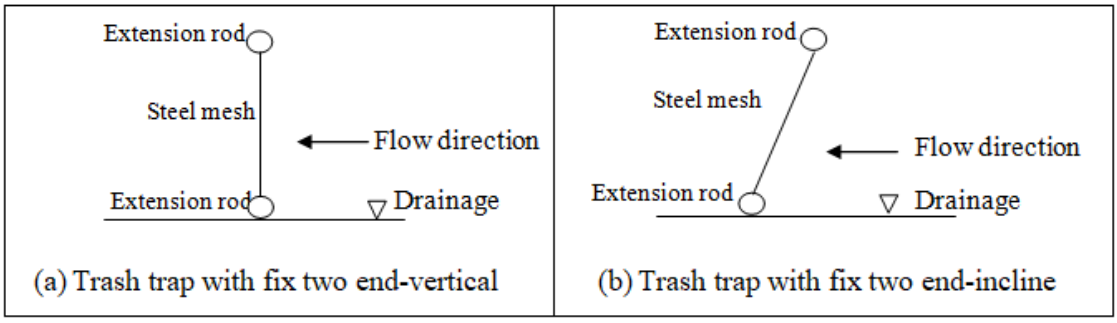


Figure 4.23: Schematic diagrams of the trash trap (side view)

The new proposed trash trap showed good performance (refer Figure 4.24). The potential failure mode of this trap was that it crashed or busted when the capacity of the trash (approximately 4kg) was achieve. This was due to no frequent clean up of the trash and under high flow condition. Currently, the immediate action was to clean up the trap from time to time when too much trash and sediment were accumulated. The preventive measure was still undefined and new design of trash trap needed to be investigated to improve the efficiency of the trap performance in open drain.

Figure 4.24: Trash trap with fix two ends -incline was capable to catch more leaves and rubbish in the sewer

4.4.4 Findings from Field Work

Due to the leaves accumulated at the trash trap, it had created a second storage phase for the tipping flush gate. This discharge from the trash trap provided a constant flow rate to the storage phase behind the tipping flush gate. The water level behind the tipping flush gate was build up and discharged consistently. The gate-leaf was closed tightly due to no fast continuous discharge from the trash trap. The gate opened when the water level reached 0.28 m and close perfectly when the water level receded to 0.19 m; with minimum leaking of water after the flushing. The average storage time from 0.19 m to 0.28 m was

21.55 s and the average discharge time was 3.65 s. Thus, the flushing operation performed smoothly and creating a good dam flushing to clean up the sediment in the open drain.

4.5 Fuzzy Inference System (FIS_RPN) Model Development

The qualitative aspects of the FMEA analysis on the tipping flush gate design that included the identification of the failure modes, severity, occurrence, and failure effect were based on the field history in literature available, design requirements, discussion with expert and the collected data from questionnaire, as well as studies on the hydraulic flush gate design. These information were used to develop the FIS_RPN model.

4.5.1 Scale Table and Fuzzy Membership Function Design

Using the linguistic variable and their descriptions, ranking of *Sev*, *Occ* and *Det* for failure mode was made in a scale basic. Tables 4.8, 4.9 and 4.10 show the scale tables for three risk factors *Sev*, *Occ* and *Det* respectively.

Table 4.8: Scale table for *Sev*

Ranking	Linguistic Terms	Descriptions
1-2	Remote	The failure has no effect on the performance of gate, and the failure may not notice. Gate can open easily and close properly. Good flushing system operation.
3-4	Low	The failure cause a sight effect on the performance of gate, and the failure can be notice. Gate can open but slightly hard to close. Flushing system operation still can perform.

Table 4.8 continued

Ranking	Linguistic Terms	Descriptions
5-7	Moderate	The failure causes effect on the gate performance and flushing operation, and the failure will be notice clearly. Gate totally open and cannot close. Flushing system operation only occurs once.
8-9	High	The failure cause significant effect on the gate performance but deterioration in flushing system operation, and the failure will be notice clearly. Gate hard to open and close. Flushing system operation is hard to perform.
10	Very High	The failure would seriously affect the ability to complete the function, no flushing effect occurs and cause the whole flushing system fail to operate.

Table 4.9: Scale table for *Occ*

Ranking	Linguistic Terms	Description
1-2	Remote	The failure is unlikely. Failure probability is ≤1 in 500.
3-4	Low	Relatively few failures. Failure probability is 1 in 100.
5-6	Moderate	Likely to occur more than once. Failure probability is 1 in 20.

Table 4.9 continued

Ranking	Linguistic Terms	Description
7-8	High	Repeated failures. Failure probability is 1 in 5.
9-10	Very High	Failure is almost inevitable. Failure probability is ≥1 in 2.

Table 4.10: Scale table for *Det*

Ranking	Linguistic Terms	Description
1-2	Very High	Potential cause and subsequent failure mode almost be detected at design control stage. No effect on flushing system performance.
3-4	High	Potential cause and subsequent failure mode may be detected at flushing gate system design control stage. Minor effect on flushing system performance.
5-6	Moderate	Potential cause and subsequent failure mode remains undetected until the system performance is affected.
7-8	Low	Potential cause and subsequent failure mode remains undetected until the system performance is reduced.
9-10	Very Low	Failure mode remains undetected until the function of system is ceased.

The fuzzy membership functions for Sev, *Occ* and *Det* were depicted in Figure 4.25, 4.26 and 4.27 respectively. The membership functions were used to build up the fuzzy rules and these rules were built depending on the requirement of the system. All the membership functions satisfied the Condition 1 of Theorem 1 (refer in Section 2.4.2). Gaussian membership function was represented as $\mu_G(x: c, \sigma) = e^{-[x-c]^2/2\sigma^2}$, where c is the center of the membership function, and σ parameterizes the width of the membership function. The

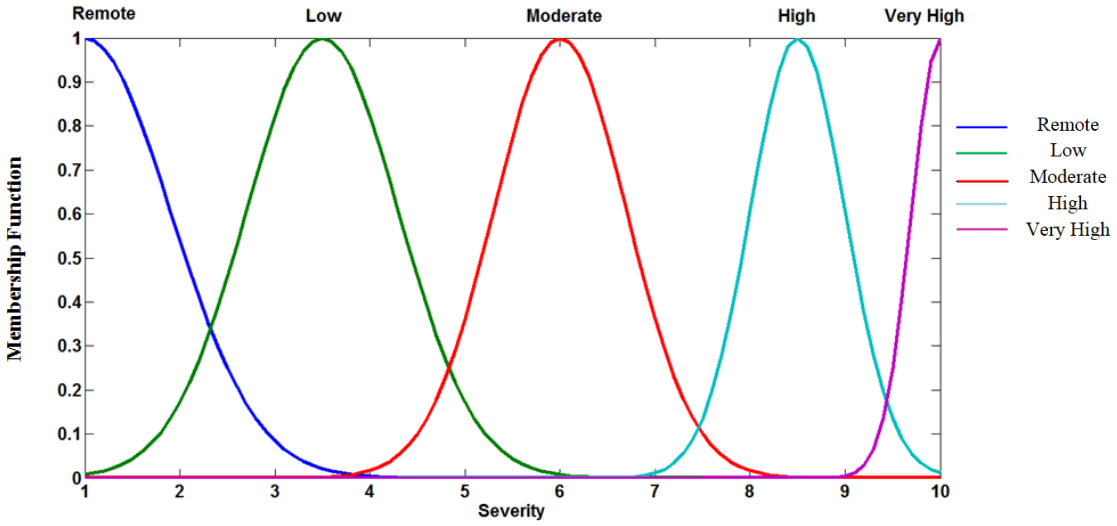


Figure 4.25: Membership functions for *Sev*

Note: Membership functions of Severity (*Remote* = $\mu(x: 1, 0.9)$; *Low* = $\mu(x: 3.5, 0.8)$; *Moderate* = $\mu(x: 6, 0.7)$; *High* = $\mu(x: 8.5, 0.5)$; *Very High* = $\mu(x: 10, 0.3)$).

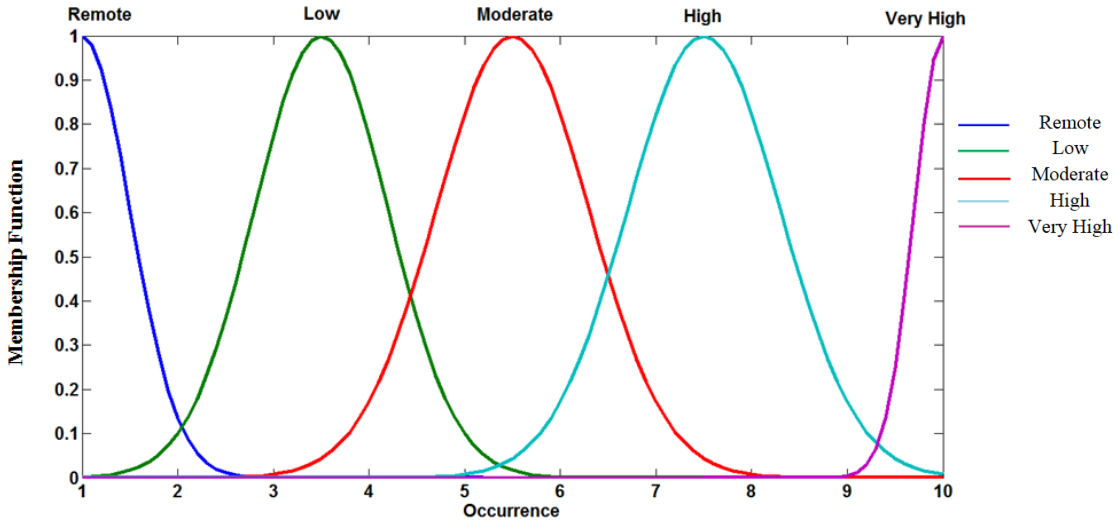


Figure 4.26: Membership functions for *Occ*

Note: Membership functions of Occurrence (*Remote* = $\mu(x: 1, 0.5)$; *Low* = $\mu(x: 3.5, 0.7)$; *Moderate* = $\mu(x: 5.5, 0.8)$; *High* = $\mu(x: 7.5, 0.8)$; *Very High* = $\mu(x: 10, 0.3)$).

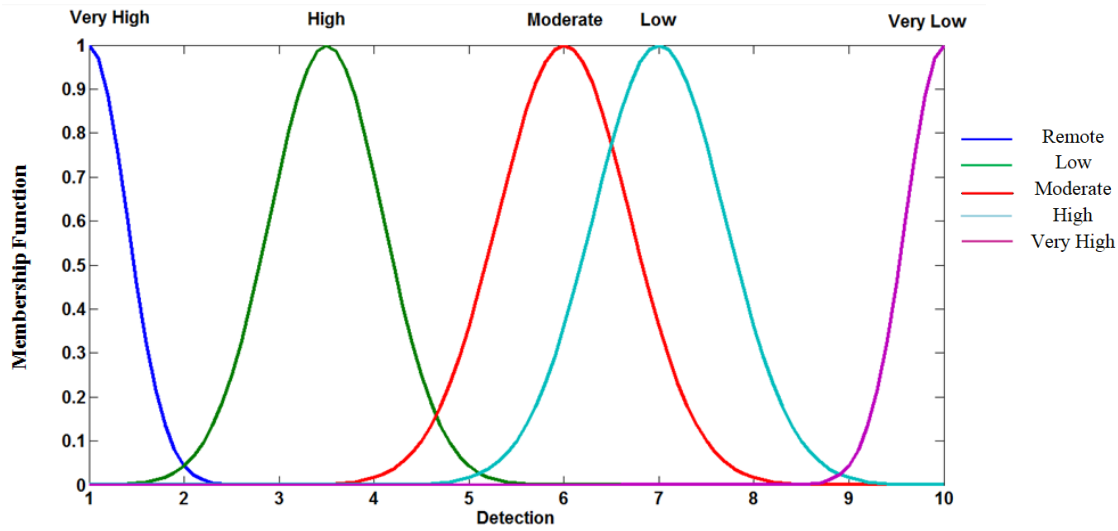


Figure 4.27: Membership functions for *Det*

Note: Membership functions of Detection (*Very High* = $\mu(x: 1, 0.4)$; *High* = $\mu(x: 3.5, 0.6)$; *Moderate* = $\mu(x: 6, 0.7)$; *High* = $\mu(x: 7, 0.7)$; *Very High* = $\mu(x: 10, 0.4)$).

4.5.2 Fuzzy Rule Gathering

The rule base describes the riskiness of each combined of input variables. The fuzzy RPN score for the FIS_RPN model was ranged from 1 to 1000. The FRPN's range was divided into five partitions namely, *Remote, Low, Moderate, High* and *Very High,* respectively, as depicted in Figure 4.28. Each fuzzy membership function was simplified to as a fuzzy singleton, i.e., the point that a fuzzy membership function is 1. Fuzzy singleton for each fuzzy membership functions was 1, 75, 260, 500 and 1000 respectively.

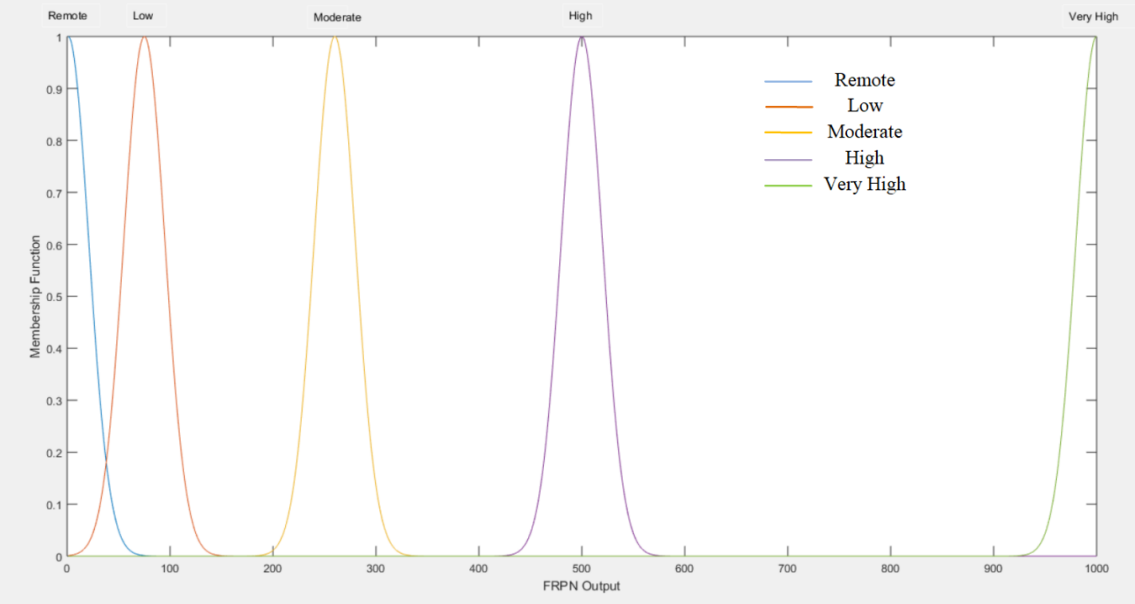


Figure 4.28: The fuzzy sets for FRPN output

Note: Membership functions of FRPN output (*Remote* = $\mu(x: 1, 20)$; *Low* = $\mu(x: 75, 20)$; *Moderate* = $\mu(x: 260, 20)$; *High* = $\mu(x: 500, 20)$; *Very High* = $\mu(x: 1000, 20)$).

The fuzzy rules were designed to fulfill Condition 2 of Theorem 1 (refer Section 2.4.2). As an example, the fuzzy singletons were 1, 75, 260, 500 and 1000. Since $1 \leq 75 \leq 260 \leq 500 \leq 1000$, *Condition 2* was satisfied.

After checking the fuzzy rule of FRPN, the magnitude of risk for the tipping flush gate design was then designed based on the membership functions of FRPN output. Figure 4.28 shown that the intersection point between membership function “Remote” and “Low” was 30. Thus, the maximum score for Remote is 30. For category “Low”, the lower score was 31; median score obtained was 75. The upper score for “Low” was calculated as [(75-30) × 2] + 30 = 120. For “Moderate” risk, the upper score was calculated as [(260-120) ×2] + 120= 400. For “High” risk, the upper score was calculated as [(500-400) ×2] + 400= 600. For “Very High” risk, the upper score was 1000.

4.5.3 Monotonicity Test for Collected Rule Base

The fuzzy rules collected from the expert were categorized as complete, i.e., all 125 fuzzy rules were obtained. However, fuzzy rules collected from experts could be noisy, resulting in nonmonotone fuzzy If-Then rules and affected the calculated result. Thus, the rules were checked to obtain monotonic function. From the monotonicity test results, the strong monotone for increasing was 2753, and that for decreasing was 10. On the other hand, the week monotone was 87. Then, the total pair was calculated as follow:

$$Total\ pair_{collect} = 2753 + 10 + 87 = 2850$$

By using the calculated value of the total pair, the monotone index of the original fuzzy rules was obtained as follow:

$$Monotone\ Index_{collect} = \frac{2753 + 87}{2850} = 0.9965$$

The calculated monotone index was less than 1. The rules categorized as nonmonotone because *Condition 2* of Theorem 1 was not fulfilled. Thus, the original collected rules were

analysed by using interval method modeling to obtain monotone result. The monotonicity index of 1 was obtained, i.e., $(2773 + 77)/2850 = 1$ which strong monotone for increasing was 2773, and that week monotone was 77. The monotone fuzzy rules were then used to develop the FIS_RPN model.

4.5.4 Simulation Results and Discussions

In this section, the risk evaluation results and the prioritization outcomes for both traditional RPN and the FIS_RPN model were compared. Table 4.11 summarizes the 25 significant risk evaluation, ranking and prioritization results with the traditional RPN model and the FIS_RPN model for the tipping flush gate design and operation system. Column "Failure mode" listed the potential failure modes, labeled as 1 to 25. Column "*Sev*", "*Occ*" and "*Det*" showed the severity, occurrence and detection rating that describe each failure mode. Failure risk evaluation and prioritization outcomes with the traditional RPN model were explained in the columns "RPN" and "RPN Output" respectively. On the other hand, the results for FIS_RPN model were explained in the columns "FRPN" and "FRPN Output".

The rating score of "*Sev*", "*Occ*", and *Det*" were based on Tables 4.8, 4.9 and 4.10 respectively. RPN and FRPN scores with the range of 1 to 30 were categorized as "Remote", 31 to 120 as "Low" and 121 to 400 as "Moderate". For the risk priority numbers with 401 to 600 were categorized as "High" whereas 601 to 1000 were categorized as "Very High".

Table 4.11: Comparison of failure risk evaluation, ranking, and prioritization results between traditional RPN model and FIS_RPN model

Failure Mode	**Rating Score**			**Traditional RPN model**		**FIS_RPN model**	
	Sev	*Occ*	*Det*	RPN	RPN Output	FRPN	FRPN Output
1	1	1	1	1	Remote	1	Remote
2	1	1	3	3	Remote	1	Remote
3	1	3	5	15	Remote	1	Remote
4	1	5	5	25	Remote	4	Remote
5	1	1	10	10	Remote	2	Remote
6	2	7	3	42	Low	83	Low
7	1	5	7	35	Low	50	Low
8	2	9	4	72	Low	98	Low
9	3	10	3	90	Low	242	Moderate
10	3	3	10	90	Low	70	Low
11	4	8	4	128	Moderate	166	Moderate
12	3	7	10	210	Moderate	257	Moderate
13	4	9	9	324	Moderate	259	Moderate
14	4	9	4	144	Moderate	169	Moderate
15	5	3	10	150	Moderate	200	Moderate

Table 4.11 continued

Failure Mode	Rating Score			Traditional RPN model		FIS_RPN model	
	Sev	*Occ*	*Det*	RPN	RPN Output	FRPN	FRPN Output
16	9	8	7	504	High	434	High
17	6	9	9	486	High	264	Moderate
18	8	6	9	432	High	361	Moderate
19	9	9	5	405	High	274	Moderate
20	10	6	7	420	High	435	High
21	10	8	9	720	Very High	857	Very High
22	10	9	9	810	Very High	863	Very High
23	10	9	7	630	Very High	446	High
24	9	8	9	648	Very High	855	Very High
25	9	9	9	729	Very High	890	Very High

The monotonicity property can be observed based on Table 4.11. As an example, failure modes #1, #2 and #5 had the same *Sev* and *Occ* rating, i.e., 1 and 1 respectively. The *Det* scores were 1, 3 and 10, for each of the failure mode respectively. With FIS_RPN model, the FRPN scores were 1, 1 and 2, respectively. These results showed that the monotonicity property was fulfilled. Notwithstanding, it was difficult to analyze the monotonicity property from Table 4.11. Hence, the monotonicity property of the constructed FIS_RPN model for tipping flush gate was analysed with surface plot as presented in Figure 4.29, Figure 4.30 and Figure 4.31. All figures show a smooth

increasing surface and these indicated that the FIS_RPN model developed satisfied the monotonicity property.

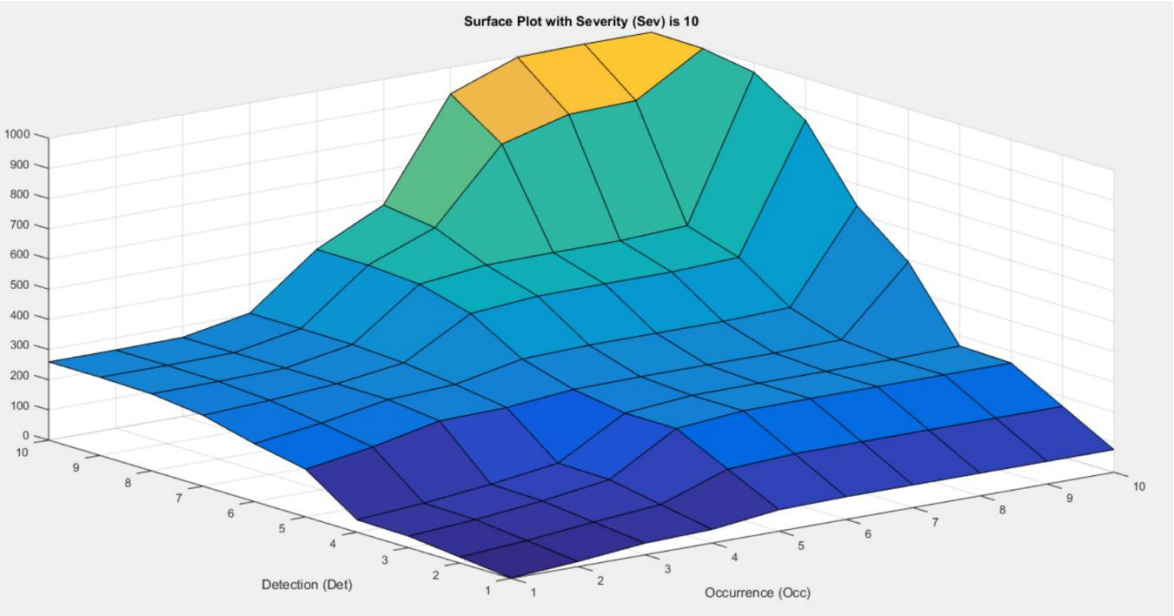


Figure 4.29: A surface plot of FRPN versus *Occ* and *Det* with *Sev* was 10

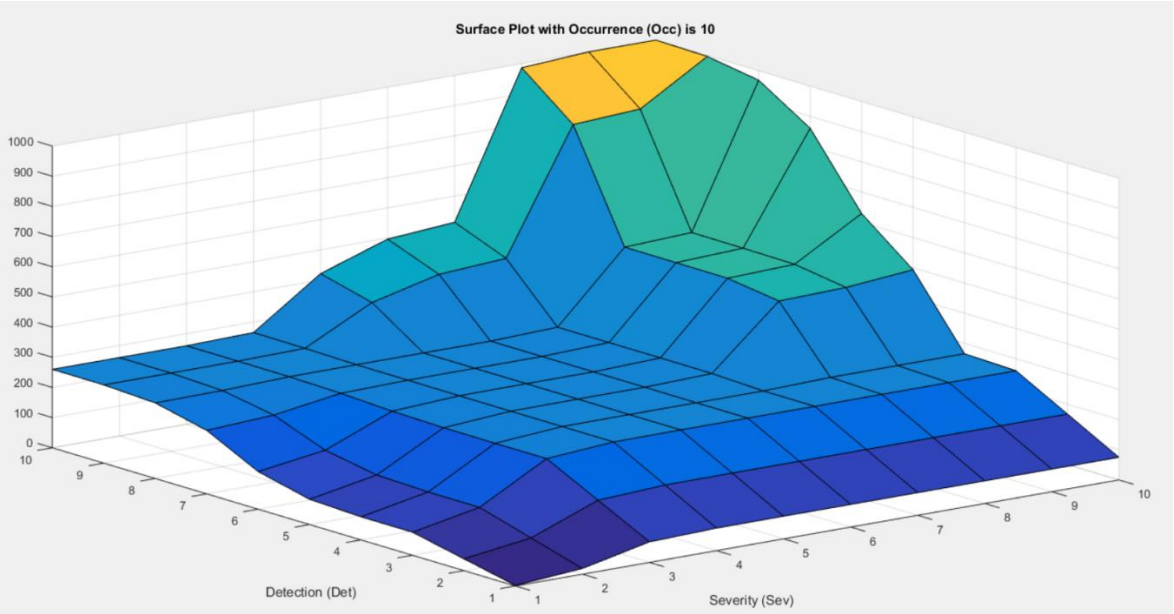


Figure 4.30: A surface plot of FRPN versus *Sev* and *Det* with *Occ* was 10

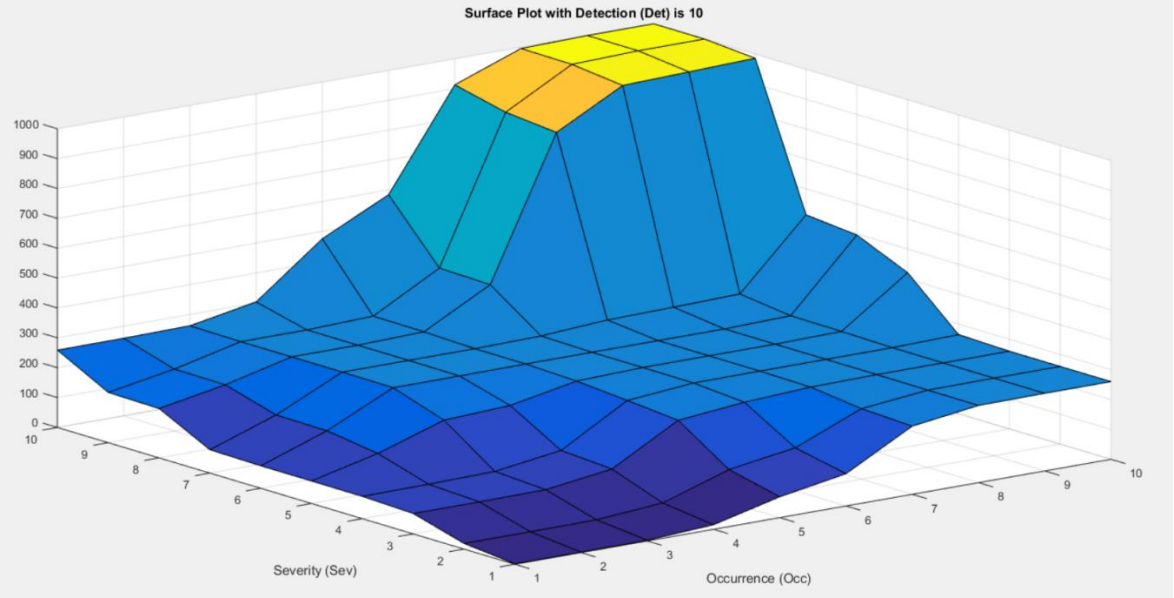


Figure 4.31: A surface plot of FRPN versus *Occ* and *Sev* with *Det* was 10

The traditional RPN model (refer Equation 2.16) stated that the RPN scores with *Sev, Occ* and *Det* were proportional. For example, from Table 4.11, failure modes #1, #2 and #5 had the same *Sev* and *Occ* rating, i.e., 1 and 1 respectively. The *Det* scores were 1, 3 and 10, for each of the failure mode respectively. RPN scores for each of the failure modes were 1, 1 and 10 respectively. However, with the FIS_RPN model, a non-linear relationship was allowed. With the same example, FPRN scores for each of these failure modes were 1, 1 and 2, respectively.

The proposed FIS_RPN model involved both qualitative and qualitative information. For example, from Table 4.11, failure mode #18 was associated with *Sev, Occ* and *Det* rating of 8, 6 and 9, respectively. *Sev* rating of 8 was associated to linguistic term "High", which denoted failure mode #18 to cause significant effect on the gate (refer to Table 4.8). *Occ* rating of 6 (associated to linguistic term "Moderate") denoted "the failure likely to occur more than once" (refer to Table 4.9). *Det* rating of 9 (associated to linguistic term "Very Low") denoted that the failure was undetected until the flushing

performance was ceased (refer to Table 4.10). The calculated RPN score was 432 which considered as “High” RPN output. On the contrary, a final FRPN score of 361 was obtained from the FIS_RPN model. In short, the model constituted as an alternative approach to deduce FRPN score. Then, different preventive measure sequence and method were taken based on the FRPN score.

One of the most critical disadvantages of the traditional FMEA was that various combinations of the *Sev*, *Occ* and *Det* rating produced an identical value of RPN. However, the risk representations could be different. For example, failure mode #9 and failure mode #10 had the same RPN score of 90, and the RPN outputs were “Low”. Conversely, the FRPN score for failure mode #9 and failure mode #10 were 98 and 242 respectively. The results show that failure mode #10 had a higher risk than failure mode #9 as failure mode #10 was at “Moderate” output as compared with failure mode #9 which was only “Low”. More preventive and immediate action should be taken to reduce failure mode #10.

In short, FMEA with FIS_RPN model was developed to obtain more accurate RPN. Subjective judgment which described in natural language could be inaccurate and uncertain. The relative importance of each RPN score calculated from traditional FMEA from the three input rating: *Sev*, *Occ* and *Det* could be overlooked and resulting in misunderstanding. The application of linguistic terms in FIS_RPN model allowed expert to provide a more reasonable and meaningful information for the three inputs. Fuzzy rule base allowed expert to construct a more realistic and logical rules. By using the fuzzy set and membership function, the imprecise information was improved to reflect the real situation. Expert’s knowledge and experience were incorporated in this risk assessment tool. The developed FIS_RPN model helped to differentiate the risk representations among

the failure modes, and resolved the difficulties arisen in conducting the procedure of the traditional FMEA.

4.6 FMEA Tables and Discussions for Tipping Flush Gate Design

The tipping flush gate system was broken down into two subsystems as by design. The components in each subsystem were considered in the fuzzy FMEA. The failure risk evaluation and prioritization outcomes for each of the failure were calculated by using FIS_RPN model. Table 4.12, Table 4.13 and Table 4.14 show the FMEA tables for two subsystem design, i.e., gate-opening (S.1), gate frame (S.2) and flush gate installation (S3), respectively. These tables showed clearly the potential failure cause of the failure modes, the subsystem and system effect, methods of failure detection and recommended actions needed to be taken to overcome the failure cause.

The *Sev*, *Occ* and *Det* scores were obtained after the discussion with expert. The scores were ranked based on the scale table designed in Section 4.5.1. The FRPN scores were calculated by using the developed FIS_RPN model. Lastly, recommended actions for each failure modes were design based its risk priority number. The critical components of the flush gate design were identified based on the generated FRPN scores. The FMEA results and reliability of the tipping flush gate designs were discussed in Section 4.6.1.

Table 4.12: FMEA table for tipping flush gate design: Gate-opening subsystem (S.1)

S.1.1 Gate-leaf											
Criterion	**Functions and Descriptions**	**Failure Mode**	**Cause**	**Failure Effect**		**Failure Detection**	***Sev***	***Occ***	***Det***	**FRPN**	**Recommended Actions**
				Subsystem Effect	**System Effect**						
S.1.1.1 Size of gate-leaf (Cut the plasboard into the designed sizing which fit the frame).	Providing allowance space for gate-leaf to rotate.	Gate-leaf size is bigger than the required size.	Error in measurement	The gate-leaf is hard to open and close.	The frequency of performing flushing reduced.	Visual inspection during flush operation of flush gate	9	8	4	258.4	1. Continuous inspection may help to determine the suitable allowance. 2. Reduce the gate-leaf size by trimming the sides of gate-leaf.
		Gate-leaf size is much smaller than the required size.	Error in measurement	Space between the frame and gate and cause leaking.	Water unable to store behind the gate. Flushing performance hardly performed.	Visual inspection	10	10	1	75.0	1. Redo
S.1.1.2 Roughness of gate-leaf (Smoothen sides of gate-leaf)	Reducing friction between gate frame and the gate-leaf during tipping process.	Not smoothen sides of gate-leaf	Not well smoothening process	The gate-leaf is hard to open and close.	The frequency of performing flushing reduced.	Inspection by opening the gate-leaf during assembly .	8	5	3	76.5	1. Smoothening the internal frame and gate-leaf using sand paper.

Table 4.12 continued

S.1.2 Tension Coil Spring											
Criterion	**Functions and Descriptions**	**Failure Mode**	**Cause**	**Failure Effect**		**Failure Detection**	***Sev***	***Occ***	***Det***	**FRPN**	**Recommended Actions**
				Subsystem Effect	**System Effect**						
S.1.2.1 Length of spring (Select suitable length of spring)	Providing spring length of 48 to 50 cm to connect gate-leaf and gate frame.	Spring length is shorter than required length	Limited choice available at market.	The gate-leaf unable open up to the desired angle.	Limited discharges through the gate during flushing. Efficiency of the flush gate reduced.	Measuring and visual inspection	8	7	3	225.9	1. Continuous inspection may help to determine the suitable string length. 2. Change the spring used.
		Spring length is longer than required length	Limited choice available at market.	The spring does provide any pulling effect in closing of the gate-leaf. The gate-leaf may not go back to equilibrium position.	Leaking of water store behind the gate. Longer duration needed to store the water.	Measuring and visual inspection	5	7	5	218.2	1. Continuous inspection may help to determine the suitable string length. 2. Change the spring used. 3. Adjust the spring location.
S.1.2.2 Tension of coil spring (Select suitable tension of spring)	Providing suitable tension spring	Spring is too tight	Limited choice available at market.	The gate-leaf unable open up to the desired angle.	Limited discharges through the gate during flushing. Efficiency of the flush gate reduced.	Measuring and visual inspection	8	8	5	268.8	1. Continuous inspection may help to determine the suitable string type. 2. Change the spring used.

Table 4.12 continued

S.1.2 Tension Coil Spring											
Criterion	**Functions and Descriptions**	**Failure Mode**	**Cause**	**Failure Effect**		**Failure Detection**	***Sev***	***Occ***	***Det***	**FRPN**	**Recommended Actions**
				Subsystem Effect	**System Effect**						
S.1.2.2 Tension of coil spring (Select suitable tension of spring).	Providing suitable tension spring	Spring is too loose	Limited choice available at market.	The spring does provide any pulling effect in closing of the gate-leaf. The gate-leaf may not go back to equilibrium position.	Leaking of water store behind the gate. Longer duration needed to store the water.	Measuring and visual inspection	7	7	5	249.1	1. Continuous inspection may help to determine the suitable string type. 2. Change the spring used.
S.1.2.3 Quality of spring (Select more durable type of tension coil spring).	Providing good quality material of tension coil spring to increase its durability.	Corrosion of spring	Collection of water in the smaller gap between the coils.	Tension of the spring reduces and hard to stretch. The gate-leaf may unable open up to the desired angle.	Limited discharges through the gate during flushing. Efficiency of the flush gate reduced.	Visual inspection	2	7	7	104.6	1. Change the spring if necessary.
		Spring broken	Direct exposure of metal to environment.	The gate-leaf may not close properly.	Leaking of water store behind the gate. Longer duration needed to store the water.	Visual inspection during or after flushing operation	6	7	1	74.9	1. Change the spring used.

Table 4.12 continued

S.1.3 Hinges											
Criterion	**Functions and Descriptions**	**Failure Mode**	**Cause**	**Failure Effect**		**Failure Detection**	***Sev***	***Occ***	***Det***	**FRPN**	**Recommended Actions**
				Subsystem Effect	**System Effect**						
S.1.3.1 Size of hinges (Select suitable hinge size).	Providing hinge size which slightly bigger than iron rod to provide allowance space for gate-leaf tipping process.	Hinge size smaller than the required size.	Similar hinge available in market.	Hinge too tight. The gate-leaf cannot tip due to no allowable space between iron rod and hinge.	Flushing operation cannot perform.	Assembly and visual detection	9	8	5	269.4	1. Use bearing to replace the current hinge. 2. Use of cable tie to provide small spacing between the iron rod and hinges.
		Hinge size bigger than the required size.	Similar hinge available in market.	The gate-leaf will bend.	Flushing operation cannot perform.	Assembly and visual detection	9	7	5	264.6	1. Use bearing to replace the current hinge.
S.1.3.2 Location of hinges (Fix the hinge at designed height).	Measuring and installing the hinge at designed location based on the designed angle (30° from horizontal axis).	Hinges installed higher than designed location	Error in measurement	The opening angle of the gate reduced. Water discharge decrease.	The flushing effect reduced.	Measuring and visual inspection	4	7	5	156.0	1. Reinstall the hinges.
		Hinges installed lower than designed location	Error in measurement	The gate-leaf cannot close properly.	Water unable to store behind the gate.	Measuring and visual inspection	5	7	5	218.2	1. Reinstall the hinges.

Table 4.12 continued

S.1.3 Hinges											
Criterion	**Functions and Descriptions**	**Failure Mode**	**Cause**	**Failure Effect**		**Failure Detection**	***Sev***	***Occ***	***Det***	**FRPN**	**Recommended Actions**
				Subsystem Effect	**System Effect**						
S.1.3.3 Number of screws for hinges (Fasten each hinge with two screws). .	Using two screws to fix each of the hinge with gate frame	Hinge not held in place	Loosen of screw during assembly or flushing over period of time.	Bending of the iron rod will occur over period of time due to water force.	Flushing operation cannot run smoothly.	Visual inspection and observation	4	4	8	78.3	1. Checking during assembly of hinge. or 2. None. Continuous inspection on site may help to identify the problem.
S.1.3.4 Material of hinge (Select suitable hinge material).	Providing suitable type of hinge material to increase its durability.	Corrosion of hinge	Collection of water in the hinge gap.	Friction between the hinge and iron rod increase. Gate-leaf is slightly hard to rotate.	Flushing operation still can perform.	Selection of material.	4	4	4	17.0	1. Select waterproof material. 2. Continuous observation on site may help to identify the problem.
S.1.4 Iron rod											
Criterion	**Functions and Descriptions**	**Failure Mode**	**Cause**	**Failure Effect**		**Failure Detection**	***Sev***	***Occ***	***Det***	**FRPN**	**Recommended Actions**
				Subsystem Effect	**System Effect**						
S.1.4.1 Material of iron rod (Select suitable type of rod).	Providing and installing iron rod with smooth surface to ensure smooth tipping process.	Rough surface of steel rod used.	Steel rod with pattern increases the friction with hinge.	Friction between the hinge and iron rod increase. Gate-leaf is hard to rotate.	Flushing operation hardly performs.	Selection of material and material testing by tipping the gate-leaf.	8	8	5	268.8	1. Change the type of iron rod used.

Table 4.12 continued

S.1.4 Iron rod											
Criterion	**Functions and Descriptions**	**Failure Mode**	**Cause**	**Failure Effect**		**Failure Detection**	***Sev***	***Occ***	***Det***	**FRPN**	**Recommended Actions**
				Subsystem Effect	**System Effect**						
S.1.4.2 Diameter of iron rod (Select iron rod with suitable diameter).	Providing suitable rod diameter that fit hinges to ensure smooth tipping process.	Diameter of iron rod is much smaller than hinge hole.	Similar rod available in market.	The rod cannot fit in position. Water force will push the gate and cause bending.	Flushing operation cannot perform.	Measuring and visual detection	8	8	5	268.8	1. Change iron rod immediately after inspection (by tipping the gate-leaf).
		Diameter of iron rod is equal or bigger than hinge hole, no allowable space between rod and hinges)	Similar rod available in market.	The rod is tight at hinges. Gate-leaf hard to rotate.	Flushing operation hardly performs.	Measuring and inspection during assembly	8	8	5	268.8	1. Change iron rod immediately after inspection (by tipping the gate-leaf).
S.1.4.3 Surface of iron rod (Select rod with good painting).	Providing iron rod with good painting for longer durability.	Corrosion	Direct exposure to environment and submerge in water.	Friction between the rod and hinges increase. Gate-leaf slightly hard to rotate.	Flushing operation still can perform.	Visual detection	3	3	3	1.7	1. Change the iron rod when necessary.
S.1.4.4 Number of brackets and screws set of iron rod.	Providing at least four brackets and screws sets to ensure strong attachment of iron rod to gate-leaf.	Less than four brackets and screws sets used	Mistake by constructor	Weak bonding between the iron rod and gate-leaf. Gate leaf might fall off.	Flushing operation cannot perform.	Visual inspection	10	1	1	1.1	1. Add brackets and screws sets until the iron rod is tightly attached together with gate-leaf.

Table 4.13: FMEA table for tipping flush gate design: Gate frame subsystem (S.2)

S.2.1 Main Frame											
Criterion	**Functions and Descriptions**	**Failure Mode**	**Cause**	**Failure Effect**		**Failure Detection**	***Sev***	***Occ***	***Det***	**FRPN**	**Recommended Actions**
				Subsystem Effect	**System Effect**						
S.2.1.1 Size of gate frame (Cut the internal frame in required size).	Cutting the plasboard in the designed sizing which fit the frame and allowance space for gate to rotate.	Gate frame size is bigger than the required size	Error in measurement	Space between the frame and gate-leaf and cause leaking.	Water unable to store behind the gate. Flushing performance hardly performed.	Visual inspection and measurement	8	1	1	1.1	1. Redo the whole frame. Or 2. Increase the size of gate-leaf.
		Gate frame size is smaller than the required size. No allowance space between gate leaf and gate frame)	Error in measurement	Gate-leaf not fit the frame. Assembly process is not completed.	Design failure. Flushing gate unable to function.	Visual inspection	8	1	1	1.1	1. Mark the required size of the frame and cut the internal frame to the smaller size. 2. Trimming the internal frame.
S.2.1.2 Roughness of gate frame (Smoothen internal surface of the frame).	Reducing friction between gate frame and the gate-leaf during tipping process.	Surface roughness at gate frame increases the friction between the gate-leaf and gate frame.	Not well smoothening process during assembly	The gate-leaf is hard to open and close.	The frequency of performing flushing reduced.	Inspection by opening the gate-leaf.	8	5	3	76.5	1. Smoothening the internal frame and gate-leaf using sand paper.

Table 4.13 continued

S.2.2 Bottom Frame Bar											
Criterion	**Functions and Descriptions**	**Failure Mode**	**Cause**	**Failure Effect**		**Failure Detection**	***Sev***	***Occ***	***Det***	**FRPN**	**Recommended Actions**
				Subsystem Effect	**System Effect**						
S.2.2.1 Size of bottom frame bar (Cut one additional plasboard bar into designed size).	Providing the additional plasboard bar with height 3 to 4 mm higher than the bottom high of main frame.	Smaller size of the additional piece of plasboard	Error in measurement	Bending at bottom gate frame might occur.	Flushing operation hardly performed.	Visual inspection and measure	8	1	1	1.1	1. Disassemble the additional plasboard. 2. Reconstruct the bottom gate frame with the new additional plasboard.
S2.2.2 Length of screws (Select specified screw length).	Specified screw length of 10 mm to 12 mm to fasten the bottom frame bar to the main frame at bottom area.	Shorter length of screws used.	Similar screws available at market	Weak bonding between the plasboard, causing unstable gate base	Contact surface of the plasboard reduce, flushing off of blockage material	Visual inspection and measure	3	1	1	1.0	1. Add new screw at the bottom frame.
		Longer length of screws used.	Similar screws available at market	The nail tip will get out of the gate frame, with potential user injury.	No system effect	Visual inspection and measure	3	1	1	1.0	1. Replace the longer screws with the specified screw immediately after assembly of gate frame.
S.2.2.3 Number of screws (Select specified number of screws).	Seven screw to fasten the bottom frame bar strongly to the main frame at bottom area.	Less than seven screws	Too few screws installed	Weak bonding between the plasboard, causing unstable gate base	Contact surface of the plasboard reduce, flushing off of blockage material	Visual inspection	3	1	5	3.8	1. Add additional screws until the two plasboard is tightly attached together.

Table 4.13 continued

S.2.3 Stopper Bar											
Criterion	**Functions and Descriptions**	**Failure Mode**	**Cause**	**Failure Effect**		**Failure Detection**	***Sev***	***Occ***	***Det***	**FRPN**	**Recommended Actions**
				Subsystem Effect	**System Effect**						
S.2.3.1 Location of stopper bar (Place the bar at designed height).	Measuring and installing the stopper bar at desired height based on the designed angle (30° from horizontal axis).	Height of stopper bar is higher than the designed height)	Error in measurement	The opening angle of the gate increase, causing gate-leaf hard to tip back to original position.	Number of flushing operation reduced.	Measuring and visual inspection	5	7	5	218.2	1. Reinstall the stopper bar. 2. Use spring to ensure proper closing.
		Height of stopper bar is lower than the designed height)	Error in measurement	The opening angle of the gate reduced. Water discharge decrease.	The flushing effect reduced.	Measuring and visual inspection	4	7	5	156.0	1. Reinstall the stopper bar.

Table 4.14: FMEA table for tipping flush gate installation process

S.3.1 Smoothen Bottom Surface of Drainage											
Criterion	**Functions and Descriptions**	**Failure Mode**	**Cause**	**Failure Effect**		**Failure Detection**	***Sev***	***Occ***	***Det***	**FRPN**	**Recommended Actions**
				Subsystem Effect	**System Effect**						
S.3.1.1 Install temporary barrier behind the gate	Holding upstream water level while installing flushing gate	Initial upstream water level is too high	After raining event	Barrier fail to be installed	Flushing gate cannot be installed.	Visual detection	4	1	1	1	1. Install barrier and flushing gate during non-raining season.
S.3.1.2 Place rubber tube at bottom gate frame	Minimizing water leaking below the gate frame	Very rough surface at the bottom surface of drainage and rubber tube is hard to be installed.	Abrasive effect of sand, gravel and debris that grinding on the drainage surface.	Water building up behind the gate slower.	Frequency of flushing operation decrease, efficiency of flushing decrease.	Visual detection	4	4	5	69.2	1. Smoothen the drainage surface by patching. 2. Thicker rubber tube needs to be placed. 3. Clean the drainage sections to remove debris before installation of gate.
S.3.2 Installation of Flushing Gate to Selected Drainage Cross Section											
Criterion	**Functions and Descriptions**	**Failure Mode**	**Cause**	**Failure Effect**		**Failure Detection**	***Sev***	***Occ***	***Det***	**FRPN**	**Recommended Actions**
				Subsystem Effect	**System Effect**						
S.3.2.1 Installation of flushing gate	To store water behind the gate and provide sediment flushing effect when water level reach designed height	Gate frame too fit (>3mm width) to the drainage cross section	Measurement effort during site investigation	Bending of the gate frame during installation.	Flushing gate cannot be installed.	On-site testing and installation	8	2	8	203.7	1. Grind the sides of the gate to suite the size of the drain.

Table 4.14 continued

Criterion	Functions and Descriptions	Failure Mode	Cause	Failure Effect		Failure Detection	*Sev*	*Occ*	*Det*	FRPN	Recommended Actions
				Subsystem Effect	System Effect						
S.3.2.1 Installation of flushing gate	To store water behind the gate and provide sediment flushing effect when water level reach designed height	Gate frame too loose (<5mm width) to the drainage cross section	Measurement effort during site investigation or measuring error during construction of flushing gate	Water leaking and water building up behind the gate slower.	Flushing gate might be flush off during heavy rain event due to high water pressure to the sides of the gate	On-site testing and installation	8	2	6	174.9	1. Put rubber tube to the sides of the frame when the differences between gate frame and drainage width is in the range of 10mm. 2. Screw additional piece of plasboard to gate frame
S.3.3 Installation of Gate Holder											
Criterion	**Functions and Descriptions**	**Failure Mode**	**Cause**	**Failure Effect**		**Failure Detection**	***Sev***	***Occ***	***Det***	**FRPN**	**Recommended Actions**
				Subsystem Effect	**System Effect**						
S.3.3.1 Install steel bar as gate holder	To hold the flushing gate tightly during flushing operation	Week gate holder	Steel bar too thin / poor material of gate holder used	Gate holder broken due to repeat impacting of water pressure.	Flushing gate might be flush off during heavy rain event	Visual detection	10	5	5	266.1	1. Select and use holder with long durability. 2. Steel plate or bar with suitable density
S.3.3.2 Fasten the steel bar holder with screws	To hold the gate holder at designed position	Insufficient screws	Error during installation	Gate holder broken due to repeat impacting of water pressure.	Flushing gate might be flush off during heavy rain event	Visual detection and on site inspection	5	4	8	195.5	1. Add additional screws until the gate holders are tightly attached to the drainage wall.
		Shorter length of screws used	Error in selection of screws	Gate holder broken due to repeat impacting of water pressure.	Flushing gate might be flush off during heavy rain event	Visual detection and on site inspection	5	3	8	194.5	1. Change the screws with suitable length and fasten it tightly.

Table 4.14 continued

S.3.4 Installation of Trash Trap											
Criterion	**Functions and Descriptions**	**Failure Mode**	**Cause**	**Failure Effect**		**Failure Detection**	***Sev***	***Occ***	***Det***	**FRPN**	**Recommended Actions**
				Subsystem Effect	**System Effect**						
S.3.3.3 Install trash trap 1m behind the gate	To trap the debris behind the gate and avoid the gate get stuck by rubbish. To provide secondary storage to flushing operation.	Trash trap broken	Too much debris trap behind the trash trap	Gate holder broken due to repeat impacting of water pressure.	Flushing operation might not perform smoothly.	Visual detection	8	8	3	255.8	1. Regular maintenance is required to maintain the capacity of trash trap.

4.6.1 Summary of Fuzzy FMEA Results of Tipping Flush Gate Design

Generally, the subsystem effects that caused by the potential failure mode of the gate-opening and gate frame subsystem included leaking of water behind the gate and improper closing and opening of gate leaf. The failure modes of the subsystems also caused the system failed to operate such as limited discharges through the gate, efficiency of the gate reduced and limited number of flushing operation. The flushing gate was constructed manually; thus, most of the failure can be detected by visual inspection and testing of the design during assembly. Some recommended actions were suggested to eliminate the risk associated with each of the potential cause.

Based on the FMEA tables, none of the components had high or very high risk. By referring to Table 4.15, the magnitude of risk for the tipping flush gate design was categorized as moderate since the calculated FRPN scores ranked from 1.0 to 269.4. Table 4.16, Table 4.17 and Table 4.18 summaries the risk evaluation and the ranking for gate-opening subsystem, gate frame subsystem and gate installation respectively. The design of hinges and gate holders with FRPN value of 269.4 should be the first priority in the design stage of the gate. They were the critical components of the flush gate design. The failures remained undetected until the flushing performance was affected. The repeated failure in the design of these two components caused flushing operation very hard to perform. Through proper implementation of actions, the FRPN score can be minimized by lowering the *Occ* and *Det* scores. The lower the FRPN score, the lower the magnitude of risk.

Table 4.15: Magnitude of risk for tipping flush gate design

Magnitude of Risk	FRPN Score
Remote	1-30
Low	31-120
Moderate	121-400
High	401-600
Very High	601-1000

Table 4.16: Risk Evaluation and ranking for gate-opening subsystem

Ranking	**Criteria of gate-opening subsystem**	**FRPN**
1	S.1.3.1 Size of hinges	269.4
2	S.1.2.2 Tension of coil spring	268.8
2	S.1.4.1 Material of iron rod	268.8
2	S.1.4.2 Diameter of iron rod	268.8
5	S.1.1.1 Size of gate-leaf	258.4
6	S.1.2.1 Length of coil spring	225.9
7	S.1.3.2 Location of hinges	218.2
8	S.1.2.3 Quality of coil spring	104.6
9	S.1.3.3 Number of screws for hinges	78.3
10	S.1.1.1 Roughness of gate-leaf	76.5
11	S.1.3.4 Materials of hinges	17.0
12	S.1.4.3 Surface of iron rod	1.7
13	S.1.4.4 Number of brackets and screws set of iron rod.	1.1

Table 4.17: Risk Evaluation and ranking for gate frame subsystem

Ranking	Criteria of gate frame subsystem	FRPN
1	S.2.3.1 Location of stopper bar	218.2
2	S.2.1.2 Roughness of gate frame	76.5
3	S.2.2.3 Number of screws for bottom frame bar	3.8
4	S.2.2.1 Size of bottom frame bar	1.1
5	S.2.1.1 Size of gate frame	1.1
6	S.2.2.3 Length of screws for bottom frame bar	1.0

Table 4.18: Risk Evaluation and ranking for tipping flush gate installation process

Ranking	Criteria of gate installation	FRPN
1	S.3.3.1 Install steel bar as gate holder	266.1
2	S.3.3.3 Install trash trap behind the gate	255.8
3	S.3.2.1 Installation of flushing gate	203.7
4	S.3.3.2 Fasten the steel bar holder with screw	195.5
5	S.3.1.2 Place rubber tube at bottom gate frame	69.2
6	S.3.1.1Install temporary barrier behind the gate	1.0

4.7 Extension work: Problem on Large Size Flush Gate [1.5 m (W) × 1.0 m (H)]

A flush gate with size of 1.5 m (W) × 1.0 m (D) was installed in the flume with the dimensions 30.0 m (L) × 1.5 m (W) × 1.0 m (D) at the hydraulic lab, REDAC, Universiti Sains Malaysia. The gate was installed 10 m away from upstream. There were some failures observed during the flushing operation. The failures and proposed actions were recorded in Table 4.19.

Table 4.19: Failure and proposed action for large size flush gate

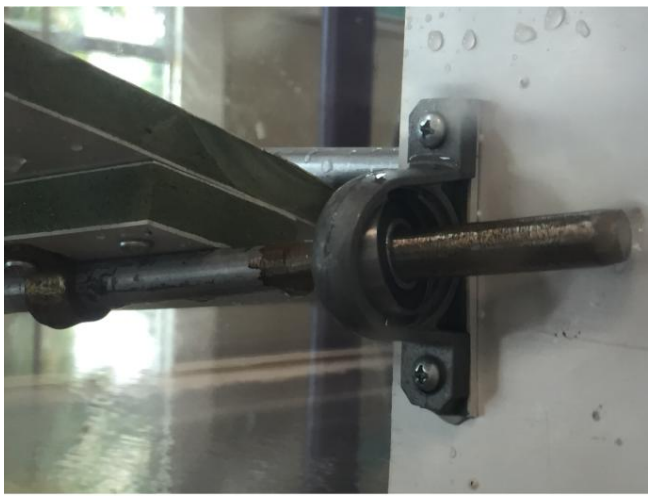
Cause of Failure	Proposed Actions
1 Short screw used for bearing  **Figure 4.32:** Bearing on left hand side was detached and the gate-leaf was separated from the gate frame  **Figure 4.33:** Bearing on right hand side was broken due to the high impact flush	**Immediate Action:** 1. Take the flushing gate out and reinstall it with correct size of screws. **Preventive Actions:** 1. Monitoring the flush gate performance after installation process. 2. Careful during the selection of components.

Table 4.18 continued

Cause of Failure	Proposed Actions
1 Install gate inversely  **Figure 4.34:** Flushing gate was installed in opposite direction	**Immediate Action:** 1. Take the flushing gate out and reinstall it before the water level building up to maximum level; **Preventive Actions:** 1. Give clear instruction during installation 2. Monitoring the flush gate performance after installation process.

4.8 Summary

In this chapter, the experiment results provided the relationships of the gate opening angle; sediment bed length and duration of flushing on the changes of sediment bed profile. The results showed that only the effects of number of flush, duration of flushing and sediment bed length were statistical significant to the sediment flushing efficiency. The correlation regression analysis equation helped to provide a direction when designing the gate and site selection as rainfall intensity was the main source to provide the system operation. On the other hand, the field monitoring helped to identify the failure

risks on site that contributed to the planning of immediate action to reduce the risk of failure or losses.

The fuzzy FMEA methodology was applied to tipping flush gate system design. The results showed that the risk associated with the current flush gate design was moderate under good condition where it was no affected by external environment. No all the components were equally important because they were identical to various FRPN values. More attention should be taken when designing the gate hinges and gate holder to reduce the potential failure mode; thus, maintaining the flush gate system performance. The flush gate installation process also needed to be done properly to reduce the risk of failure during operation stage.

Despite the use of FMEA and risk analysis in hydraulic flushing gate, the lack of publically available FMEA analysis for hydraulic flushing gate made it difficult to evaluate the results. This was the first attempt to provide a complete FMEA analysis for hydraulic flushing gate, i.e., tipping flush gate and it required a substantial work in collecting information. Besides, the current tipping flush gate design did not cause adverse effect to the sewer system during heavy rain based on the on-site monitoring work. The results from field monitoring work showed that it was necessary to concern about the trash trap design. This was because the installation of trash trap helped to increase the flushing performance of the tipping flush gate and reduced the failure of the gate.

CHAPTER 5

DESIGN GUIDELINE

5.1 Introduction

Maintenances to remove sediment deposit and debris in open drain involve a number of special considerations. Because of the difficulties of site accessibility it may be necessary to provide active flow by using tipping flush gate. This would allow self-cleansing of sewer by producing successive flushing wave at high velocity to scour and flush out the accumulated sediment to the drainage sump. This solution does not have limitation of flush way length and no external water supply required. The gate is suitable to be use for open or covered storm sewer. However, it is often sufficient to assume that the gate is close for dry season. A detailed analysis of the gate sizing requirements will required data on the existing drainage design, site surveying and site condition.

5.2 System Component

The general system components for tipping flush gate flushing system (Figure 1) include the following:

- Tipping Flush Gate – Flush gate is installed at the section of the sewer to store water from upstream sewer section. It releases the wave by sudden opening of the gate to clean the entire sewer during raining event.
- Sumps – The sump receive the inflow of storm water and sediment prior to flushing. Sediment could be extracted at sump rather than cleaning the whole section of the sewer manually.

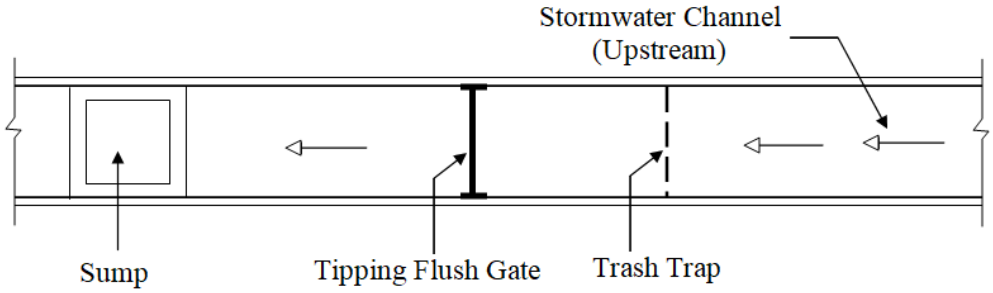


Figure 5.1: Typical layout and system components of tipping flush gate system

5.3 Planning Process

- Site Location – The selected catchment area should be located which has high rainfall frequency and intensity. More frequent flushing operation will clean the sewer more effectively.
- Flush Gate Location – The flush gate should be installed far away from sump or after a sump (Bong et al., 2016). This is to ensure that the larger flush effect could be generated and reach further without the disturbance of depression along the downstream sewer section. The gate should be installed to the section where sediment accumulation was observed or estimated.
- Sewer Selection – The sewer shall not have backwater effect at downstream of the gate so that flushing operation can be conducted smoothly. Besides, the width of the sewer shall not less than 0.6 m.

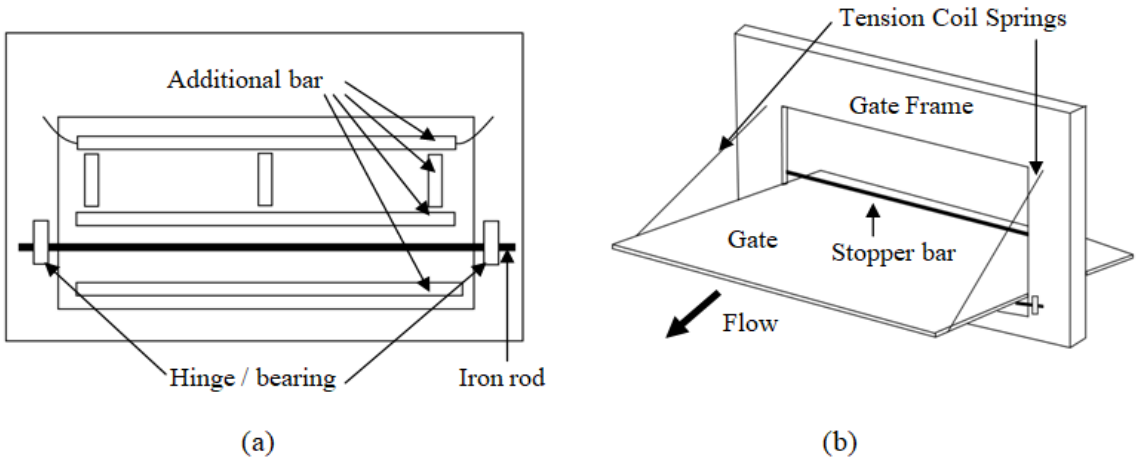


Figure 5.2: Typical tipping flush gate structure (a) front view (b) isometric view

- Gate Size – The size of the flush gate should be determined early during planning process. The width of the gate gap must not be too small or cause flow contraction within the sewer during gate operation that may cause the sewer to overflow. The height of the gate gap depends on the bottom invert level of the inlet to the sewer bottom. This is so that the water level behind the gate just before the gate opens won't be over the lower invert level of the inlet, therefore preventing backwater through the inlet. Also, the total height of the gate gap and gate frame should not be more than the total depth of the sewer. This allows freeboard for water to overflow over the gate just in case the gate is stuck and could not open.
- Gate Opening Angle – The gate can operate without the spring with opening angle of 60° from the vertical axis (30° from horizontal axis). For larger gate opening angle, tension coil springs are required to connect the edge of the gate and gate frame. The spring will compress upon by a force that restores the gate tipping to equilibrium position to ensure proper closing of the gate.

5.4 Other Facilities and Requirements

- Gate Holder – Use gate holder with long durability to hold the flushing gate tightly during flushing operation. For example, steel plate or bar with high density.
- Trash Trap – Trash trap should be provided at upstream channel section if large debris is anticipated. For drainage width less than 0.6 m, netting can be used to screen the trash. However, bar screens may need to be installed for drainage width more than 0.6 m or area where trash problem is serious. The screen inlet should be adequately sized by taking into consideration of the partial clogging of the inlet by debris that prevents the full flood flows. The trash trap should be maintained properly, and on a regular schedule to avoid blockage.
- Water Storage Chamber – Water storage chamber is recommended to place behind the gate so that the water level can build up faster and more flushing operation.
- Monitoring and Maintenance – The best overall procedure to assure the proper functioning of a tipping flush gate is the implementation of a regular schedule of maintenance conducted by trained, experienced personnel. Suggested time frame is three months after the first installation of flush gate then follow by one time per year to clean up the sump and flush gate maintenance checking.

5.5 Design Procedure for Tipping Flush Gate

The workflow of flushing gate in open drain is shown in Figure 5.3. The design procedure is referred to the suggested design guideline for tipping flush gate by Bong et al. (2016).

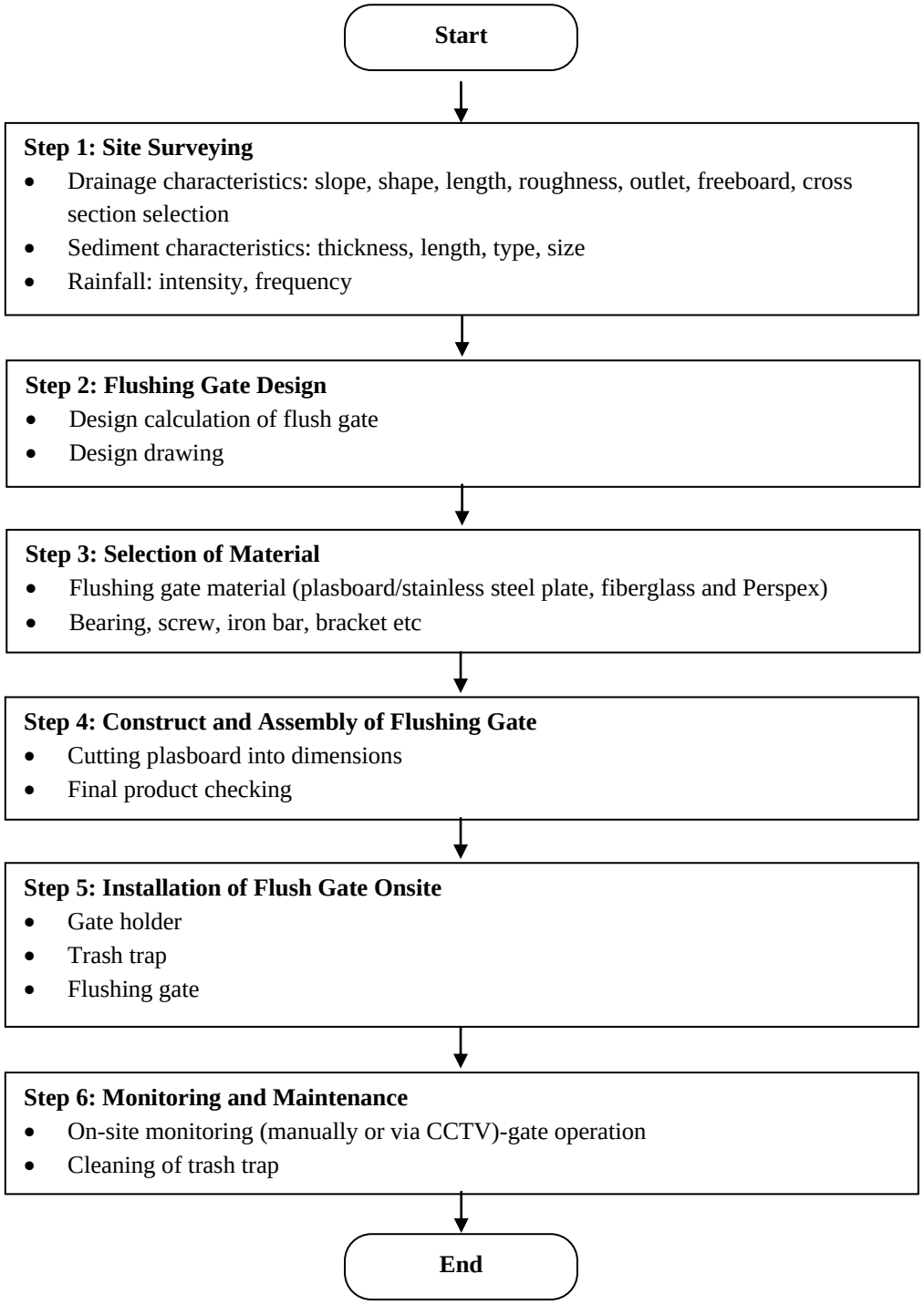


Figure 5.3: Workflow for flushing gate in open stormwater system

Step 1: Site Surveying

Site survey work need to be done to obtain the sewer characteristics such as dimensions, shape and slope. Besides, the location and the height of bottom invert of the inlets along the sewer should be determined so that the flush gate design is within the freeboard range.

Step 2: Flushing Gate Design

The size of a flushing gate is designed based on the site surveying data. Furthermore, the gate opening and closing water level is designed depending on the site of the channel and the rainfall intensity on site. As the flush gate operates based on the changes of water level and the difference of moment on the upper portion (above the hinge) and lower portion (below the hinge) of the gate, the force acting on the gate is considered in design stage as shown in Figure 5.4 and Figure 5.5.

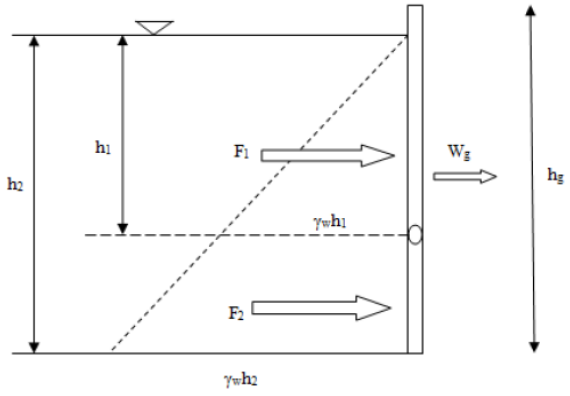


Figure 5.4: Forces acting on tipping flush gate before opening (Bong et al., 2016)

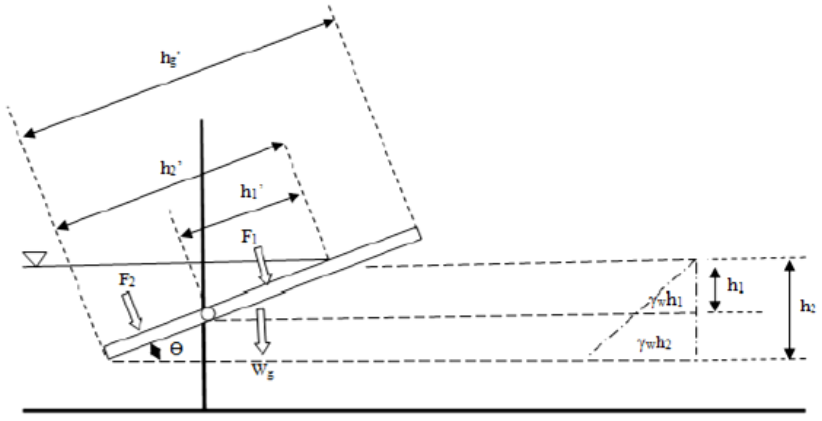


Figure 5.5: Forces acting on tipping flushing gate when open (Bong et al., 2016).

The gate component should be designed as follow:-

- Gate hinge positioning – Using the Equation 6.1 and Equation 6.2 to calculate the required position of the hinge after the maximum water level for the gate to open has been determined.

$$h_1 > [2(h_2 - h_1)^3 + 3h_1(h_2 - h_1)^2]^{1/3} \quad (6.1)$$

$$h_{hng} = h_2 - h_1 \quad (6.2)$$

Where h_{hng} is the height of the hinge from the bottom of the pressure prism [m]; h_1 is the distance of the water surface to the centre of the hinge [m]; h_2 is the distance of the water surface to the bottom of the pressure prism [m].

- Gate opening angle – Set the gate opening angle to 60° from the vertical axis (30° from horizontal axis) unless otherwise stated.

- Closing water level – Using Equation 6.3 to check the water level for tipping flush gate (plasboard with density = 1092 kg/m^3) to close. If other material is used instead of plasboard, the Equation 6.3 is subject to checking and revision.

$$h'_1{}^3 + 0.0393 h_g \left(h_g - h_{hng}\right) \tan\theta < 2(h'_2 - h'_1)^3 + 3h'_1(h'_2 - h'_1)^2 \quad (6.3)$$

Where h'$_1$ is the vertical distance of the water surface to the centre of the hinge [m], h'$_2$ is the vertical distance of the water surface to the bottom of pressure prism [m].

Step 3: Selection of Material

Material for the gate – Material used for the gate must be durable waterproof and high bending strength to withstand water force. Other materials that can be used for the gate are stainless steel plate, fiberglass and Perspex. The dimensions and the size of component such as bearing, screw, iron bar, bracket etc. should be selected based on the size of the gate which can sustain the water force during gate operation.

Step 4: Construction and Assembly of Flush Gate

The construction and assembly process of flush gate consists of ten stages as shown in Figure 5.6. After the final product should be tested before install it for on-site operation.

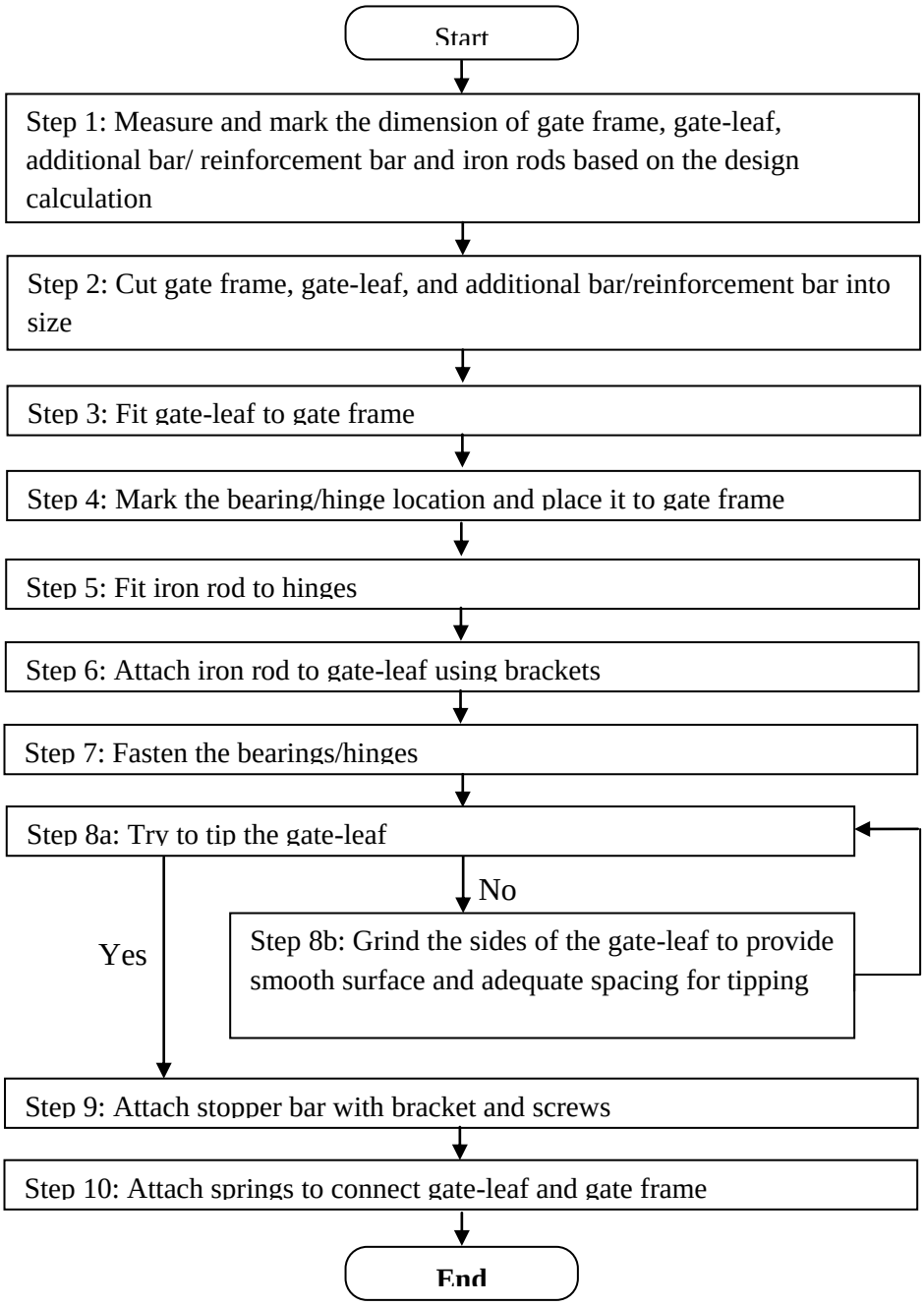


Figure 5.6: Tipping flush gate construction and assembly process chart

Step 5: Installation of Flush Gate Onsite

The installation of flush gate consists of four steps. The gate holder should be installed such that to hold the flush gate tightly and avoid it to be flush off during flushing operation.

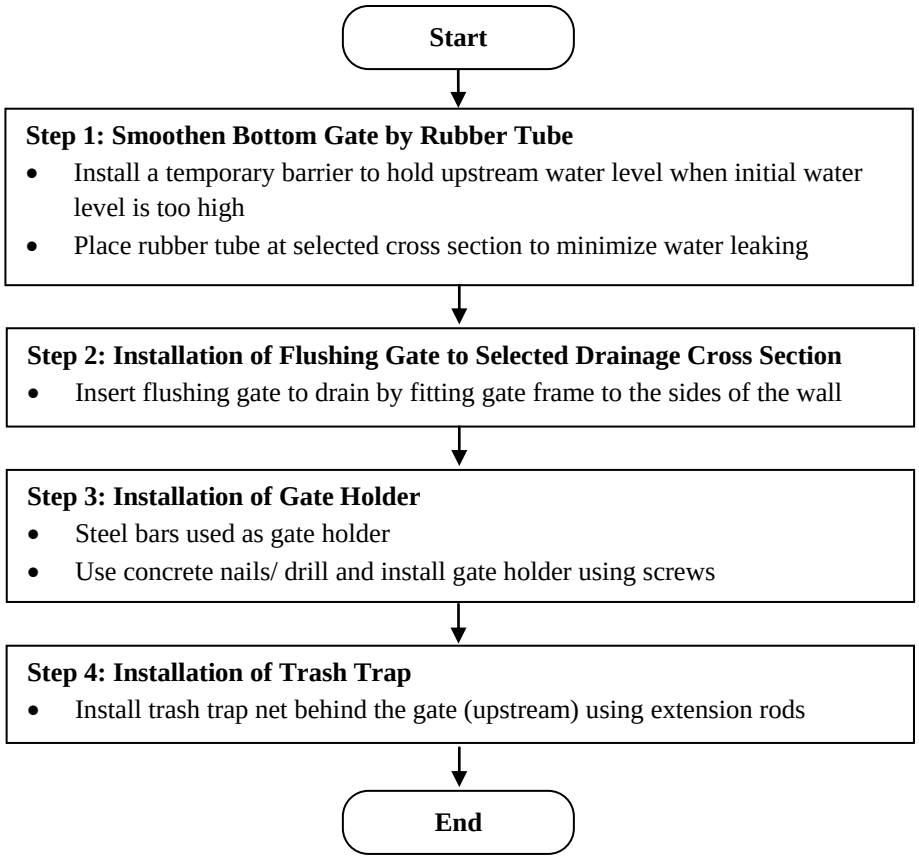


Figure 5.7: Flushing gate installation process

Step 6: Monitoring and Maintenance

Refer to Section 5.4, the monitoring and maintenance work need to be done systematically to prevent the gate from not working properly.

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

This study helped to improve the design of tipping flush gate, ensure smooth and reliable hydraulic flushing operation. As stated in Chapter 1, there were four objectives for the current study; namely to determine the factors that influenced the sediment removal efficiency of hydraulic flushing; to identify the potential failure mode, effect and root cause in using hydraulic flushing gate; to apply fuzzy FMEA with FIS_RPN model and obtain FRPN for risk assessment of hydraulic flushing in managing sedimentation in open drain; and to establish a general guideline and management plan for active sedimentation control in open drain. From the results of the current study, the conclusions that could be drawn are as presented in the following subsections.

6.1.1 Determine Factors Influence the Sediment Removal Efficiency of Hydraulic Flushing

The experimental results had proven that the effects of number of flush, duration of flushing, sediment bed length, sediment size and gate opening angle. However, the correlation analysis showed that the sediment size and gate opening angle did not have statistically significant on the sediment flushing efficiency. Thus, it was not necessary to design the gate with opening angle greater than 60° measured from the vertical axis as gate opening of 60° can perform similar flushing efficiency with greater opening angle. In addition, gate opening of 60° operated smoothly without addition use of string and reduced the production cost. Besides, sediment flushing efficiency did not get much affected by the sediment size with coarse, loose, granular properties. In contrast, the site selection for flush

gate installation was more critical as rain was the key to drive the system. The rainfall intensity contributed to the number of flush and duration of flushing of the flush gate. Short flush with more frequent flushing operation resulted in higher sediment flushing efficiency. Furthermore, the sediment bed length on-site must be measured during the site investigation so that the number of flush gate required can be calculated.

6.1.2 Identify Potential Failure Mode, Effect and Root Cause of Hydraulic Flushing Gate

The scale tables were tabulated with the agreement from expert. The scale evaluation was divided into five categories. Questionnaire was distributed to expert to collect data related to flush gate design. Besides, some of the failure modes were collected during the construction of flush gate and field testing. The collect failure modes provided better understanding and direction in preparing the design guideline of flush gate system such as the installation and maintenance action. The failure modes in this study included the design, installation and operation failure modes.

6.1.3 Apply FMEA with FIS_RPN model to Sediment Flushing Gate System Design

A fuzzy FMEA approach that combined the qualitative (expert experience) and qualitative (tipping flush gate field operation data) knowledge was applied in this study. The smooth surface plot of the constructed FIS_RPN showed that the modeling was done correctly. The fuzzy risk priority number (FRPN) calculated from FIS_RPN model helped to categorize the risk in the process of prioritization of failure modes which made FMEA more realistic, more practical and more flexible. Single expert model of FIS_RPN model was used in this study. The model helped to evaluate the level of risk for each failure mode so that actions plan could be provided according to its ranking as summarized in the

FMEA tables. The results showed that the failure of flush gate component such as hinges, iron rod, tensional coil spring and installation of gate holder affected the flush gate performance till the system failed to operate. Thus, extra attention needed to be taken during the construction and installation stage. The recommended actions for each potential failure cause were listed in the respective FMEA tables. The implementation of the actions helped to reduce the potential failure mode in the design, installation and operation stage. The actions provided were based on the risk priority number of each failure mode.

6.1.4 Establish a General Design Guideline and Management Plan for Active Sedimentation Control in Open Drain

A general design guideline and management plan on flush gate system component, planning process, facilities and requirements and design procedure were presented. The design procedures covered the method of site surveying, flushing gate design, selection of material, construction and assembly process, installation process; monitoring and maintenance process with is helpful the application of using active sedimentation control in open drain.

6.2 Recommendations for Future Works

Even though application of fuzzy FMEA to tipping flush gate system had been conducted, the analysis should include more expertise knowledge to obtain more suggestions. More comprehensive risk analysis may be obtained. In order to provide good flushing operation environment for the tipping flush gate, the design of the trash trap needed to be improved. The effect of the trash trap to the tipping flush gate operation and performance still need to be further investigated. The problem of sediment build up behind the trash trap and plan for removing it can be further studied.

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APPENDICES

Appendix A Sediment Specific Gravity Data

Table A.1: Sediment d_{50} size (0.71 mm) specific gravity analysis

Pycnometer number	A1	A2	A3
mass of bottle + soil+ water, m3 (g)	89.797	88.864	90.432
mass of bottle + soil, m2 (g)	46.174	45.537	47.007
mass of bottle full of water, m4 (g)	80.034	79.520	81.041
mass of bottle, m1 (g)	30.332	30.325	31.476
mass of soil, m2-m1 (g)	15.842	15.212	15.531
mass of water in full bottle, m4-m1 (g)	49.702	49.195	49.565
mass of water used, m3-m2 (g)	43.623	43.327	43.425
volume of soil particles (m4-m1)-(m3-m2) (ml)	6.079	5.868	6.140
Particle density, mg/m3	2.606	2.592	2.529
Average value, mg/m3	2.576		

Table A.2: Sediment d_{50} size (1.18 mm) specific gravity analysis

Pycnometer number	B1	B2	B3
mass of bottle + soil+ water, m3 (g)	93.849	90.854	88.531
mass of bottle + soil, m2 (g)	51.111	47.917	44.350
mass of bottle full of water, m4 (g)	83.215	80.673	79.948
mass of bottle, m1 (g)	33.568	31.260	30.485
mass of soil, m2-m1 (g)	17.543	16.657	13.865
mass of water in full bottle, m4-m1 (g)	49.647	49.413	49.463
mass of water used, m3-m2 (g)	42.738	42.937	44.181
volume of soil particles (m4-m1)-(m3-m2) (ml)	6.909	6.476	5.282
Particle density, mg/m3	2.539	2.572	2.625
Average value, mg/m3	2.579		

Table A.3: Sediment d_{50} size (2 mm) specific gravity analysis

Pycnometer number	C1	C2	C3
mass of bottle + soil+ water, m3 (g)	91.894	91.157	87.774
mass of bottle + soil, m2 (g)	49.811	48.539	44.575
mass of bottle full of water, m4 (g)	80.773	80.165	76.693
mass of bottle, m1 (g)	31.601	30.682	26.431
mass of soil, m2-m1 (g)	18.210	17.857	18.144
mass of water in full bottle, m4-m1 (g)	49.172	49.483	50.262
mass of water used, m3-m2 (g)	42.083	42.618	43.199
volume of soil particles (m4-m1)-(m3-m2) (ml)	7.089	6.865	7.063
Particle density, mg/m3	2.569	2.601	2.569
Average value, mg/m3	2.580		

Appendix B Flushing Gate Experimental Data

Table B.1: Experiment data for various gate opening angle and sediment size

No. of Flush	Gate opening angle (deg)	Sediment size (mm)	Sediment thickness at 0.50m (cm)	Sediment thickness at 0.75m (cm)	Sediment thickness at 1.0m (cm)	Sediment thickness at 1.25m (cm)	Sediment thickness at 1.5m (cm)	Sediment thickness at 1.75m (cm)	Sediment thickness at 2m (cm)	Sediment thickness at 2.25m (cm)	Sediment thickness at 2.5m (cm)
0	90	2	5	5	5	5	5	5	5	5	5
5	90	2	0	4.1	4.4	4.2	3.7	1.7	1	1.2	1.2
10	90	2	0	0	4.2	4.2	3.4	2	1.2	1.5	1.3
15	90	2	0	0	0	2	3.3	2.3	1.7	1.4	1.4
20	90	2	0	0	0	0	0.2	1.6	2.2	1.9	1.7
25	90	2	0	0	0	0	0	0	0	0.3	2.2
0	75	2	5	5	5	5	5	5	5	5	5
5	75	2	0.5	3.8	4.2	3.9	3.6	1.7	1.2	1.7	1.7
10	75	2	0	2.6	3.8	2.9	2.9	1.8	1.2	1.8	1.9
15	75	2	0	0	2.9	2.9	2.8	2.1	1.1	1.7	1.7
20	75	2	0	0	0	2.8	3	2.1	1.5	1.2	1.1
25	75	2	0	0	0	0	1.4	1.7	1.6	1.5	1.3
0	50	2	5	5	5	5	5	5	5	5	5

Table B.1 continued

No. of Flush	Gate opening angle (deg)	Sediment size (mm)	Sediment thickness at 0.50m (cm)	Sediment thickness at 0.75m (cm)	Sediment thickness at 1.0m (cm)	Sediment thickness at 1.25m (cm)	Sediment thickness at 1.5m (cm)	Sediment thickness at 1.75m (cm)	Sediment thickness at 2m (cm)	Sediment thickness at 2.25m (cm)	Sediment thickness at 2.5m (cm)
5	50	2	0.2	3.7	4.2	4.2	3.9	2.2	1.5	1.5	1.3
10	50	2	0	2.9	3.7	3.9	3.5	2.2	1.9	1.2	1.2
15	50	2	0	0.2	3.6	3.4	3.2	2.5	1.7	1.4	1.5
20	50	2	0	0	0.2	2.9	3.5	2.9	2.8	1.8	1.5
25	50	2	0	0	0	0.2	2.6	3	2.9	2.5	2.5
0	90	1.18	5	5	5	5	5	5	5	5	5
5	90	1.18	0	3.5	4.1	3.5	3.1	1.8	1.8	1.8	1.8
10	90	1.18	0	0	2.3	3.6	2.9	2.1	1.2	1.2	1.2
15	90	1.18	0	0	0.1	2.2	2.2	1.5	1.3	1.2	1.1
20	90	1.18	0	0	0	0	0	0	1	1.9	1.8
25	90	1.18	0	0	0	0	0	0	0	0	0.1
0	75	1.18	5	5	5	5	5	5	5	5	5
5	75	1.18	0.2	3.5	4	3.8	3.5	1.8	1.1	1.4	2
10	75	1.18	0	3	3.4	3.1	2.8	1.7	1.9	1.6	1.6

Table B.1 continued

No. of Flush	Gate opening angle (deg)	Sediment size (mm)	Sediment thickness at 0.50m (cm)	Sediment thickness at 0.75m (cm)	Sediment thickness at 1.0m (cm)	Sediment thickness at 1.25m (cm)	Sediment thickness at 1.5m (cm)	Sediment thickness at 1.75m (cm)	Sediment thickness at 2m (cm)	Sediment thickness at 2.25m (cm)	Sediment thickness at 2.5m (cm)
15	75	1.18	0	0	2.8	2.6	2.6	2.1	1	1.2	1.5
20	75	1.18	0	0	0	2.5	2	2.1	1.4	1.2	1.3
25	75	1.18	0	0	0	0	1	2	2	1.7	1.5
0	50	1.18	5	5	5	5	5	5	5	5	5
5	50	1.18	0.3	3.5	3.9	3.9	3.6	2.6	1.4	1.7	1.8
10	50	1.18	0.1	2.9	3.9	3.1	3	2.1	1.4	1.5	1.8
15	50	1.18	0.1	0.5	3.2	3.4	2.6	2.1	1.5	1.4	1.5
20	50	1.18	0	0	2.1	3.8	3	2.2	1.5	1.1	1.1
25	50	1.18	0	0	0.1	2.5	2.5	1.7	1.3	1.2	1.2
0	90	0.71	5	5	5	5	5	5	5	5	5
5	90	0.71	0	3.4	4.2	4.2	3.2	1.9	0.9	1.2	1.4
10	90	0.71	0	0	2.7	3	2.8	1.7	0.9	1.2	1.1
15	90	0.71	0	0	0	1.2	1.6	1.4	1	1.2	1
20	90	0.71	0	0	0	0	0	0.1	0.2	1.1	1.2

Table B.1 continued

No. of Flush	Gate opening angle (deg)	Sediment size (mm)	Sediment thickness at 0.50m (cm)	Sediment thickness at 0.75m (cm)	Sediment thickness at 1.0m (cm)	Sediment thickness at 1.25m (cm)	Sediment thickness at 1.5m (cm)	Sediment thickness at 1.75m (cm)	Sediment thickness at 2m (cm)	Sediment thickness at 2.25m (cm)	Sediment thickness at 2.5m (cm)
25	90	0.71	0	0	0	0	0	0	0	0	0.1
0	75	0.71	5	5	5	5	5	5	5	5	5
5	75	0.71	0	2.8	3.5	3.4	3.2	1.8	1.2	1.4	1.5
10	75	0.71	0	0	3	2.6	2.4	1.6	1	1.2	1.1
15	75	0.71	0	0	0	1.9	2.2	1.2	1.2	1.2	1.4
20	75	0.71	0	0	0	0	1.8	1.2	1.4	1.6	1.6
25	75	0.71	0	0	0	0	0	0	0	1.3	2
0	50	0.71	5	5	5	5	5	5	5	5	5
5	50	0.71	0	3.5	3.8	4.2	3.4	1.8	1.1	1.1	1.5
10	50	0.71	0	0	3.2	3.3	3	1.8	1.5	1.5	1.7
15	50	0.71	0	0	0.2	2.3	2.9	2.2	1.7	1.7	1.7
20	50	0.71	0	0	0	0	2.3	2.3	1.5	1.5	1.6
25	50	0.71	0	0	0	0	0	1	2.1	2.1	2.2

Table B.2: Experiment data for various sediment bed length

No. of Flush	Sediment bed length	Sediment size (mm)	Sediment thickness at 0.50m (cm)	Sediment thickness at 0.75m (cm)	Sediment thickness at 1.0m (cm)	Sediment thickness at 1.25m (cm)	Sediment thickness at 1.5m (cm)	Sediment thickness at 1.75m (cm)	Sediment thickness at 2m (cm)	Sediment thickness at 2.25m (cm)	Sediment thickness at 2.5m (cm)
0	0.5m	2	5	5	5	0	0	0	0	0	0
5	0.5m	2	0	0.2	1.5	1.5	0.9	0.9	0.5	0.3	0.5
10	0.5m	2	0	0	0	0	0.5	0.9	0.6	0.8	0.4
15	0.5m	2	0	0	0	0	0	0	0	0.7	1.7
20	0.5m	2	0	0	0	0	0	0	0	0	0.1
25	0.5m	2	0	0	0	0	0	0	0	0	0
0	1m	2	5	5	5	5	5	0	0	0	0
5	1m	2	0.2	3	2.3	2.3	1.7	0.9	0.7	0.7	0.7
10	1m	2	0	0.2	0.9	1.4	2.5	1.6	1	1	0.9
15	1m	2	0	0	0.2	0	1.3	1.8	1.4	1.7	1
20	1m	2	0	0	0	0	0	0.2	1.7	2	1.8
25	1m	2	0	0	0	0	0	0	0	0.5	1.8
0	2m	2	5	5	5	5	5	5	5	5	5
5	2m	2	0.2	3.7	4.2	4.2	3.9	2.2	1.5	1.5	1.3

Table B.2 continued

No. of Flush	Sediment bed length	Sediment size (mm)	Sediment thickness at 0.50m (cm)	Sediment thickness at 0.75m (cm)	Sediment thickness at 1.0m (cm)	Sediment thickness at 1.25m (cm)	Sediment thickness at 1.5m (cm)	Sediment thickness at 1.75m (cm)	Sediment thickness at 2m (cm)	Sediment thickness at 2.25m (cm)	Sediment thickness at 2.5m (cm)
10	2m	2	0	2.9	3.7	3.9	3.5	2.2	1.9	1.2	1.2
15	2m	2	0	0.2	3.6	3.4	3.2	2.5	1.7	1.4	1.5
20	2m	2	0	0	0.2	2.9	3.5	2.9	2.8	1.8	1.5
25	2m	2	0	0	0	0.2	2.6	3	2.9	2.5	2.5
0	0.5m	1.18	5	5	5	0	0	0	0	0	0
5	0.5m	1.18	0	0.1	1	1.4	1	0.3	0.2	0.2	0.7
10	0.5m	1.18	0	0	0	0	0.1	0.6	1.3	1.1	1.1
15	0.5m	1.18	0	0	0	0	0	0	0	0	1.3
20	0.5m	1.18	0	0	0	0	0	0	0	0	0
25	0.5m	1.18	0	0	0	0	0	0	0	0	0
0	1m	1.18	5	5	5	5	5	0	0	0	0
5	1m	1.18	0.2	3.5	2.5	1.9	1.4	0.6	0.5	0.5	0.5
10	1m	1.18	0	0.2	2.1	1.8	1.8	1.1	0.9	1.1	1.3
15	1m	1.18	0	0	0	0	1.6	1.5	1.2	1.5	1.4

Table B.2 continued

No. of Flush	Sediment bed length	Sediment size (mm)	Sediment thickness at 0.50m (cm)	Sediment thickness at 0.75m (cm)	Sediment thickness at 1.0m (cm)	Sediment thickness at 1.25m (cm)	Sediment thickness at 1.5m (cm)	Sediment thickness at 1.75m (cm)	Sediment thickness at 2m (cm)	Sediment thickness at 2.25m (cm)	Sediment thickness at 2.5m (cm)
20	1m	1.18	0	0	0	0	0	0	1.4	2.2	1.7
25	1m	1.18	0	0	0	0	0	0	0	0.2	1.8
0	2m	1.18	5	5	5	5	5	5	5	5	5
5	2m	1.18	0.3	3.5	3.9	3.9	3.6	2.6	1.4	1.7	1.8
10	2m	1.18	0.1	2.9	3.9	3.1	3	2.1	1.4	1.5	1.8
15	2m	1.18	0.1	0.5	3.2	3.4	2.6	2.1	1.5	1.4	1.5
20	2m	1.18	0	0	2.1	3.8	3	2.2	1.5	1.1	1.1
25	2m	1.18	0	0	0.1	2.5	2.5	1.7	1.3	1.2	1.2
0	0.5m	0.71	5	5	5	0	0	0	0	0	0
5	0.5m	0.71	0	0	1.1	1.5	1.3	0.8	0.2	0.2	0.3
10	0.5m	0.71	0	0	0	0	0	0.2	1	1.3	0.1
15	0.5m	0.71	0	0	0	0	0	0	0	0	0.8
20	0.5m	0.71	0	0	0	0	0	0	0	0	0
25	0.5m	0.71	0	0	0	0	0	0	0	0	0

Table B.2 continued

No. of Flush	Sediment bed length	Sediment size (mm)	Sediment thickness at 0.50m (cm)	Sediment thickness at 0.75m (cm)	Sediment thickness at 1.0m (cm)	Sediment thickness at 1.25m (cm)	Sediment thickness at 1.5m (cm)	Sediment thickness at 1.75m (cm)	Sediment thickness at 2m (cm)	Sediment thickness at 2.25m (cm)	Sediment thickness at 2.5m (cm)
0	1m	0.71	5	5	5	5	5	0	0	0	0
5	1m	0.71	0	2.5	2.5	2.3	1.4	0.7	0.5	0.7	0.8
10	1m	0.71	0	0	1.5	2.2	1.6	1	0.7	0.5	0.8
15	1m	0.71	0	0	0	0	1.5	0.9	1.1	1.3	1.3
20	1m	0.71	0	0	0	0	0	0	0.2	1.5	1.7
25	1m	0.71	0	0	0	0	0	0	0	0	0.2
0	2m	0.71	5	5	5	5	5	5	5	5	5
5	2m	0.71	0	3.5	3.8	4.2	3.4	1.8	1.1	1.1	1.5
10	2m	0.71	0	0	3.2	3.3	3	1.8	1.5	1.5	1.7
15	2m	0.71	0	0	0.2	2.3	2.9	2.2	1.7	1.7	1.7
20	2m	0.71	0	0	0	0	2.3	2.3	1.5	1.5	1.6
25	2m	0.71	0	0	0	0	0	1	2.1	2.1	2.2

Table B.3: Experiment data for various flushing duration

Duration Type	Distance from the gate (m)	Initial sediment thickness (cm)	Sediment thickness after 1.5 mins flushing (cm)	Sediment thickness after 3.0 mins flushing (cm)	Sediment thickness after 4.5 mins flushing (cm)	Sediment thickness after 6.0 mins flushing (cm)	Sediment thickness after 7.5 mins flushing (cm)
short	0.50	5	0	0	0	0	0
short	0.75	5	3.3	0	0	0	0
short	1.00	5	3.5	0	0	0	0
short	1.25	5	3.4	2.5	0	0	0
short	1.50	5	3.2	3	0.2	0	0
short	1.75	5	1.9	2	1.9	0	0
short	2.00	5	1.3	1	2.1	0	0
short	2.25	5	1.5	0.8	2.4	0.2	0
short	2.50	5	1.6	1	1.8	2	0
long	0.50	5	0	0	0	0	0
long	0.75	5	2.8	0	0	0	0
long	1.00	5	4.1	3.1	2.3	0	0
long	1.25	5	3.8	3.8	2.6	2.3	0
long	1.50	5	3.3	4.1	3.5	2.2	1.7
long	1.75	5	2	2.3	3	2.3	1.6
long	2.00	5	0.5	0.6	1.8	1.9	1.6
long	2.25	5	1.2	1	1.1	2.5	2.1
long	2.50	5	1.3	1.2	0.7	2	1.7
long	2.00	5	0.5	0.6	1.8	1.9	1.6
long	2.25	5	1.2	1	1.1	2.5	2.1
long	2.50	5	1.3	1.2	0.7	2	1.7

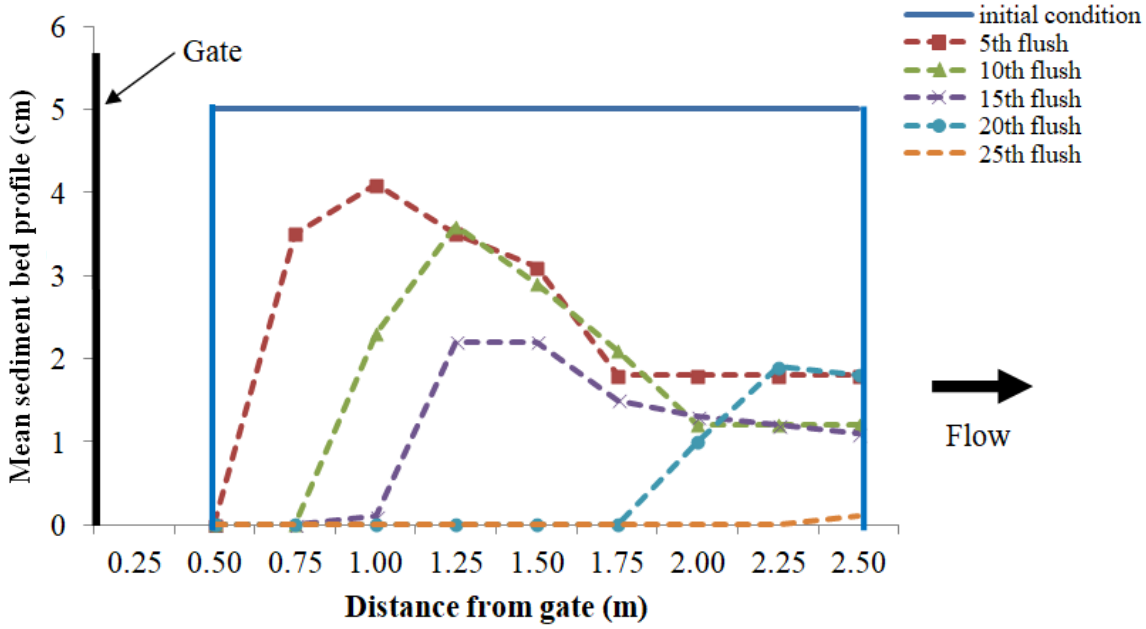

Figure B.1: Sediment profiles for sediment d_{50} of 1.18 mm laid starting from 0.5 m from the gate with θ = 90° after flushes for 5 cm initial sediment deposition thickness

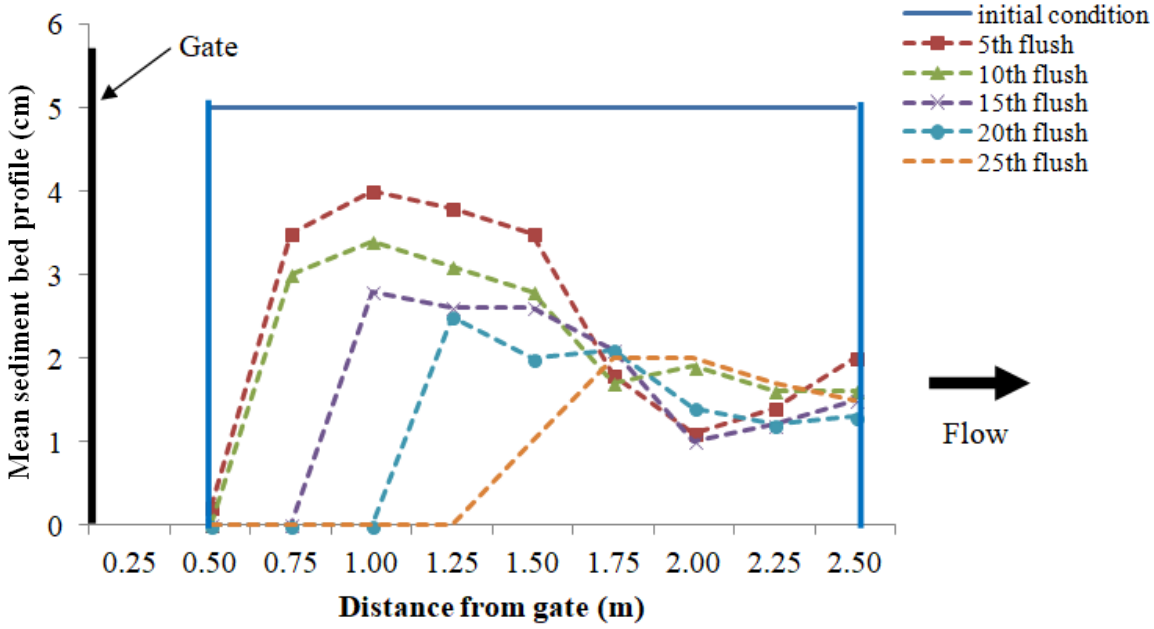

Figure B.2: Sediment profiles for sediment d_{50} of 1.18 mm laid starting from 0.5 m from the gate with θ = 75° after flushes for 5 cm initial sediment deposition thickness

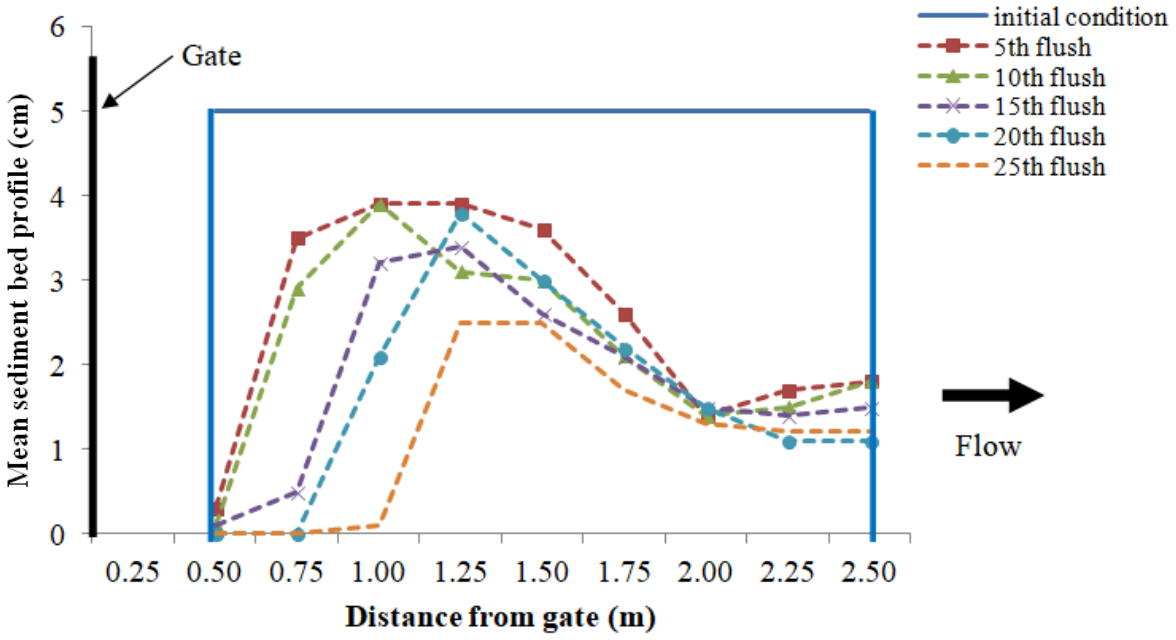

Figure B.3: Sediment profiles for sediment d_{50} of 1.18 mm laid starting from 0.5 m from the gate with $\theta = 60°$ after flushes for 5 cm initial sediment deposition thickness

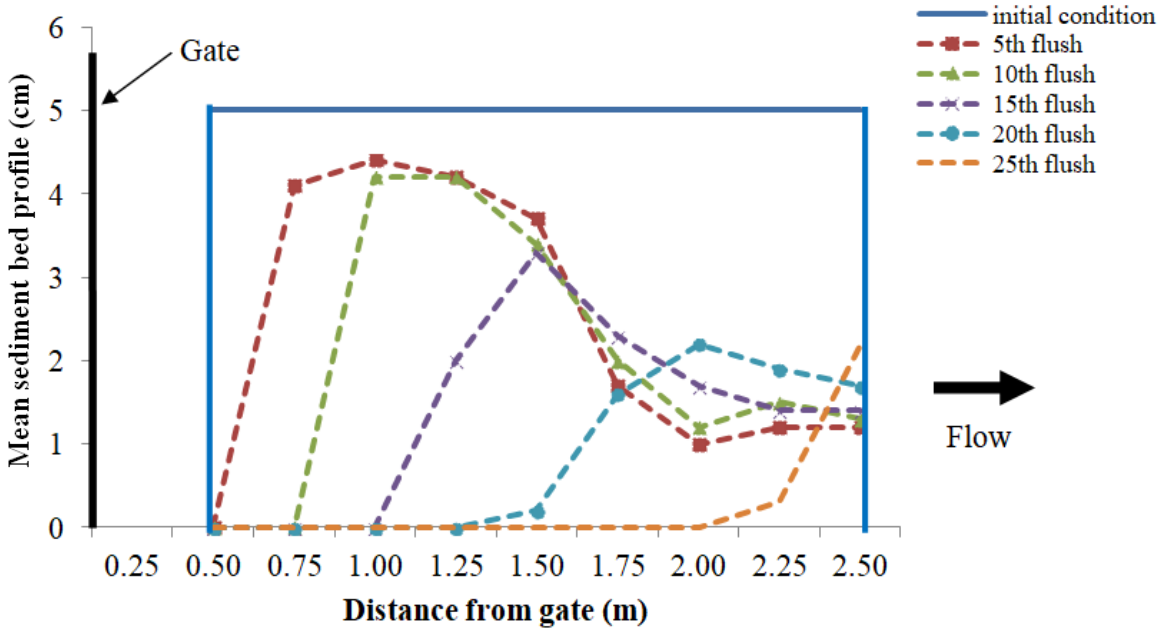

Figure B.4: Sediment profiles for sediment d_{50} of 2 mm laid starting from 0.5 m from the gate with $\theta = 90°$ after flushes for 5 cm initial sediment deposition thickness

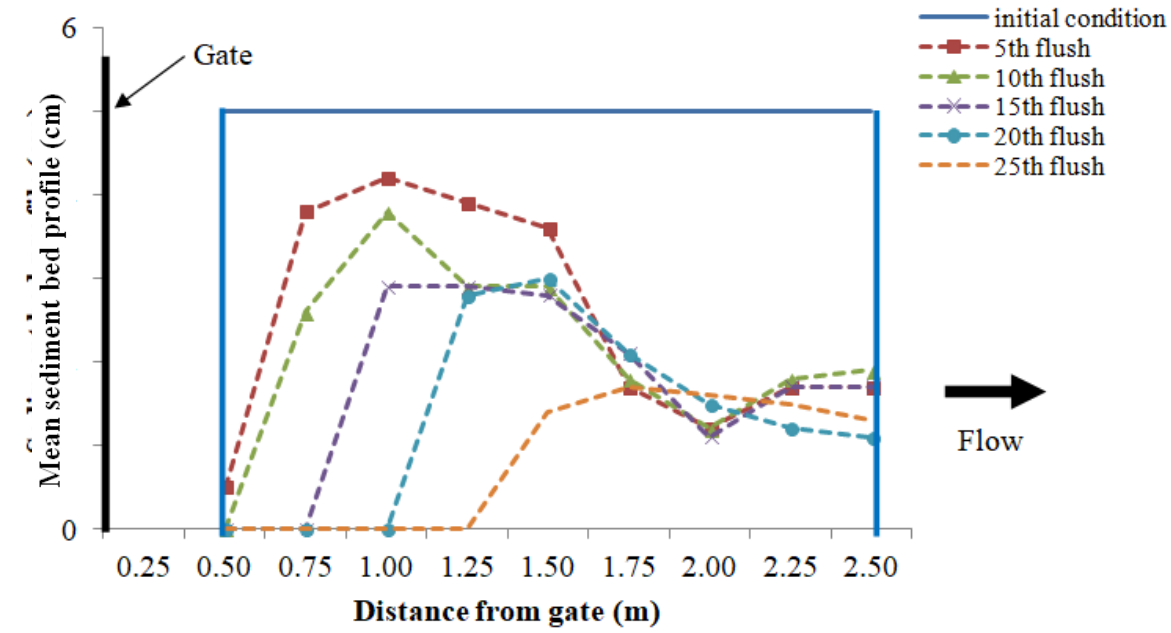

Figure B.5: Sediment profiles for sediment d_{50} of 2 mm laid starting from 0.5 m from the gate with θ = 75° after flushes for 5 cm initial sediment deposition thickness

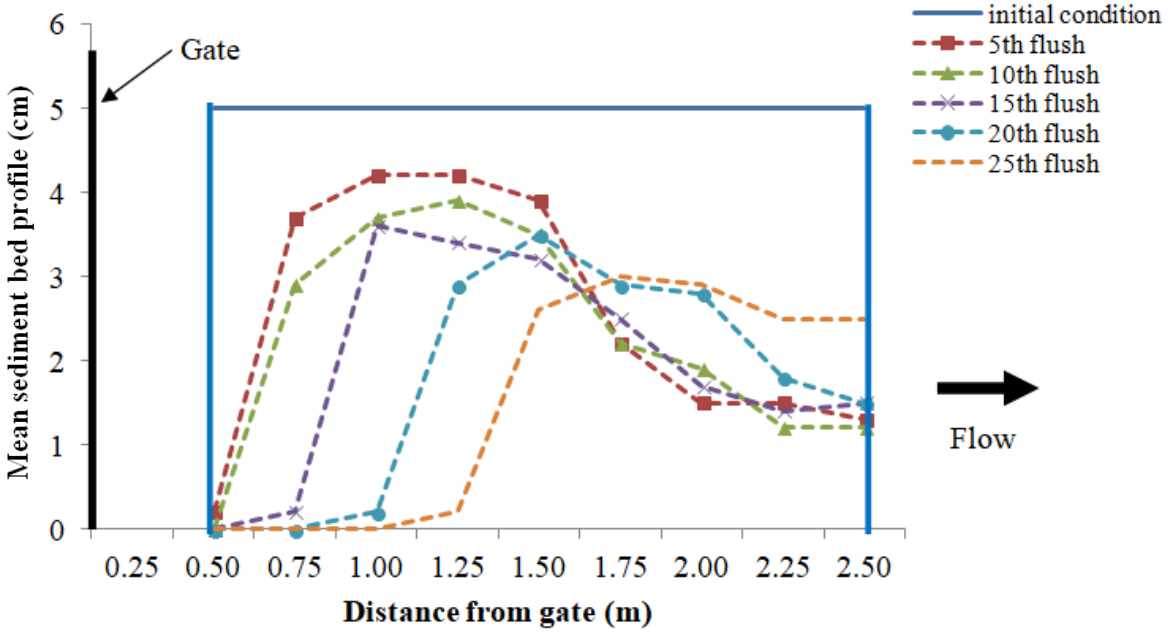

Figure B.6: Sediment profiles for sediment d_{50} of 2 mm laid starting from 0.5 m from the gate with θ = 60° after flushes for 5 cm initial sediment deposition thickness

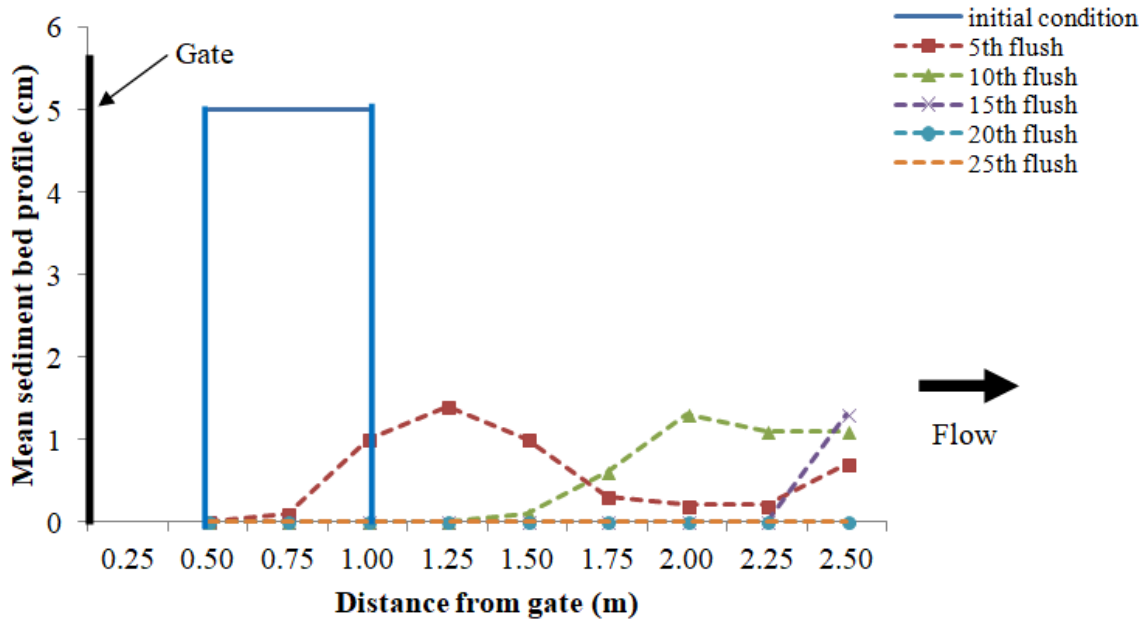

Figure B.7: Sediment profiles for sediment d_{50} of 1.18 mm laid starting from 0.5 m to 1.0m from the gate with $\theta = 60°$ after flushes for 5 cm initial sediment deposition thickness

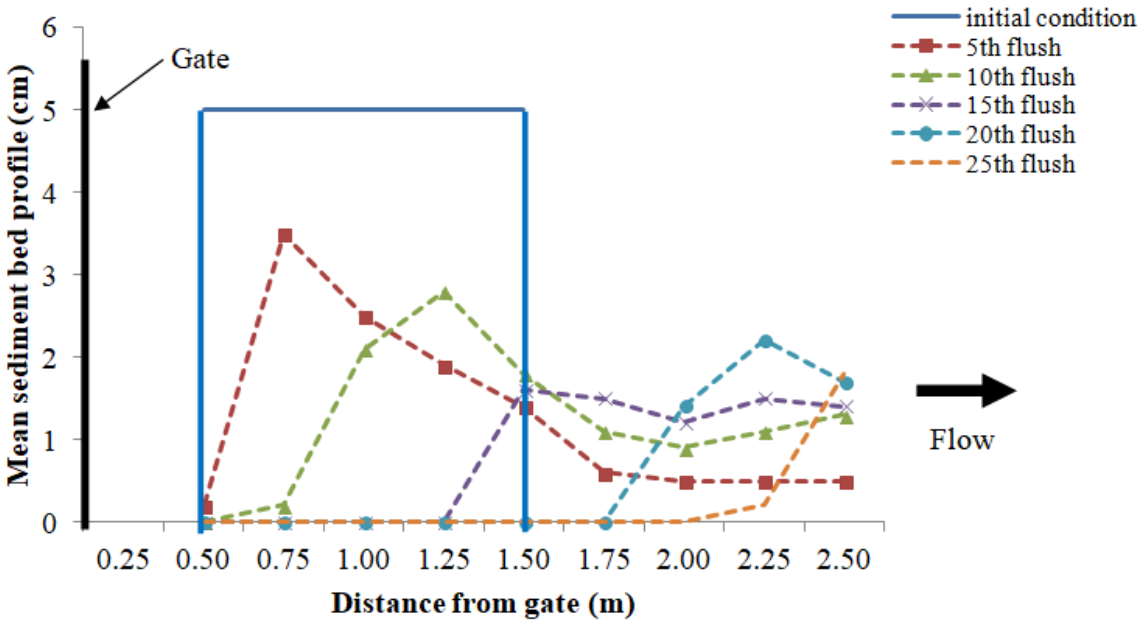

Figure B.8: Sediment profiles for sediment d_{50} of 1.18 mm laid starting from 0.5 m to 1.5m from the gate with $\theta = 60°$ after flushes for 5 cm initial sediment deposition thickness

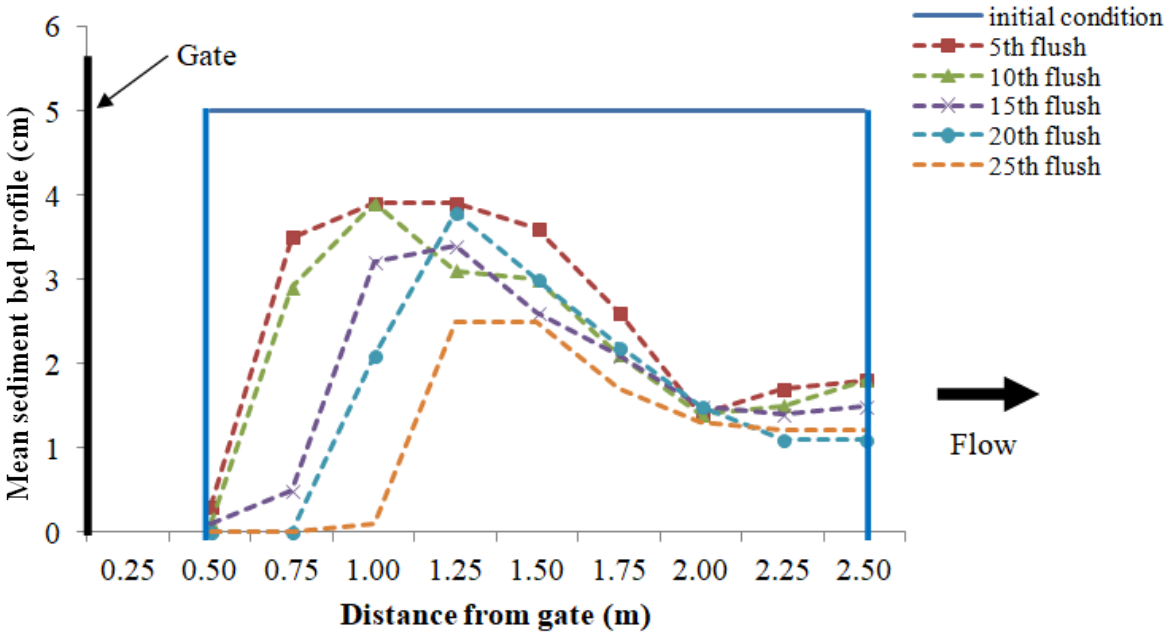

Figure B.9: Sediment profiles for sediment d_{50} of 1.18 mm laid starting from 0.5 m to 2.5 m from the gate with $\theta = 60°$ after flushes for 5 cm initial sediment deposition thickness

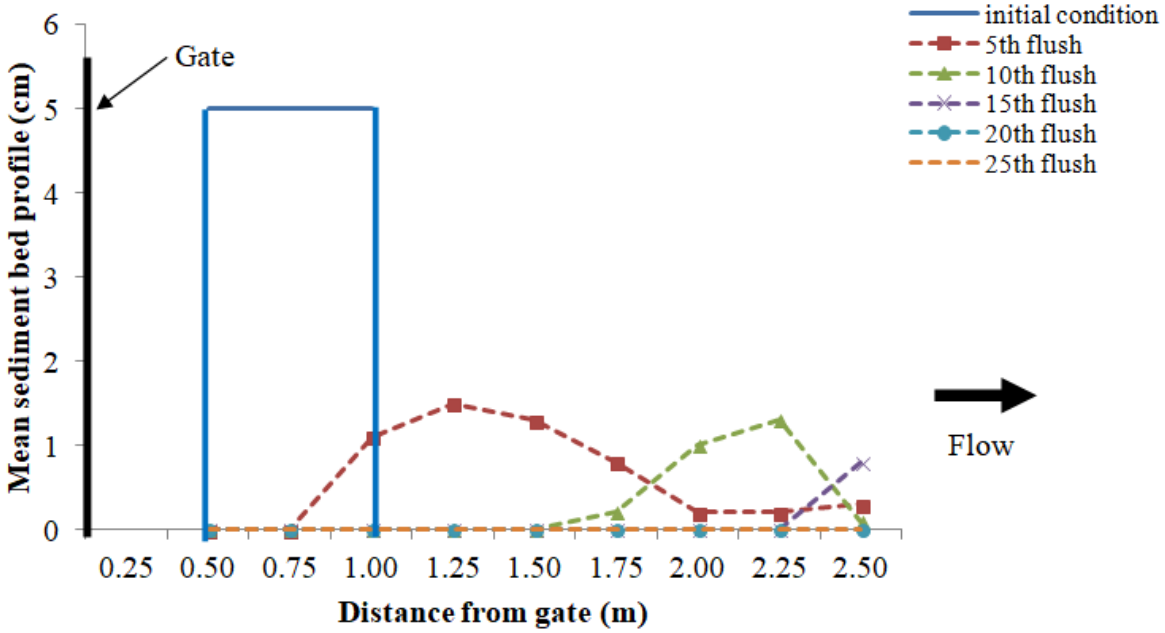

Figure B.10: Sediment profiles for sediment d_{50} of 0.71 mm laid starting from 0.5 m to 1.0m from the gate with $\theta = 60°$ after flushes for 5 cm initial sediment deposition thickness

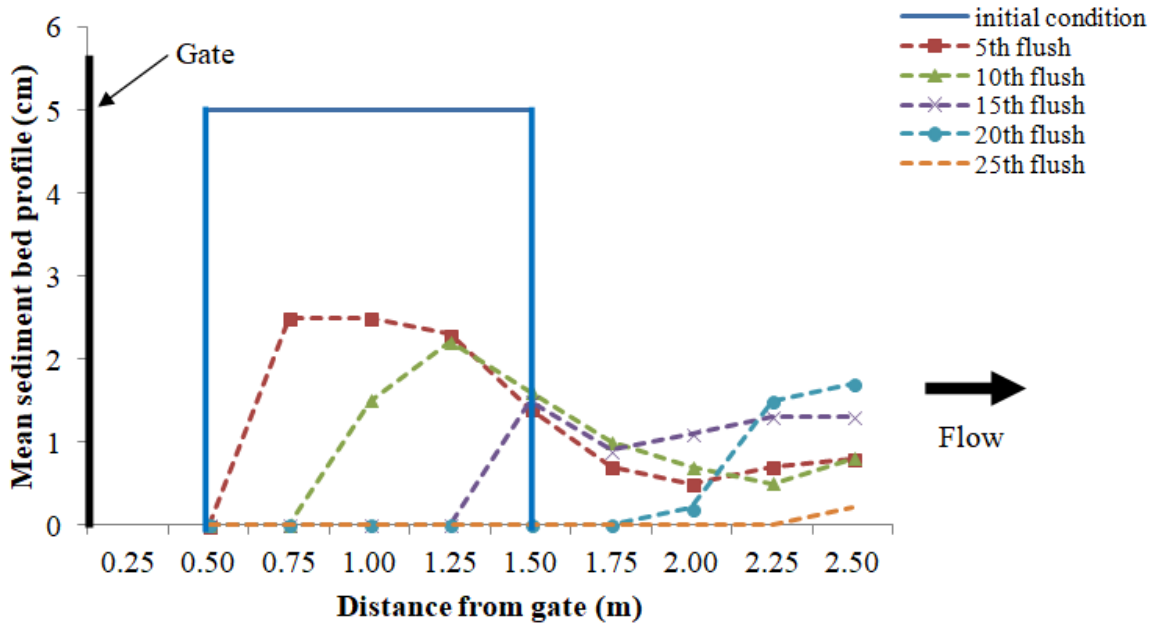

Figure B.11: Sediment profiles for sediment d_{50} of 0.71 mm laid starting from 0.5 m to 1.5m from the gate with $\theta = 60°$ after flushes for 5 cm initial sediment deposition thickness

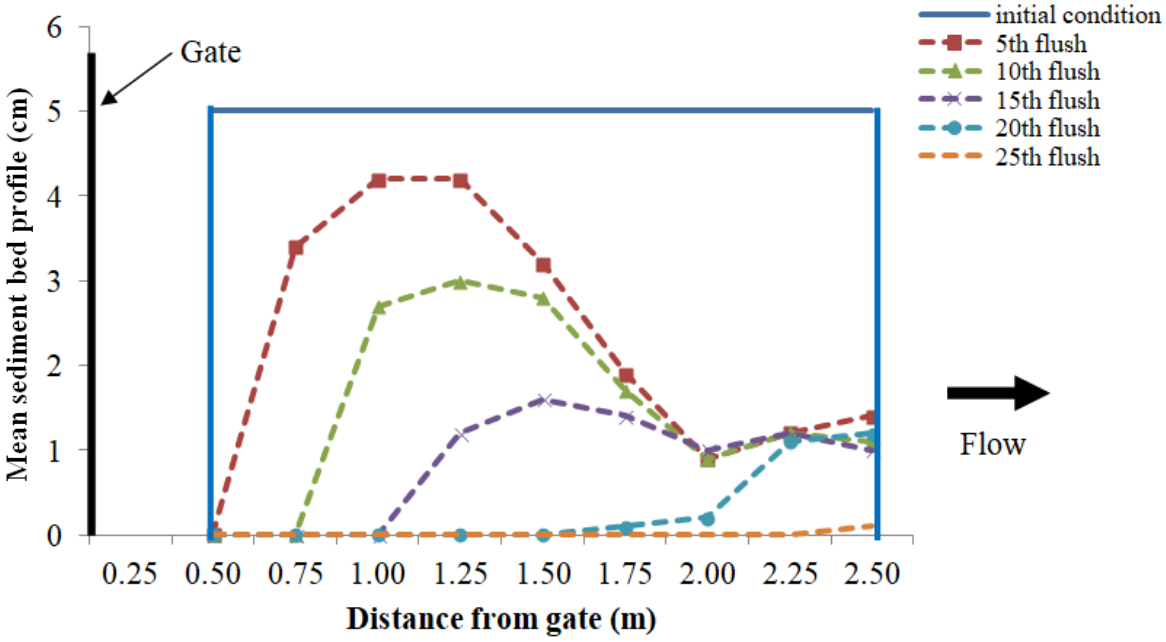

Figure B.12: Sediment profiles for sediment d_{50} of 0.71 mm laid starting from 0.5 m to 2.5 m from the gate with $\theta = 90°$ after flushes for 5 cm initial sediment deposition thickness

Appendix C - 125 Fuzzy Database for Application of FUZZY FMEA to Tipping Flush Gate Design

Expert:
Department:
Email:

No	Severity	Occurance	Dectection	Output
1	Remote	Remote	Very High	
2	Remote	Remote	High	
3	Remote	Remote	Moderate	
4	Remote	Remote	Low	
5	Remote	Remote	Very Low	
6	Remote	Low	Very High	
7	Remote	Low	High	
8	Remote	Low	Moderate	
9	Remote	Low	Low	
10	Remote	Low	Very Low	
11	Remote	Moderate	Very High	
12	Remote	Moderate	High	
13	Remote	Moderate	Moderate	
14	Remote	Moderate	Low	
15	Remote	Moderate	Very Low	
16	Remote	High	Very High	
17	Remote	High	High	
18	Remote	High	Moderate	
19	Remote	High	Low	
20	Remote	High	Very Low	
21	Remote	Very High	Very High	
22	Remote	Very High	High	
23	Remote	Very High	Moderate	
24	Remote	Very High	Low	
25	Remote	Very High	Very Low	
26	Low	Remote	Very High	
27	Low	Remote	High	
28	Low	Remote	Moderate	
29	Low	Remote	Low	
30	Low	Remote	Very Low	
31	Low	Low	Very High	
32	Low	Low	High	
33	Low	Low	Moderate	

34	Low	Low	Low	
35	Low	Low	Very Low	
36	Low	Moderate	Very High	
37	Low	Moderate	High	
38	Low	Moderate	Moderate	
39	Low	Moderate	Low	
40	Low	Moderate	Very Low	
41	Low	High	Very High	
42	Low	High	High	
43	Low	High	Moderate	
44	Low	High	Low	
45	Low	High	Very Low	
46	Low	Very High	Very High	
47	Low	Very High	High	
48	Low	Very High	Moderate	
49	Low	Very High	Low	
50	Low	Very High	Very Low	
51	Moderate	Remote	Very High	
52	Moderate	Remote	High	
53	Moderate	Remote	Moderate	
54	Moderate	Remote	Low	
55	Moderate	Remote	Very Low	
56	Moderate	Low	Very High	
57	Moderate	Low	High	
58	Moderate	Low	Moderate	
59	Moderate	Low	Low	
60	Moderate	Low	Very Low	
61	Moderate	Moderate	Very High	
62	Moderate	Moderate	High	
63	Moderate	Moderate	Moderate	
64	Moderate	Moderate	Low	
65	Moderate	Moderate	Very Low	
66	Moderate	High	Very High	
67	Moderate	High	High	
68	Moderate	High	Moderate	
69	Moderate	High	Low	
70	Moderate	High	Very Low	
71	Moderate	Very High	Very High	
72	Moderate	Very High	High	
73	Moderate	Very High	Moderate	
74	Moderate	Very High	Low	

75	Moderate	Very High	Very Low	
76	High	Remote	Very High	
77	High	Remote	High	
78	High	Remote	Moderate	
79	High	Remote	Low	
80	High	Remote	Very Low	
81	High	Low	Very High	
82	High	Low	High	
83	High	Low	Moderate	
84	High	Low	Low	
85	High	Low	Very Low	
86	High	Moderate	Very High	
87	High	Moderate	High	
88	High	Moderate	Moderate	
89	High	Moderate	Low	
90	High	Moderate	Very Low	
91	High	High	Very High	
92	High	High	High	
93	High	High	Moderate	
94	High	High	Low	
95	High	High	Very Low	
96	High	Very High	Very High	
97	High	Very High	High	
98	High	Very High	Moderate	
99	High	Very High	Low	
100	High	Very High	Very Low	
101	Very High	Remote	Very High	
102	Very High	Remote	High	
103	Very High	Remote	Moderate	
104	Very High	Remote	Low	
105	Very High	Remote	Very Low	
106	Very High	Low	Very High	
107	Very High	Low	High	
108	Very High	Low	Moderate	
109	Very High	Low	Low	
110	Very High	Low	Very Low	
111	Very High	Moderate	Very High	
112	Very High	Moderate	High	
113	Very High	Moderate	Moderate	
114	Very High	Moderate	Low	
115	Very High	Moderate	Very Low	

116	Very High	High	Very High	
117	Very High	High	High	
118	Very High	High	Moderate	
119	Very High	High	Low	
120	Very High	High	Very Low	
121	Very High	Very High	Very High	
122	Very High	Very High	High	
123	Very High	Very High	Moderate	
124	Very High	Very High	Low	
125	Very High	Very High	Very Low	

Score	Output
	Remote (1)
	Low (2)
	Moderate (3)
	High (4)
	Very High (5)
Score is from 0-1000	

Appendix D - Questionnaire for Data Collection

"APPLICATION OF FUZZY FMEA TO HYDRAULC FLUSHING GATE"

Questionnaire No. _____

Dear Researchers / Consultants,

I am inviting you to participate in this research project to survey the critical factors that might result in the failure of hydraulic flushing gate in open/ close drain. This survey is carried out as a part of the Bachelor of Engineering with Honours (Civil Engineering), at Universiti Malaysia Sarawak. This questionnaire consists of 25 questions that focus on obtaining views from the experts regarding the potential failure mode of hydraulic flushing gate and its effect for sediment removal in open drain.

Based on this survey, I want to understand and introduce what can be the possible preventive measures, strategies and guideline to avoid the failure mode of hydraulic flushing gate implementation at open drain. I have attached a short questionnaire about the failure factors for the hydraulic flush gate. The questionnaire can be found on the form itself. Each questionnaire is numbered to help keep track of the return. I promise that I will respect your privacy. I will make sure that your answers cannot be linked to you personally. Please be assured that all the information you provided will be used for academic research only.

If you choose to participate in this survey, please fill in your answers and send the questionnaire back to me. There is no risk to you and your privacy if you decide to join this study by filling out this questionnaire. Participation in this study is voluntary. You can choose not to take part and you can choose not to finish the questionnaire or omit any question you prefer not to answer without penalty or loss of benefits. Even if you decide not to participate that is fine. I will be very happy to share my result with you if you are interested.

If you have any questions about the survey, or about being in this study as FMEA team members, you may contact me at leongteng93@gmail.com. I hope you will view this as an important matter, and take some of your time to complete the questionnaire as your participation represents a valuable contribute to this research project. Thank you in advance for your valuable time and effort in completing the questionnaire. Your help is greatly appreciated.

This survey deals with identification of the failure mode and effect of the failure of hydraulic flushing gate implementation in Malaysia. While filling this questionnaire, please do consider the following scenario:

Country	Malaysia
Type of Channel	Open
Type of Hydraulic Flushing Gate Proposed	Tipping Flushing Gate (refer to **Figure 1** and **Table 1**)
Purpose of Hydraulic Flushing Gate	Removal of sediment deposited in open drain.
Main Material for The Gate	GCV Plasboard (Density:1092 kg/m^3 ; Thickness:12 mm)
Please do consider the implementation of hydraulic flush gate project cycle start from Planning > Design > Assembly > Implementation > Operation and Maintenance > Improvement ✓ Planning: Scoping the project, Identify the System, and approval of budget and schedule. ✓ Design: Design the hydraulic flushing gate based on the hydraulic characteristic of the gate and flushing mechanism. ✓ Assembly: Assembly all the components to produce a flushing device. ✓ Implementation: Configuring and implementing the flushing device in channel. ✓ Operation and Maintenance: Implementation problems are identify and fixed and flushing performance improves. ✓ Improvement: Achieving the benefits and focusing on continuous improvement and transformation.	

Fuzzy Failure Mode and Effect Analysis (FMEA): Fuzzy FMEA is applied to hydraulic flushing gate as early preventative plans in design which helps to avoid known failure and errors from happening. This analysis also provides framework of information for risk management decision making.

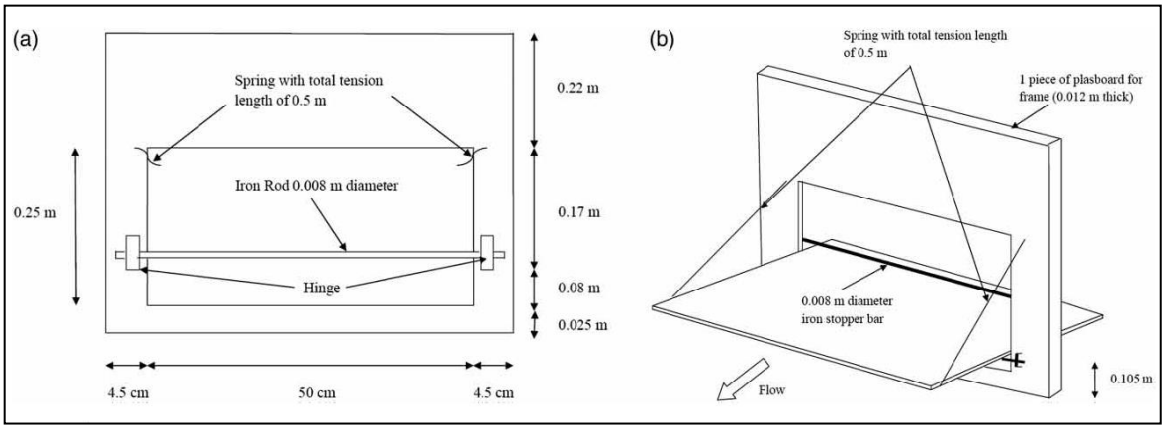

Figure 1. Views of the model tipping flush gate (a) front view; and (b) isometric view (not to scale) (Bong, Lau and Ab. Ghani, 2013)

Table 1. The function of the tipping flush gate components

Component	Function
Spring	To ensure proper closing.
Iron stopper bar (behind the gate)	To prevent the agate from tipping further from the desire angle of opening (during opening) and also to avoid the gate tipping further when closing.
Hinge	To enable the gate performs rotation.
Wooden bar frame	To prevent the gate from buckling due to pressure of water.
Iron rod	To attach the gate with the hinges.
Rubber gate holder (below the gate)	To prevent water leaking.
Wooden gate holder (at both side the gate)	To hold the gate properly.
Gate opening	To store water at storage phase and release water when flushing.

SECTION A: General Information

Expert Name	
University/ Organization Name	
Current Position	
Nationality	
Type of Hydraulic Flushing Gate Implemented/ Proposed/ Study	Hydrass Gate/ Hydroself Flushing Gate/ Tipping Flush Gate/ Chamber with Gate/ Tipping Bucket Other: _____
Sectors which Hydraulic Flush Gate Implementation done by you	Research ( ) Industry: Manufacturing ( )/ Assembly Line ( )/ Service ( ) Other: _____
Years of Experience in the Sector	

SECTION B: Hydraulic Flushing

1. How you define sediment removal efficiency of hydraulic flushing?

_____

_____

_____

SECTION C: Potential Failure Mode of Tipping Flushing Gate

Please do rank in the box which best represents your opinion for the potential failure mode and effect of the hydraulic flush gate implementation on a scale of 1 to 10 based on scale table for severity, occurrence and detection (refer to Table 2, Table 3 and Table 4 respectively. (Please rank **Only One** value for each question).

Table 2. Scale table for Severity (*Sev*)

Ranking	**Description**
1-2	The failure has no effect on the performance of gate, and the failure may not notice. Gate can open easily and close properly. Good flushing performance.
3-4	The failure cause a sight effect on the performance of gate, and the failure can be notice. Gate can open but slightly hard to close. Flushing performance still can perform.
5-7	The failure causes effect on the gate and flushing performance, and the failure will be notice clearly. Gate totally open and cannot close. Flushing performance only occurs once.
8-9	The failure cause significant effect on the gate but deterioration in flushing performance, and the failure will be notice clearly. Gate hard to open and close. Flushing performance is hard to perform.
10	The failure would seriously affect the ability to complete the function, no flushing effect occurs and cause the whole system fail to operate.

Table 3. Scale table for Occurrence (*Occ*)

Ranking	**Description**
1-2	The failure is unlikely.
3-4	Relatively few failures.
5-6	Likely to occur more than once.
7-8	Repeated failures.
9-10	Failure is almost inevitable.

Table 4. Scale table for Detection (*Det*)

Ranking	**Description**
1-2	Failure would almost be detected during inspection.
3-4	Failure may be detected during inspection.
5-6	Failure remains undetected until the system performance is affected.
7-8	Failure remains undetected until the system performance is reduced.
9-10	Failure remains undetected until the function of system is ceased.

Please do read the following statement and rank it in appropriate box to express your degree of opinion regarding your views about **severity, occurrence and detection** of the **potential failure mode of tipping flushing gate implementation.**	Scale		
	Sev	*Occ*	*Det*
1. Improper closing of gate.			
2. Improper opening of gate.			
3. Loosen of screw during assembly or service of flushing gate.			
4. Damage of gate surface area.			
5. Stress crack at gate frame.			
6. Improper fitting between gate frame and drainage.			
7. Rusting on iron stopper bar.			
8. Loss spring strength.			
9. Spring broken.			
10. Spring corrosion.			
11. Wrong position of the hinge.			
12. Cracking of rubber below the gate holder.			

13. Bending of gate frame.			
14. Improper installation of gate holder.			
15. Improper installation of stopper bar.			
16. Join separation at hinge.			
17. Bending of gate.			
18. Damage of gate frame.			
19. Improper location of the iron stopper bar (behind the gate).			
20. Improper wooden bar frame/gate holder installation.			
21. Rusting on iron rod.			
22. Loosen in fitting between iron rod and hinge.			
23. Loosen of screw during assembly or service of wooden gate holder to drainage.			
24. Water leaking through gate frame.			
25. Water leaking between the gate and gate frame.			

****SECTION D: <u>Others Suggestions for Improvement Based on Other Type of Hydraulic Flush Gate</u>**

Based on your experience, what are the potential failure modes and effect of hydraulic flushing gate during design, assembly and implementation stage? Please do advice any potential failure modes, effects and causes which are missing in above questionnaire but that will contribute in the hydraulic flushing implementation at open channel.

Type of Hydraulic Flushing Gate: _____					Scale		
Item/ Function	Potential Failure Modes	Potential Effect of Failure	Potential Cause of Failure	Action Taken	Sev	Occ	Det

Attachment (if any):

Thank you for your cooperation!
Thank you for your participation and valuable suggestion.

I sincerely thank you for your valuable time and information which will help me with a great deal. I assure you complete confidentially of the information given by you.

Sincerely,

Leong Geok Teng

REFERENCES

Ab. Ghani, A., Bong, C. H. J., & Lau, T. L. (2013). Sediment Flushing using Tipping Flush Gate in an Open Storm Concrete Drain - A Case Study in Nibong Tebal, Penang , Malaysia. In *IAHR World Congress*.

Bong, C. H. J., Lau, T. L., & Ab. Ghani, A. (2013). Hydraulics characteristics of tipping sediment flushing gate. *Water Science & Technology, 68*(11), 2397-2406.

Bong, C. H. J., Lau, T. L., & Ab. Ghani, A. (2016). Potential of tipping flush gate for sedimentation management in open stormwater sewer. *Urban Water Journal, 13*(5), 486-498.